Regulating Magnetic Field Fluctuations While Pulsing Field Gradients

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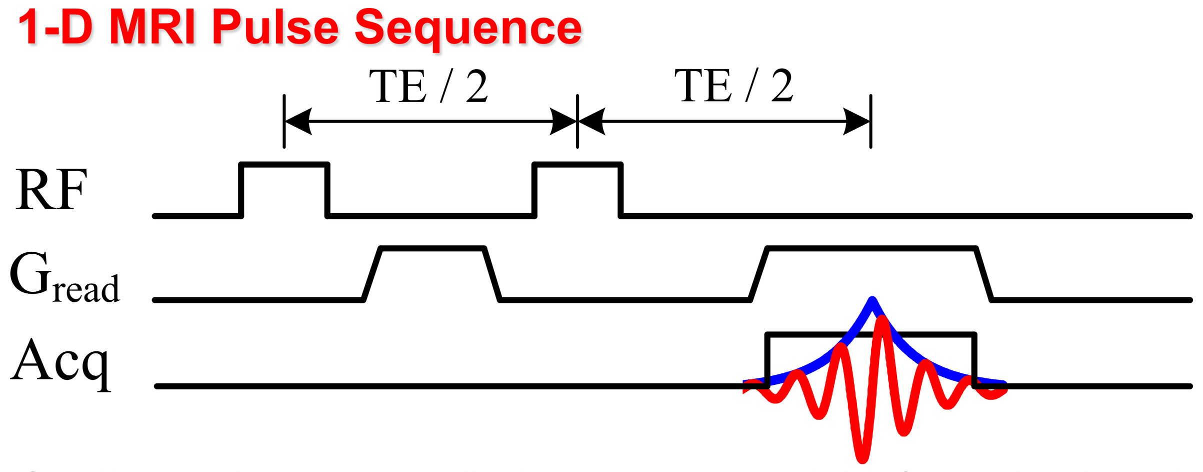
Abstract

Nuclear magnetic resonance (NMR) experiments are typically conducted using superconducting magnets. Powered magnets, though, have advantages for NMR because they can reach higher field strengths. However, powered magnets suffer from field fluctuations due to ripples in the power supply and changes in the cooling water temperature. Feedback control systems have been shown to greatly reduce field fluctuations, but they cannot distinguish pulsed field gradients from field fluctuations. As a result, feedback control systems unintentionally correct for and remove pulsed field gradients needed for certain NMR experiments such as magnetic resonance imaging (MRI), making these experiments impossible to perform [1,2]. A possible solution to this is feedforward gradient correction.

