International Journal on Magnetic Particle Imaging
Vol 6, No 2, Suppl 1, Article ID 2009065, 3 Pages

Infinite Science Publishing

Proceedings Article

Vector modulator based active compensation of direct feedthrough

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Abstract

In magnetic particle imaging (MPI), simultaneous excitation and signal acquisition leads to direct feedthrough problems. While this direct-feedthrough can be mitigated up to some extent with passive compensation, this may not be sufficient given the time-variant nature of the system. Active compensation methods are proposed to overcome this challenge. In magnetic resonance imaging (MRI), we have recently proposed a promising active compensation technique that uses a vector modulator-like structure to modify a copy of the transmitted signal and use it for subtracting the direct-feedthrough in analog domain. In this work, this technique is adapted to MPI for active compensation of the direct-feedthrough. We demonstrate a significant increase in detection sensitivity at the fundamental harmonic on an in-house arbitrary waveform relaxometer.

I Introduction

In magnetic particle imaging (MPI), excitation and signal acquisition occurs simultaneously, leading to a direct feedthrough problem. The direct feedthrough is especially problematic considering the drastic disparity between the transmitted and received power. The direct feedthrough signal may saturate the pre-amplifier, reducing the dynamic range and the detection sensitivity. This in turn jeopardizes MPI's excellent promise of high sensitivity [1]. To tackle these issues, gradiometer receive coils are frequently used as a passive compensation method. However, these coils are difficult to design and tune perfectly, and the tuning is prone to degradation due to external effects (e.g., vibration, heating). Even for a fine-tuned gradiometer coil, the remaining direct-feedthrough can still exceed the signal from a low concentration of magnetic nanoparticles (MNPs). To overcome challenges arising from passive compensation, active compensation methods have also been proposed in MPI [7,8]. The elimination of direct-feedthrough is an active research area in other fields as well, such as telecommunications (full-duplex radio) [2, 3] and Magnetic Resonance Imaging (MRI) [4-6].

We have recently proposed an active compensation method in MRI using a vector modulator structure based on copying the excitation signal and modifying it in analog domain [6]. In this work, we adapt this technique to MPI for active compensation of the direct feedthrough. With experiments on an in-house Arbitrary Waveform Relaxometer (AWR), we demonstrate a significant increase in detection sensitivity at fundamental harmonic.

II Material and methods

For an amplitude modulated (AM) drive field (DF) with a center frequency of f_0 and envelope of $A(t)$, assuming

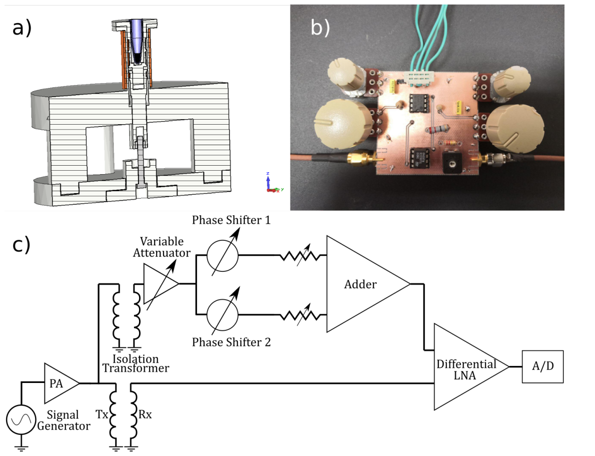

Figure 1: a) Schematic of the in-house AWR. b) Implemented active compensation circuit. c) Schematic of the system and compensation circuit, which acts as a vector modulator.

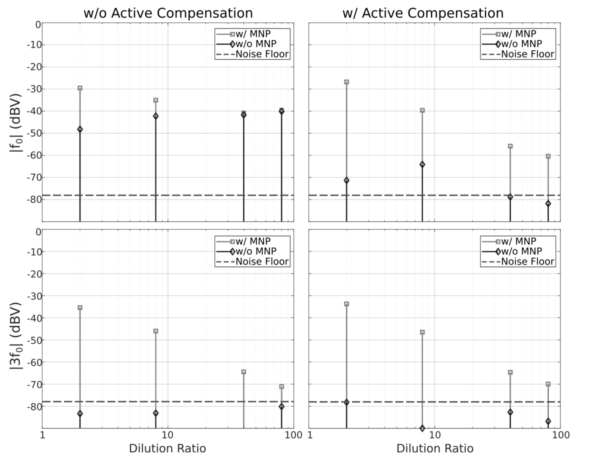

Figure 2: Signal at the fundamental harmonic and the third harmonic, with and without active compensation for four samples with different dilution factors. $f_0 = 10.8$ kHz.

