Automated cancellation of direct feedthrough in magnetic particle imaging

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Abstract: Magnetic Particle Imaging (MPI) uses oscillating magnetic fields for measuring the spatial distribution of magnetic nanoparticles. Due to the simultaneous excitation and acquisition, a feedthrough voltage is induced in the receive coil, limiting the available dynamic range of the converters for the digitization of the particle response. This can be overcome by using an automated cancellation process based on an adaptive feedforward control algorithm. The FPGA implementation shows a dampening factor of Δ=2.7±0.3 compared to an ideal factor of Δ=4.6.

I. Introduction

Magnetic particle imaging (MPI) uses an oscillating magnetic field for exciting magnetic nanoparticles, which change their magnetization and therefore induce a signal in a receive coil [1]. This signal is superimposed by the excitation signal, which couples into the receive chain and is usually several orders of magnitude higher. Due to the limited dynamic range of available analog-to-digital converters (ADC) it is a challenging task to distinguish the particle signal from the system background [2].

Common solutions to this problem are analog band-stop filters removing the strong signal at the fundamental frequency and gradiometric setups, cancelling the excitation signal with a second coil of opposing polarity, which only detects the excitation signal. However, both solutions have intrinsic issues. Band-stop filters do not only reduce the excitation feedthrough but also the first harmonic of the particle signal and cancellation setups are limited in their attenuation due to the necessary phase precision [2].

In this article we propose an alternative solution to the problem by actively creating an inverse signal, which can be used to cancel the interfering signal and extend the dynamic range of the particle signal.

II. Material and methods

ADCs and their counterparts, digital-to-analog converters (DAC), are limited in their dynamic range. The dynamic range is closely linked to the sampling rate, which must be high enough to resolve the particle signal harmonics without aliasing. Since the excitation signal has a limited bandwidth, the creation of the active cancellation signal can be performed with a high signal-to-noise ratio (SNR) by a DAC possibly followed by a low pass filter. If the SNR of the DAC is higher than necessary for not inducing a significant noise above the coil noise level, the bandwidth of the DAC can be increased, allowing for the cancellation of more harmonics. Since the particle response changes over time, a very fast adaption to the receive signal is necessary, introducing a notion of feedback. Fig. 1 illustrates this idea for a specific combination of DAC and ADC. Since the output of the DAC is known, the canceled particle response can be recovered. With an empty bore measurement, the remaining excitation signal can be removed digitally and the overall dynamic range is improved.

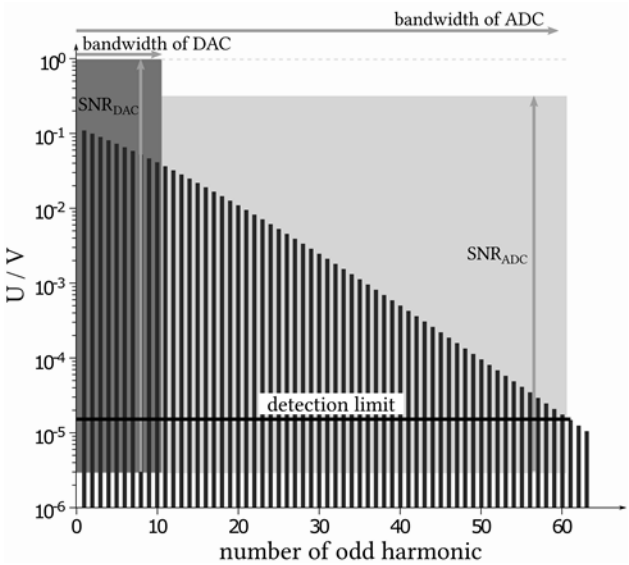

Figure 1: Exemplary combination of a 16-bit ADC at 10 MHz and an 18-bit DAC at 1 MHz. The lower bandwidth of the DAC gives a comparably higher SNR. This allows for the cancellation of the first harmonics resulting in a higher overall SNR.

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As a first prototype, a commercial low noise amplifier (LNA; SR560, Stanford Research Systems, Inc., California) in combination with a custom-built injection transformer for introducing the compensation signal is used. For synthesizing the cancellation signal and acquiring the residual signal, a STEMLab 125-14 board (Red Pitaya d.d., Slovenia) is used. It features a Xilinx Zynq 7010 FPGA and provides hard real-time capabilities necessary for adapting the cancellation signal during acquisition. In order to simplify the complexity of the test setup, the FPGA board is used to generate a simulated 1D MPI signal, instead of using an external excitation source.