Experiment Setup

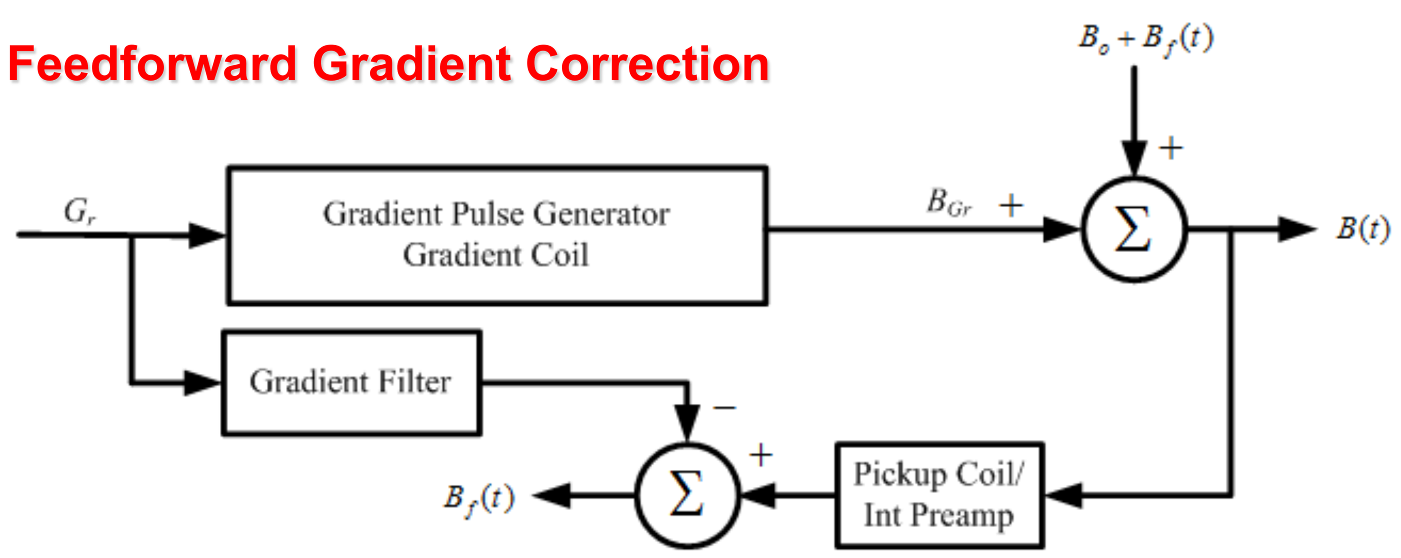
To test the effectiveness of feedforward gradient correction, 1-D MRI experiments were performed on a water sample within a 300 MHz superconducting magnet. Prerecorded noise from the Keck 25T powered magnet was injected into the superconducting magnet to simulate powered magnet field fluctuations.

1-D MRI Pulse Sequence



Gradient pulses are applied to encode spatial information into the NMR signal.

Feedforward Gradient Correction



The goal of feedforward gradient correction is to subtract out the gradient's contribution to the field before the controller makes an estimate of the field fluctuations and tries to correct for the pulse. In order to know what to subtract out, the relationship between gradient pulses and the measured field output must be found using system identification.

System Identification Method

Using the prediction-error method (PEM) of system identification, consider a model described by

$$y[n] = G(q)u[n] + H(q)e[n]$$

where y[n] is the measurement of field fluctuations and u[n] is the applied gradient input. The error between measured output and input is