coupling between drive and receive coil is time-invariant, the direct feedthrough signal can be formulated as,

$$s(t) = k \cdot A(t) \cdot \sin\left(2\pi f_0 t + \phi\right) \quad (1)$$

where $k$and ϕ are the attenuation coefficient and phase shift stemming from mutual coupling, respectively. Most active compensation methods estimate/measure parameters k and ϕ, and then reconstructs $s(t)$ given that the other parameters in Eq. 1 are known. In this work, instead of reconstructing direct-feedthrough, a low-amplitude copy of the transmit signal is taken directly from the input of the DF coil and modified in the analog domain, to match k and ϕ.

II.I Active Compensation Circuit

A circuit that can modify the phase and amplitude of its input was designed, as shown in Fig. 1. The circuit consisted of three stages. The first stage was a variable attenuator/amplifier that also acts as an input buffer. The next stage was divided into several branches containing phase shifters (unity gain all pass filters). The phase at f_0 can be adjusted by varying resistance R according to $\phi(2\pi f) = -2\tan^{-1}(2\pi f RC)$ for a low-pass topology and $\phi(2\pi f) = \pi - 2\tan^{-1}(2\pi f RC)$ for a high-pass topology. Hence, by combining multiple of these two phase shift elements, one can reach any desirable phase shift. The last stage acts as a combiner and consists of a summer Op-Amp. The weights of the summation operation can be adjusted with variable resistors in each branch. With weighted combination of these stages, (k, ϕ) parameter space can be covered efficiently.

The circuit can be built using $(n+2)$ Op-Amps, where n is the number of desired branches. The number of branches is a trade-off between the degree of freedom, the coverage of parameter space and the circuit complexity. Here, TL082 Op-Amps were used to implement all stages.

II.II Experiment Setup

The operation of the proposed technique was demonstrated on an in-house AWR, which had a DF coil with a small (3.1 μH) inductance that eliminated the need for impedance matching [10]. The receiver coil was a gradiometer coil, with a manual adjustment knob to reach more than 80 dB decoupling. AM modulated waveforms were created by data acquisition card (DAQ) and amplified using a power amplifier (PA). The received signal was pre-amplified by a low noise amplifier (LNA) and digitized by the same DAQ. The compensation signal was copied from the output of the PA using an isolation transformer to isolate the DF and receive chains. The output of the circuit was subtracted from the received signal using the differential input of the LNA.

To demonstrate the increase in detection sensitivity, four samples of Perimag (Micromod GmbH, Germany) with dilution factors of x2, x8, x40, and x80 were prepared. Each sample had 20 μL total volume. DF at 5 mT and 10.8 kHz was applied. The first and the third harmonics were investigated with and without active compensation.

III Results and Discussion

Despite the passive decoupling of the AWR, the remaining direct-feedthrough was still more than 40 dB above the noise level. With careful adjustment of the potentiometers in the active compensation circuit, the direct-feedthrough was successfully reduced down to noise floor, as shown in Fig. 2.

Figure 2 shows a comparison at the fundamental and third harmonics, with and without active compensation. In both cases, signal amplitude at f_0 was above the direct-

10.18416/ijmpi.2020.2009065

feedthrough for x2 and x8 dilutions. However, for x40 and x80 dilutions without active compensation, the MNP signal was dominated by the direct-feedthrough. For x80 dilution, since the third harmonic was reduced almost to noise level, it was not possible to detect the signal with the passive decoupling alone. In contrast, with active compensation, the MNP could be easily detected from the recovered fundamental harmonic, showing a significant improvement in sensitivity of up to 40 dB.

There are two main advantages of this approach compared to the active compensation methods that use an independent signal source to create compensation signal [4,8]. First, the addition of this circuit does not increase the noise floor, unlike other methods that add an independent noise source to the received signal. Next, our method is more robust against voltage drop of DF coil due to heating, since it will also be reflected on the compensation circuit input. However, a change in mutual coupling (e.g., due to vibrations etc.) will not be reflected. One potential solution could be to replace mechanical potentiometers with digital ones and automating the compensation process, which would also eliminate variations in compensation performance.

IV Conclusions

A vector modulator active compensation circuit is proposed for the direct feedthrough problem in MPI. This method copies the excitation signal and modifies in analog domain, reducing the direct feedthrough signal down to noise floor. This method achieves a significant increase in detection sensitivity at fundamental harmonic.

Acknowledgments

The authors thank Suheyl Taraghinia for his expertise and help on analog electronics.

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