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A Digital Flux-Locked Loop for High Temperature SQUID Magnetometer and Gradiometer Systems with Field Cancellation

Kraus Jr., R.H., Bracht, R., Flynn, E. R., Jia, Q., Maas, P.[1], Reagor, D., and Stettler, M.
Los Alamos National Laboratory, Box 1663, Los Alamos NM, 87545,USA;
[1]Strathclyde University, Dept. of Physics and Applied Physics,Glasgow G4ONG, Scotland

I. Introduction

Numerous challenges stand in the way of "fieldable" biomagnetic sensors that can be practically used unshielded in everyday ambient environments. A few of the possible applications of a fieldable biomagnetic sensor include bedside monitoring and emergency medical diagnosis of cardiac and brain function (i.e., trauma), and monitoring of cardiac or brain activity in specialized environments such as the NASA shuttle. One futuristic vision of a miniature portable biomagnetic sensor has been related by Wikswo[1]. To date, however, biomagnetic measurements of the heart and brain using Superconducting QUantum Interference Device (SQUID) sensors have been made almost exclusively inside shielded rooms or within systems of field cancellation coils, with only a few noted exceptions[2,3]. Shielding or active cancellation is usually necessitated by the debilitating affect of everpresent ambient background fields and radio-frequency (RF) interference on the performance of SQUIDs. Methods of shielding or compensating the ambient background fields use bulky hardware that is not practical for portable field applications and, in the case of shielded rooms, are extremely expensive. A further impediment to miniaturizing SQUID sensor systems has been the bulk associated with the cryogenic systems required to maintain low critical-temperature (LTC) devices at liquid helium temperatures (to maintain the superconducting state).

Recent advances in the noise characteristics of high critical-temperature (HTC) SQUIDs have opened the door for using these devices in both biomagnetic and non-biomagnetic applications. Because of the large heat content and low cost of liquid nitrogen (LN), HTC SQUID sensor systems are far more practical for portable field applications than LTC SQUID systems that use liquid helium (LHe). Not only is the cost of LN more than one hundred times less than for LHe per watt cooled, other factors including quantity of thermal shielding, volume of coolant, and boiling induced noise strongly favor HTC over LTC systems for portable field applications.

The SQUID sensor is typically operated in a null detector mode where an analogue flux-locked-loop, FLL, provides a negative feedback to maintain linear operation[4]. The modulated SQUID signal is amplified, filtered, demodulated, and integrated in the FLL. The resulting analog signal is a measure of the magnetic field and noise at the SQUID and is also fed back to the modulation and feedback (M&F) coil to null the flux at the SQUID to maintain the linear operating point. Thus, the FLL output signal is proportional to the change in magnetic field at the SQUID pickup coil, provided the slew rate and dynamic range of the SQUID and FLL system are not exceeded.

The goal of the work presented here is to advance technologies needed for a practical fieldable SQUID biomagnetic sensor. We used HTC SQUIDs to realize the benefits noted above. We also implemented the FLL algorithm on a digital-signal-processor (DSP) to realize a number of benefits including (1) software control of noise filtering and background rejection to enable unshielded use of SQUID sensors, (2) flux quanta countin and resetting SQUID operating point to increase system slew rate and dynamic range, (3) programmable FLL adaptable to numerous specific applications, (4) digital signal output (up to 32-bit precision), and (5) reduced FLL package cost. General aspects of this system concept have been described previously[5,6]. This paper presents results of external signal rejection for a sensor system using HTC SQUIDs, preamplifier circuit, and DSP FLL designed and built at our laboratory. We also note a companion paper in these proceedings[7] and other references to the use of DSP in SQUID applications [8,9].

II. Methods

Figure 1 is a block diagram illustrating the complete SQUID and DSP-FLL system and excitation source. All ADCs and DACs were 18-bit/10V, 200kHz devices. The dashed box labeled "SQUID" represents the components that are on the SQUID chip, consisting a superconducting-normal-superconducting (SNS) junction HTC SQUID with