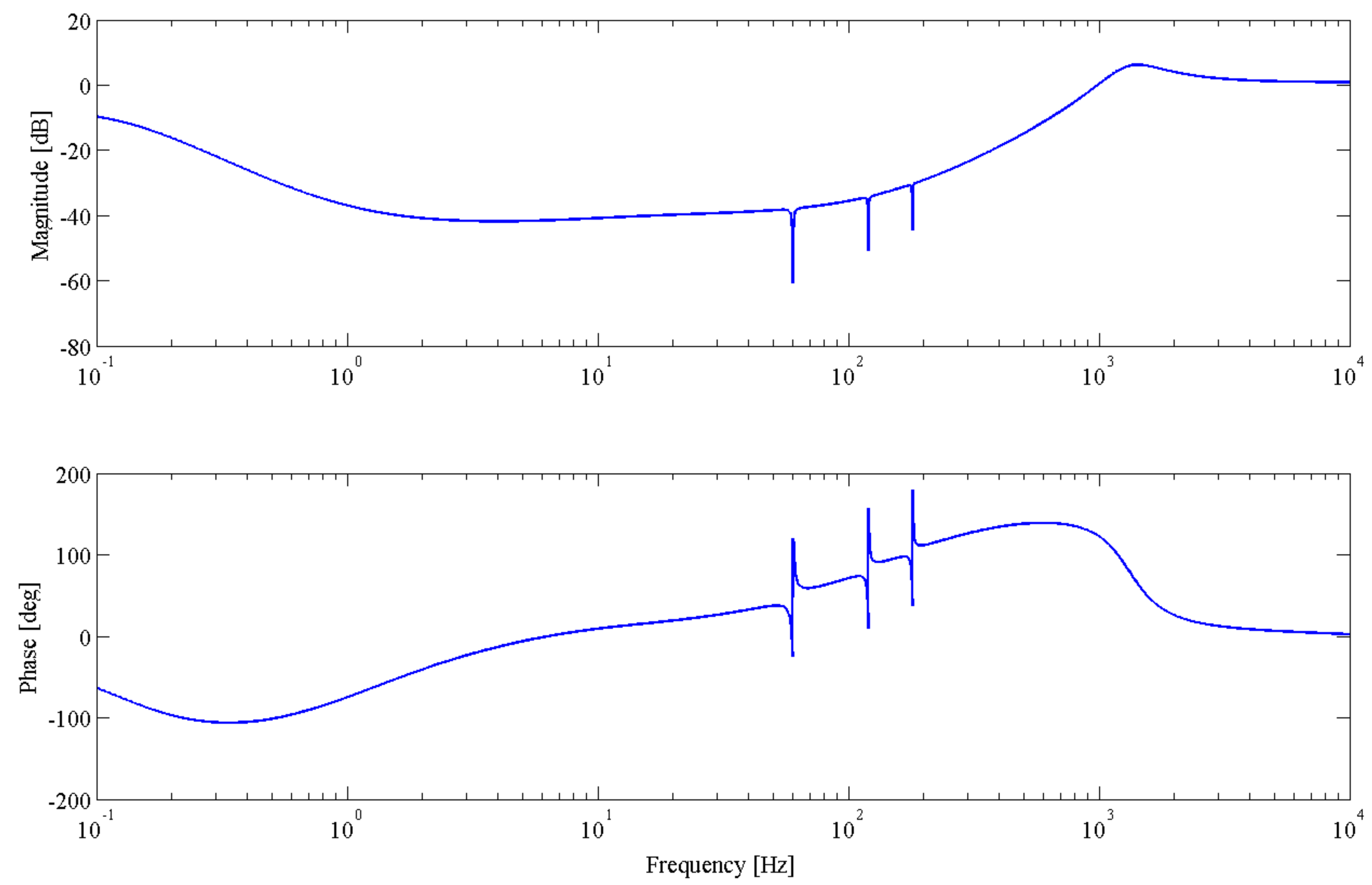
$$e[n] = H^{-1}(q)\{y[n] - G(q)u[n]\}.$$

