Ultra-low-noise amplifier for ultra-low-field MRI main field and gradients

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Abstract. In ultra-low-field (ULF) MRI, applied fields on the order of 100 µT are present during the measurement with one or more SQUID sensors. The current noise in the coils that produce the fields must be extremely small in order not to add noise to the measurement, especially when measured using magnetometer pickup coils. In addition, to allow other than the most basic pulse sequences, the applied fields must often be ramped up and down at millisecond time scales, requiring relatively high voltages and a sufficient bandwidth. Since commercial power amplifiers are far from satisfying these requirements, we designed and implemented a dedicated ULF MRI current amplifier. We demonstrate that, using our amplifier, it is possible to make ULF MRI measurements without increased noise even with magnetometer pickup coils that are oriented to directly measure the magnetic field component along the applied field. Using tailored amplifiers for pulsing gradients and uniform fields opens many opportunities in developing and implementing advanced ULF MRI pulse sequences.

1. Introduction

In contrast to the radio-frequency signals of conventional tesla-range MRI, an ultra-low main magnetic field $\vec{B}_0$ on the order of 100 µT results in nuclear magnetic resonance (NMR) in the kilohertz range. MRI at such low frequencies is made feasible by the use of superconducting quantum interference devices (SQUIDs), since they can be configured as highly sensitive magnetic-field sensors with sensitivities independent of frequency [1]. Over the past few years, interest in ultra-low-field (ULF) MRI has spread rapidly (see e.g. Refs. [2–5]). Motivations for studying ULF MRI include its safety, cost-effectiveness, and its compatibility with other electromagnetically sensitive technologies such as magnetoencephalography (MEG) [2–3].

ULF MRI has further possibilities that are not available in conventional MRI. Generally, in MRI, it is the design of magnetic field pulse sequences that enables the continuing development of new innovative contrast mechanisms in addition to the traditional ones based on T_1 and T_2 relaxation times. Besides the more established diffusion-tensor imaging and functional MRI, examples are contrasts based on magnetic permeability and electric current density, of which the latter may be particularly suitable for ULF MRI [6–7]. A notable advantage of ULF-MRI is to ability to independently change the polarizing and measurement field strengths, even during the sequence. However, ULF-MRI-specific sequence development is hindered by the lack of amplifier electronics capable of producing the sequences.

A central issue in the amplifier electronics is that extremely low-noise currents are required in order not to increase the noise level of the measurement, as at least two applied fields are usually

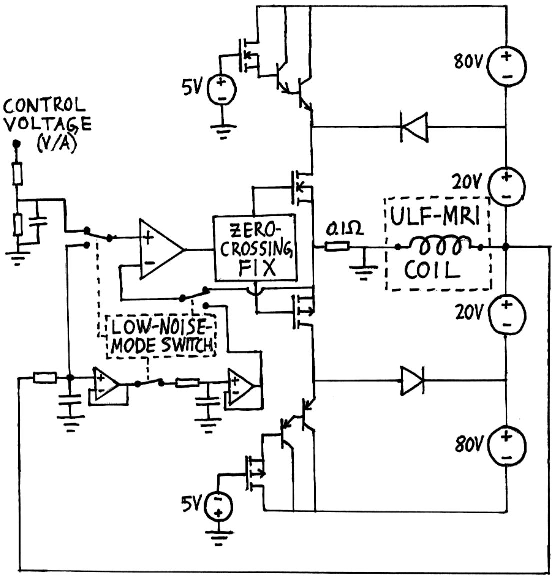

Figure 1. Simplified circuit diagram of the amplifier. The amplifier is currently in its normal mode. To switch into ultra-low-noise mode, the three semiconductor switches are toggled, which changes the feedback scheme of the main operational amplifier.

Figure 2. Photograph of the amplifier enclosure with the top plate removed.

present during signal acquisition. While the problem exists even with gradiometric sensors [8], it is particularly challenging when magnetometer pickup-coils are used. The required dynamic range from fT-level noise to 100 µT fields is as high as 180 dB (10 kHz bandwidth). Additional difficulties arise from ramping the current of multiple amperes up and down in the inductive load at millisecond time scales. The pulse sequences extend into the kilohertz range, overlapping with the signal frequency band, within which the system must have extremely low noise (see Ref. [9] for more discussion). It is difficult, however, to achieve both low noise and precise current feed for an inductive load within the same frequency band. This overlap of frequency bands is virtually nonexistent in conventional MRI, which explains why electronics thereof is not very suitable for ULF MRI.

To solve the current-feed issue, we have developed a specialized current amplifier for the $\vec{B}_0$ and gradient coils in ULF-MRI for use in our combined ULF MRI and MEG system at Aalto University [2]. In this paper, we describe design details of the amplifier and show measurement results of its properties and, in particular, its noise performance.