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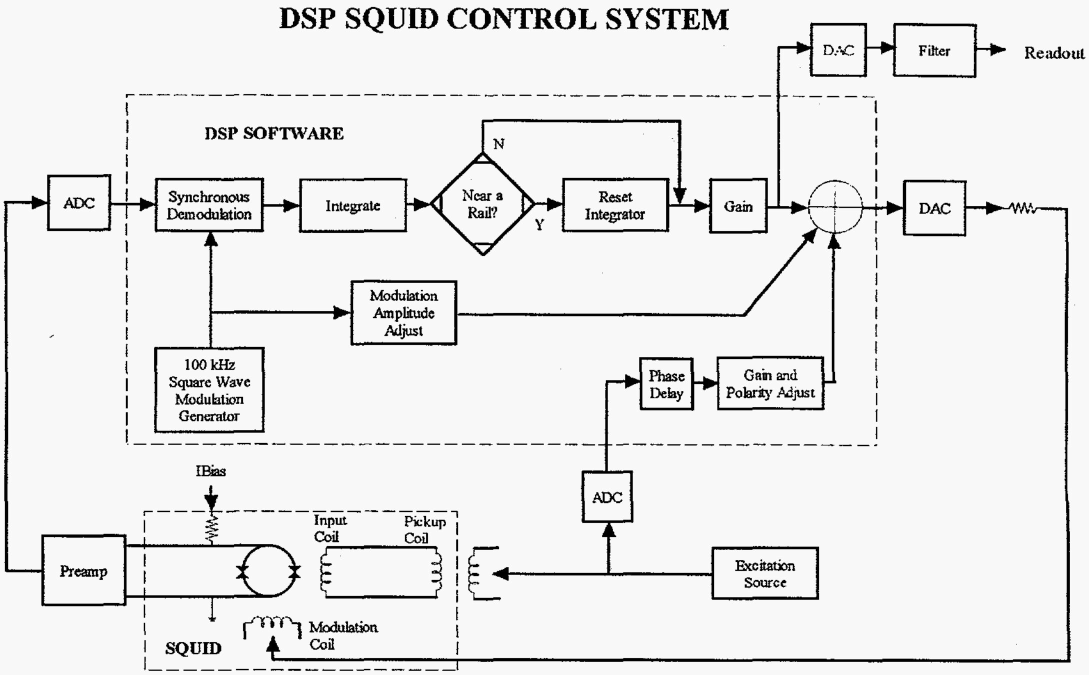

Figure 1

0.04mm^2 area pickup coil and modulation coil. The SNS-junctoin SQUID was characterized open-loop with $30\mu V/\Phi_0$ modulation depth and $<20\mu V/\sqrt{Hz}$ noise after fabrication. The output of the preamplifier, which is directly coupled to the HTC SQUID, is digitized read by the DSP. The simplest algorithm implemented on the DSP controlled FLL is surrounded by the dashed box labeled "DSP Software." The DSP-FLL algorithm shown performs all of the functions of a traditional analog FLL and adds automatic SQUID reset and feedback cancellation capabilities. The summed digital M&F signals are converted to an analog signal by a DAC that drives the modulation coil. The demodulated digital SQUID output signal is also converted to analog, though this step is in general unnecessary and introduces additional noise, however was performed for compatibility with our existing data acquisition system.

Numerous preamplifier designs were tested including one- and two-transformer, and directly coupled designs. Although the two-transformer design was optimized with a narrow transmission peak at the modulation frequency to eliminate noise at other frequencies, it was impractical because the resonance peak would drift with time due to a variety of factors including transformer temperature. We chose a directly coupled low-noise broad-band preamplifier design, schematically shown in Figure 2. The modulation depth of the HTC SQUID mounted in our test apparatus and connected to the preamplifier and DSP-FLL was measured to be approximately $12\mu V/\Phi_0$. Trapped flux that could not be eliminated by cycling the SQUID is believed to cause the reduction in modulation depth. Substantial noise entered the system through the prototype preamplifier making SQUID noise measurements impossible.

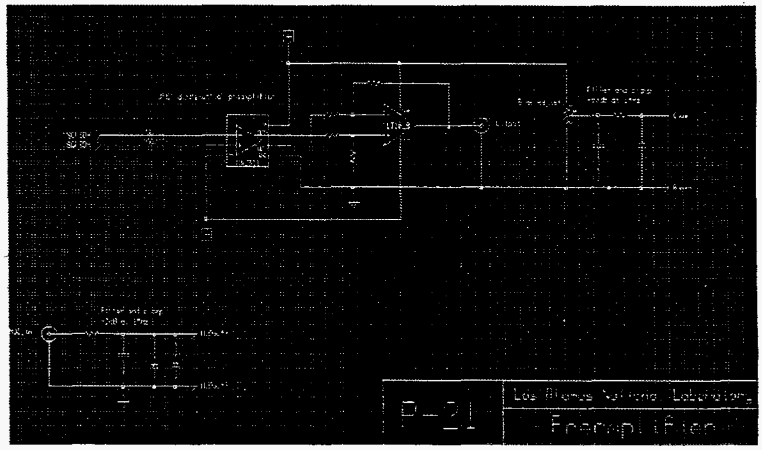

Figure 2

The SQUID sensor was mounted in a 6 inch diameter fiberglass dewar. A signal generator was used to drive a small coil placed inside a shielded chamber under the SQUID dewar. The SQUID signal leads were connected to the prototype preamplifier outside the shielded chamber. Ambient fields were reduced to approximately 100nT and other noise sources including 60Hz and harmonics were substantially reduced inside the shielded chamber. This allowed accurate measurement of the primary signal and feedback rejection for specific signals of interest. As shown in Figure 1, the same signal that was used to drive the excitation coil near the SQUID was also digitized and used by the DSP to sum into the M&F drive signal. In principle, proper adjustment of the phase delay and gain will cause the flux generated by the M&F coil to perfectly cancel the external flux carried to the SQUID by the pickup coil. A LABVIEW software interface was used to control the operational parameters of the DSP-FLL. An existing CAMAC data acquisition system was used to acquire the data, as noted above, because the PC-based LABVIEW system had insufficient bandwidth to perform this function.