The goal of PEM is to minimize the cost function

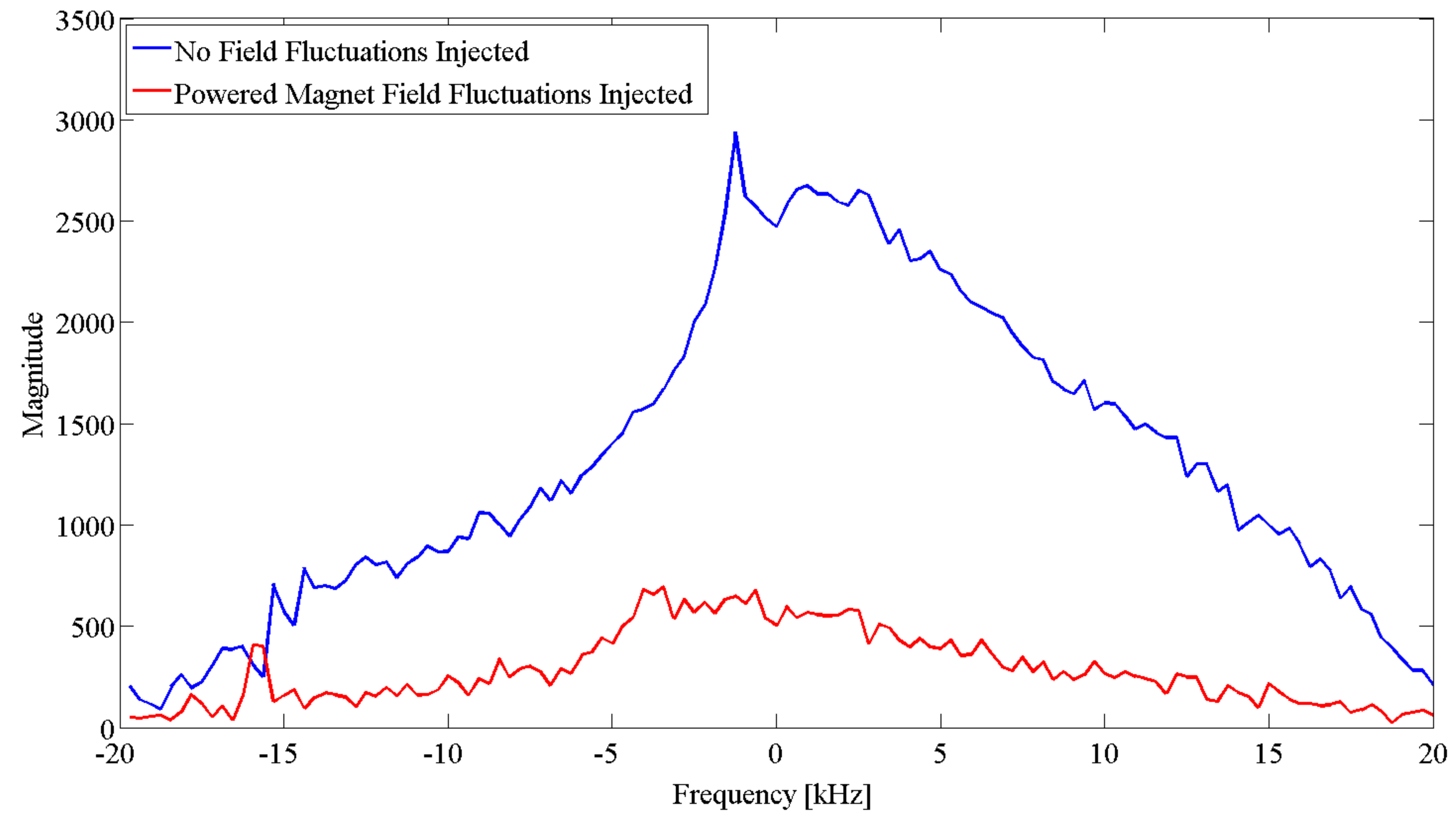
$$J(G,H) = \sum_{n=1}^{N} e^2[n].$$

When the cost function is minimized, the resulting model is the estimate of the relationship between the gradient input and the measured field output [3].

