Minimizing Field Inaccuracy in MRI Electomagnet Control Systems

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Introduction

Electromagnets are used extensively in MR systems—hyperpolarized gas, prepolarized, and other low field imaging systems often use electromagnets for the main field, and conventional superconducting systems commonly use electromagnets for the shim and gradient coils. The field produced by an electromagnet is only as temporally stable as the current supply that powers it. The steady state accuracy of a current supply is fundamentally limited by noise and long-term drift of the control electronics, and the accuracy of a current supply subject to transient demands of a system, such as our Prepolarized MRI system, is fundamentally limited by the dynamic response of the coil itself. With main field and shim coils, current inaccuracy translates into frequency modulation of the MR signal, or into an equivalent undesired phase accumulation in the rotating reference frame. With gradient coils, current inaccuracies translate into k-space error. Our intent is to develop a smart electromagnet control system to eliminate all sources of error in an electromagnet control system not due to fundamental limits of the control electronics or coil and achieve field stability in a pulsed electromagnet system as close a possible to that of a superconducting system.

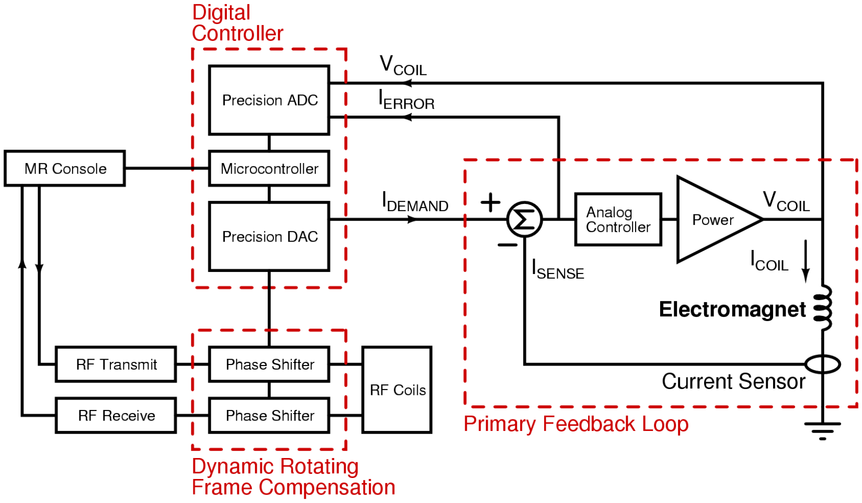

Figure 1: Block diagram of a complete electromagnet control system designed to minimize all sources of field errors.

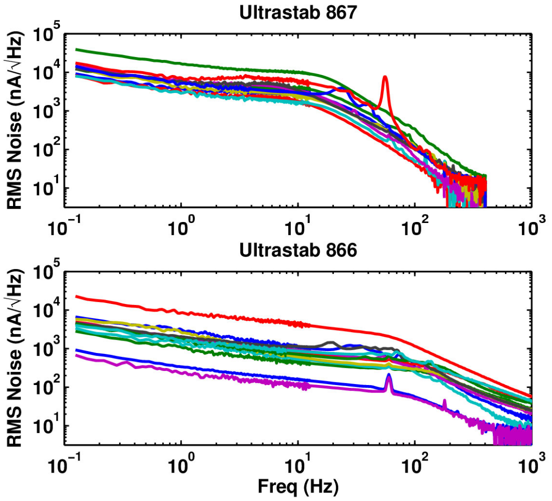

Figure 2: Input referred noise floor measurements of 20 Danfysik Ultrastab current transducers at 0 A.

Analysis and Methods

The “Primary Feedback” block in Fig. 1 shows a typical magnet current control system. System analysis shows that the error in the coil current, I_{COIL}, is most sensitive to error in sensor signal, I_{SENSE}, and the reference signal, I_{DEMAND}. Therefore, the fundamental limits of the steady state error are determined by the noise and drift of the current sensor and DAC voltage reference. Due to the inverse relationship between maximum NMR phase error and frequency of the field error, the low frequency drift and noise dominate the errors in MR data. The Danfysik Ultrastab 866 and 867 current transducers are common state-of-the-art current sensors with a DC to 100 kHz bandwidth. Using a low frequency spectrum analyzer, a low noise preamp, and meticulous double layer μ-metal shielding, we measured the noise floor levels of 20 Ultrastab devices from 0.1 to 1000 Hz, using an hour of averaging per device due to the low frequency. While the Ultrastabs demonstrate very low noise floors, we found a factor of 50 variation of the low frequency noise floor between devices (Fig. 2). These measurements indicate a typical equivalent RMS variation on shot-to-shot time scales (0.1-100 Hz) of 0.03 ppm of full scale sensor current. As for errors caused by transients in the system, such as a change in I_{DEMAND} or a transient from another inductively coupled coil, these errors can be analytically determined based on the dynamic response of the coil.

Errors resulting from the dynamic response of the coil when subjected to transients in the system, such as a change in I_{DEMAND} or a transient from another inductively coupled coil, pose a fundamental limit on precision because circulating currents within the coil due to self-resonance cannot be externally controlled. These errors can be minimized with optimal coil damping.

Discussion

We measured the Ultrastab drift to be less than that of the most stable voltage reference available, the LTZ1000 voltage reference, which specifies as low as 0.29 ppm peak-to-peak voltage drift (depends on buffer circuitry). Therefore, efforts to minimize drift should be focused on the voltage reference. Paralleling multiple voltage references or current sensors can decrease the noise they contribute to the system, but if the paralleled devices have a large noise variation, this benefit is lost if the noise of one device is significantly more than that of the others in parallel. In addition, the control circuit electronics must be carefully constructed to minimize other sources of error, such as thermocouple junctions and electromagnetic interference, or these will dominate the system error. Feedback of the coil voltage can be used to reduce error due to thermal effects in the coil (expansion and resistive changes) [1]. Digitizing the current error signal can be used for post-processing correction of k-space errors in gradient coils. Repeatable transient field errors can be compensated by measuring the field error with the NMR signal and successively applying a laboratory frame correction (preemphasis of I_{DEMAND}) or a rotating frame correction (phase shift of the RF transmit/receive) [2]. Shot-to-shot field drift can be measured and corrected using frequency navigators [3]. Figure 1 combines all of these compensation methods into a single smart electromagnet controller capable of achieving the limits of electromagnet field stability.

References

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Ultrastab test devices courtesy of Ian Walker,
GMW Associates, San Carlos, CA