2. Amplifier circuit

A simplified circuit diagram of the amplifier is depicted by Fig. 1. The circuit was designed and implemented as a tailored linear amplifier with a field-effect-transistor (FET) output stage. Its ULF-MRI-specific features include the ability to freeze the current into an ultra-low-noise state for signal acquisition, effectively providing the required dynamic range. In addition, the amplifier has circuitry that increases the available voltage temporarily to allow millisecond-scale ramping of the current I in the inductive load with currents up to around 10 A. Neglecting the

Journal of Physics: Conference Series **507** (2014) 042050 doi:10.1088/1742-6596/507/4/042050

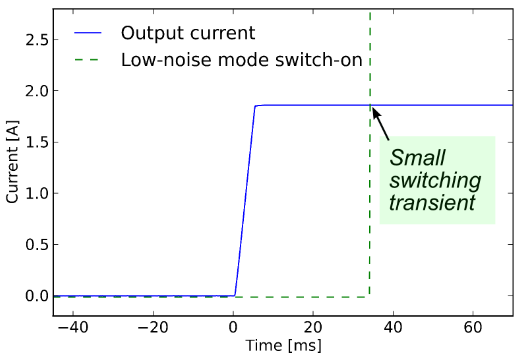

Figure 3. A sample current pulse with switching to ultra-low-noise mode. The mode switching transient is very small and therefore not visible in the figure.

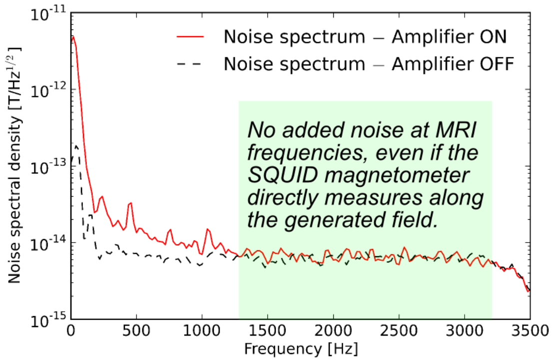

Figure 4. The noise amplitude spectrum seen by a SQUID magnetometer with no B_0 coil current (dashed) and with the magnetometer directly measuring the field produced by the B_0 coil with a 2-A current in ultra-low-noise mode (solid).

parasitic capacitance of the coil, the voltage U over the coil is given by

$$U = RI + L\frac{dI}{dt} \; , \tag{1}$$

where I is the current in the coil, R the coil resistance ($\sim$ 1 Ω), and L the coil inductance ($\sim$ 10 mH). Consequently, a 80-V voltage boost corresponds to a ramp time of 1 ms for a 8-A current.

The circuit is built around a single low-noise precision operational amplifier, which drives the FET output stage through a network that ensures the flow of at least a small quiescent current in the FETs at all times. This 'zero-crossing fix' allows distortion-free switching of the output polarity, and consists of two Zener diodes and resistors. The output stage is powered from separate floating voltage sources of e.g. 20 V. Additional Darlington configurations control the use of higher-voltage sources during ramps when needed. To provide this 'intelligent' behavior, we introduce a relatively simple trick, in which constant ground-referenced voltages are provided at the gates of two FETs that control the bipolar Darlington pairs. As soon as the remaining voltage over an output stage transistor becomes too low, the higher voltage source begins to provide current. Diodes are used to force this current into the output stage.

The ultra-low-noise mode, on the other hand, is implemented by switching into another feedback scheme. A sample-and-hold circuit is set to sample and remember the potential at the non-grounded end of the load coil, and the main operational amplifier is configured to steadily maintain the sampled state. Consequently, the current noise decreases by orders of magnitude, because the inductive reactance of the coil now suppresses the noise of the operational amplifier. In addition, since the amplifier is decoupled from the control voltage signal, any noise in the signal does not affect the current in the coil. At least at low frequencies, the remaining noise is likely to originate dominantly from the low-noise operational amplifiers.

A photograph of the amplifier can be found in Fig. 2.

3. Results

Figure 3 shows the beginning of a measured trapezoidal current pulse fed into our B_0 coil. During the pulse, the amplifier is given a signal to switch into ultra-low-noise mode. The mode switching is fast, and the resulting transient is so small that it cannot be seen in the figure. Also the current offset between the two amplifier modes has been adjusted to nearly zero. A small transient can be seen at the end of the ramp-up, which should be removed by changing some component values.

The noise performance of the amplifier in ultra-low-noise mode is shown in Fig. 4. We used one SQUID magnetometer in our system to measure the field generated by a current in our B_0 coil, which has a field efficiency of 16.7 µT/A at the SQUID sensor. At our typical NMR signal frequencies between 2 and 3 kHz, the current fed by the amplifier does not increase the noise of the measurement, suggesting that the noise is below roughly 1 fT/$\sqrt{\text{Hz}}$, corresponding to less than 60 pA/$\sqrt{\text{Hz}}$ in the spectral density of the amplifier output current noise. However, at lower frequencies, where the inductive reactance of the coil is smaller, the measurement noise is somewhat elevated even in ultra-low-noise mode.

4. Conclusions

In the absence of suitable commercially available amplifier candidates, we have designed and constructed a tailored $\vec{B}_0$ and gradient coil amplifier for ULF MRI, providing both fast current ramping and low noise. By switching between normal and ultra-low-noise states, the amplifier effectively achieves a dynamic range of over 180 dB at our typical NMR frequencies, adding no noise to the measurement. At low frequencies the measurement noise is somewhat elevated, but still low enough that, in a multichannel measurement, signal processing techniques or so-called software gradiometers could be used to reject the noise. It may also be possible to decrease the amplifier noise even further.

The capabilities of existing amplifiers have been limiting the progress of ULF MRI. In the future, ULF MRI systems could potentially use a single amplifier model for all coils except perhaps the polarizing coil. This would provide a highly flexible platform for a rich variety of pulse sequences, including sequence types that are not possible in traditional MRI.

Acknowledgment

This work has received funding from the Academy of Finland, from the iBioMEP graduate school, from the Finnish Cultural Foundation, and from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement No. 200859.

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