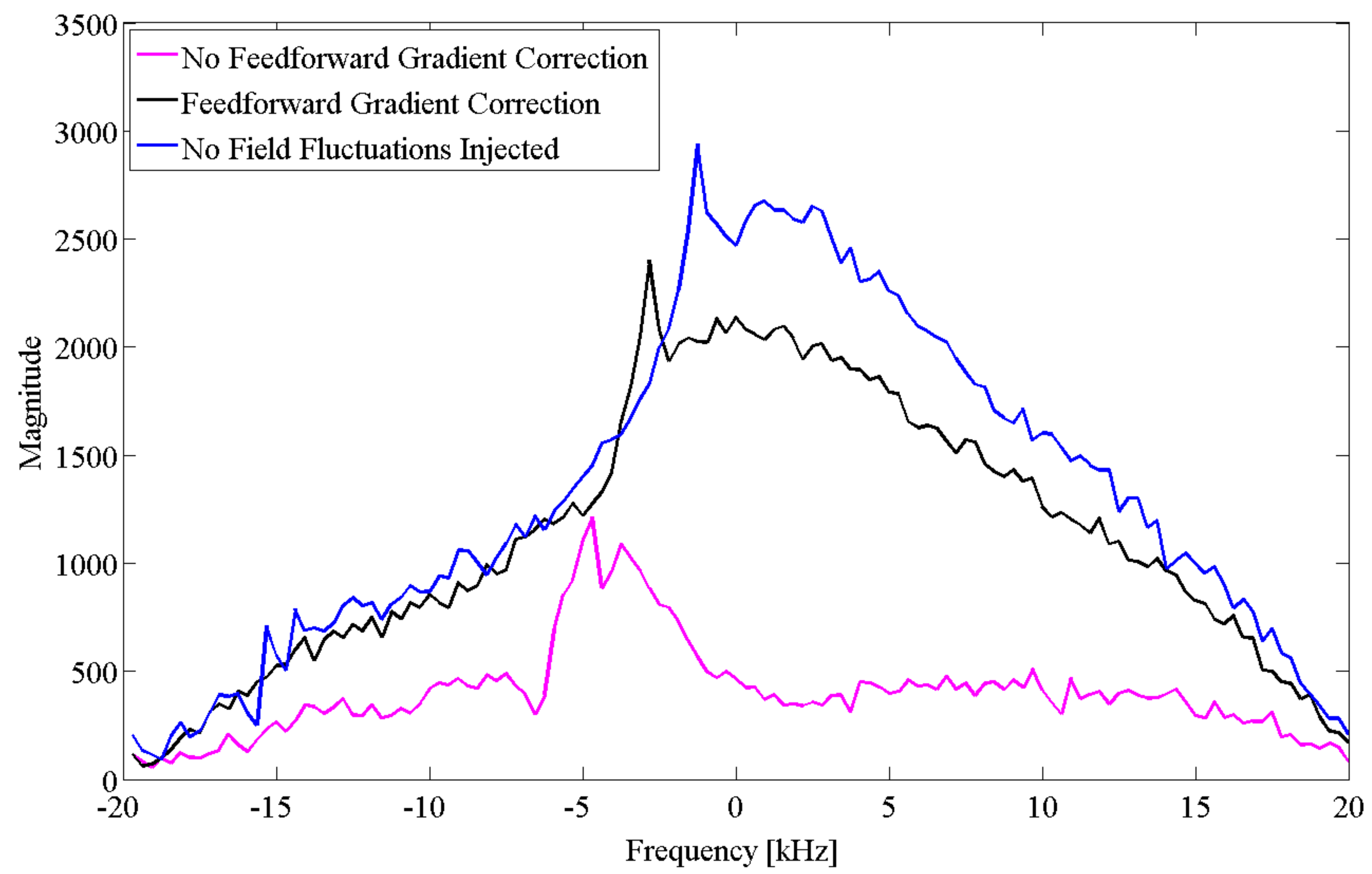
Disturbance rejection of the feedback control system