The system relies on feedback and therefore needs a control strategy exploiting the repetitive nature of the signal. This is achieved here by a modified version of the adaptive feedforward control (AFC) algorithm in [3]. The AFC scheme uses a gradient descent for estimating phase and amplitude of the individual harmonics and only requires a forward model of the system. The absence of an inverse model makes it also suited for controlling non-minimum-phase systems. Internally, both the harmonics to be cancelled and the remaining harmonics can be estimated in order to have a complete estimation of all harmonics. The cancellation signal is computed using a Fourier synthesis of only the harmonics to be cancelled, which is implemented using direct digital synthesis IP cores supplied by the FPGA vendor. This separation allows for flexibility in selecting the cancelled bandwidth. While the cancellation signal is synthesized at 125 MHz, a gradient descent update rate of 5 MHz is considered sufficient, even for high-bandwidth systems. The different clocks are required since the output of the DAC only relies on the estimated phase and amplitude values and can be calculated within a few nanoseconds by multiple DSP slices whereas the gradient descent has a longer critical path. The test implementation of the algorithm is designed for cancelling 10 odd harmonics of the measured signal with the first harmonic being at 25 kHz. An internal representation of the higher harmonics was not included due to the limited resources.

III. Results and discussion

We define the dampening factor Δ as the ratio of the undampened and the damped signal's peak-to-peak value, since this ratio determines the possible change in the gain of the LNA. For a fair comparison with the implementation, the maximum possible dampening factor for a perfect cancellation was calculated to be $\Delta=4.6$ for the 10 first harmonics using a low-pass filter with a cut-off at 1 MHz. Simulations of the algorithm in MATLAB Simulink reveal a dampening factor of $\Delta=4.0$ compared to the measurements with $\Delta=2.7\pm0.3$. Simulations show, that the signals amplitude is almost reduced by 50 % after half a period. Steady state is reached within two periods of the simulated signal.

The dampening factor of the implemented algorithm shows, that the real-time generation of a sufficiently accurate cancellation signal is indeed feasible. The simulation of the algorithm almost reaches the same dampening factor as the ideal one. Due to limiting factors such as noise and inaccuracies in the measurements of the system function, the realized setup does not completely achieve the simulated dampening factor. An exemplary spectrum is shown in Fig. 2. Further simulations suggest, that including an internal model with more harmonics further increases the dampening factor and reduces periodic oscillations in steady state. These oscillations occur due to the gradient descent not being able to completely cancel the residual signal with a limited number of harmonics. Note that the algorithm is suitable for dampening even time-varying particle signals due to its fast convergence.

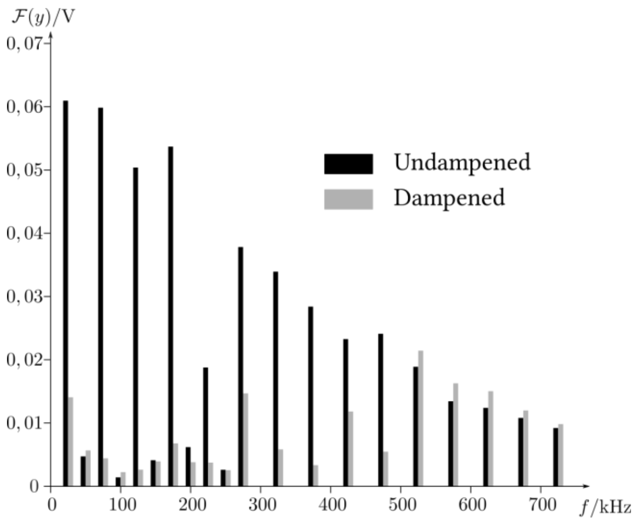

Figure 2: Exemplary spectrum comparing the undampened signal to its dampened counterpart. Up to a frequency of 475 kHz a clear decrease in amplitude for the odd harmonics can be seen while the higher harmonics are left untouched.

IV. Conclusions

This study shows that an active cancellation can be realized not only for the excitation frequency but also for the harmonics of the resulting particle signal. Depending on the dynamic range of both ADC and DAC, a combination of the presented method with a cancellation setup [2] is favorable. This would not only allow for the suppression of the excitation signal but even going beyond, leading to high dynamic range MPI while having a flexible receive chain capable of multi frequency MPI.

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Author's statement

Authors state no conflict of interest. Early results of this research have also been published by the authors at the International Workshop on Magnetic Particle Imaging 2018 under the title "An Approach for Actively Cancelling Direct Feedthrough".

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