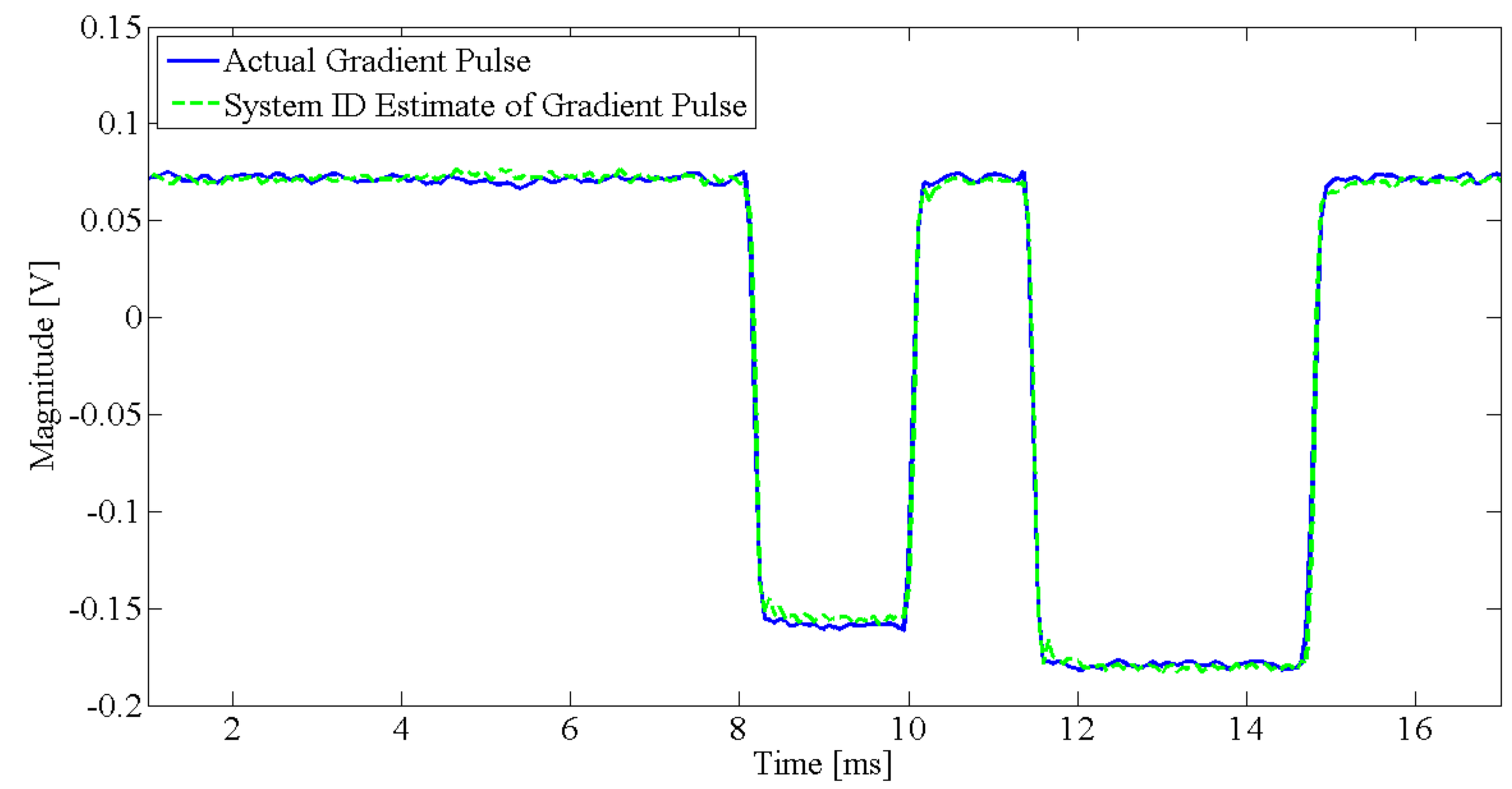
MRI is significantly affected by Powered Magnet field fluctuations



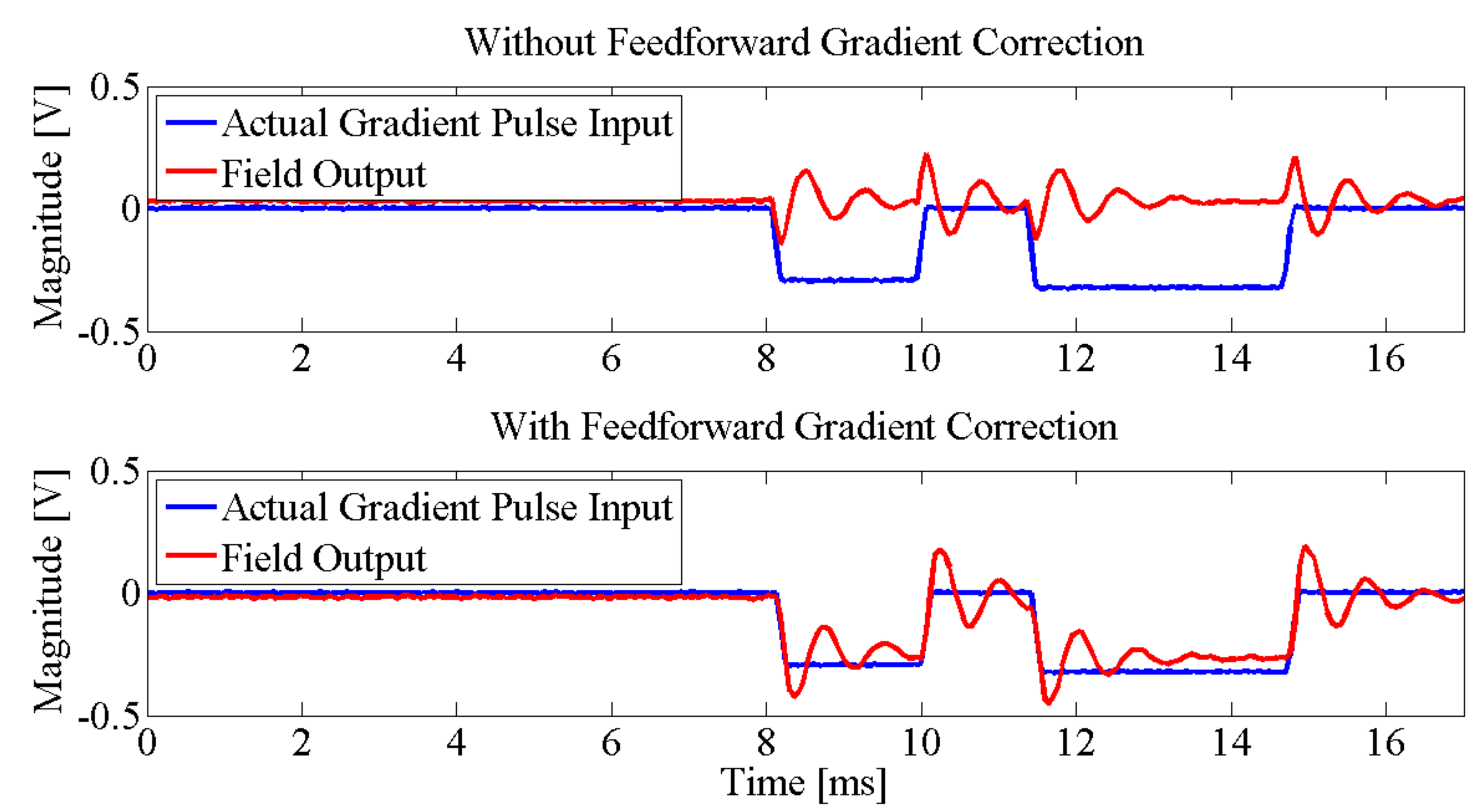
1-D MRI in powered magnets is possible using feedback control with feedforward correction



System Identification of Gradient Pulses



Effect of Feedback Control System on Gradient Pulses



Without feedforward gradient correction, the feedback controller attempts to correct for the gradient pulse. Using feedforward gradient correction recovers the gradient pulse. The ringing in the signal occurs from the controller affecting the residual portions of the gradient pulse not fully accounted for in the system identification.

Conclusions

Separating the gradient signal from the field fluctuations using feedforward gradient correction can allow feedback controllers to work in the presence of pulsed field gradients. Since the system identification is not perfect, there is some ringing in the gradient pulse signals. Even so, this experiment shows that a feedback controller in conjunction with feedforward gradient correction could be used to conduct 1-D MRI experiments in resistive magnets. Future work includes improving the system identification and investigating other methods to reduce the effects of the controller on the gradient pulses.

Acknowledgements

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References

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[2] B. McPheron. Flux Regulation in Powered Magnets: Enabling Magnetic Resonance Experiments With Pulsed Field Gradients, Dissertation Proposal, The Pennsylvania State University, May 2013

[3] L. Ljung. System Identification Theory for the User. 2nd ed. Prentice Hall (1999)