III. Results

A variety of waveforms were used to drive the excitation coil placed in the shielded chamber with the HTC SQUID. The phase and gain (amplitude) of the digitized excitation coil drive signal were adjusted in the DSP algorithm by software command and optimized for maximal signal cancellation. These measurements were performed to simulate, in a controlled fashion how one might use such an algorithm to cancel a background or a primary excitation signal at the SQUID. The results of two sample measurements are shown in Figures 3 and 4. In each figure, the lower trace shows the SQUID sensor response to the excitation coil with the gain of the cancellation signal set to zero (no cancellation). This is analogous to a normal FLL control of the SQUID where the output is proportional to the rate of change of the flux in the pickup coil. The SQUID output observed for the unconcealed signal in both cases was between 400mV and 600mV. The upper trace in each figure shows the SQUID output when the feedback signal bias and gain are optimized for maximal cancellation. Note that the upper traces are multiplied by a factor of 100 to magnify the characteristics of the residual cancelled signal on the scale of the plot. The SQUID output as a function of magnetic flux was not calibrated for these measurements.

Figure 3 illustrates the measured signals resulting from a sine wave excitation. The rms amplitude of the unconcealed (feedback gain=0) SQUID output signal was 580mV. After optimizing the feedback gain (gain=281) and phase delay for maximal cancellation, the rms amplitude of the cancelled was observed to be 2±1mV. The feedback gain is

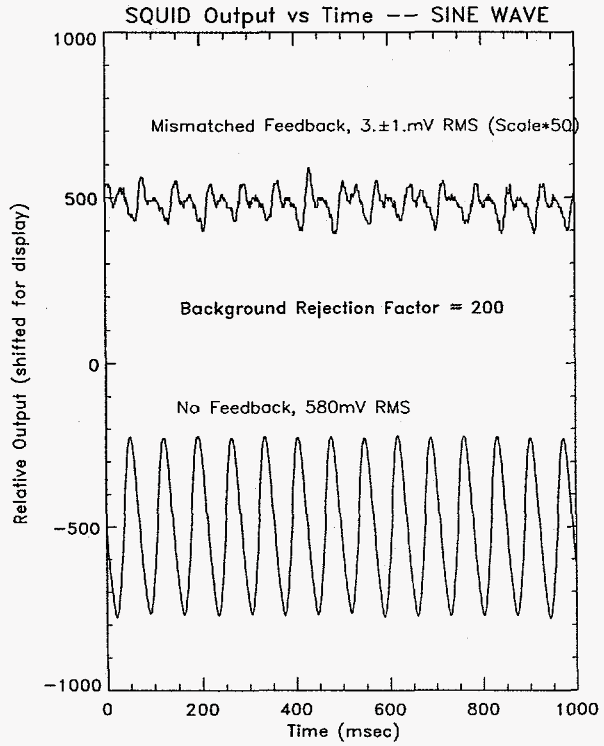

Figure 3

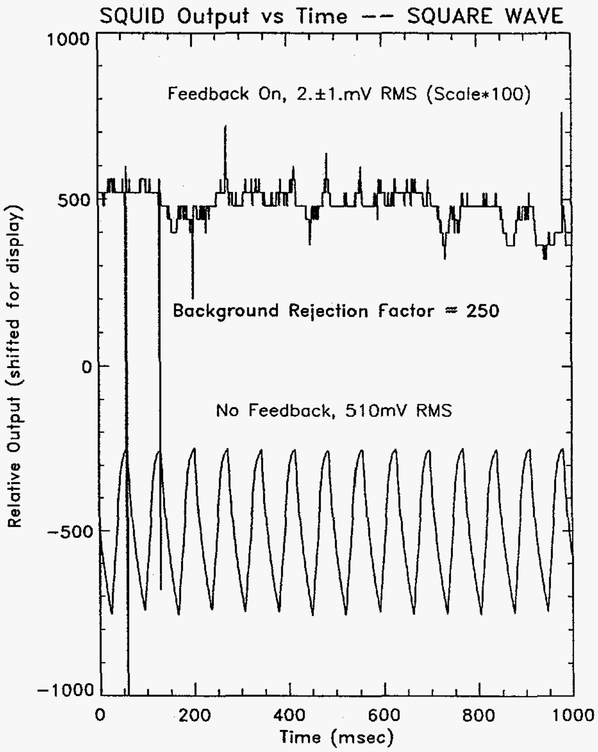

Figure 4

simply a binary value in the DSP between -32,768 and +32,768, however the relatively poor matching of the signal generator amplitude to the ADC dynamic range limited the precision of the feedback gain and consequently the precision with which the feedback could match the excitation signal at the SQUID.

Figure 4 shows the measured signals for a square wave excitation. The poor reproduction of the square waveform results from the long integration time required to optimize the system dynamic range. The reason for this is not understood at present. The cancelled signal residual shows a similar behavior to that noted in Figure 3. The large spikes shown in the cancelled signal are unique to the square wave data and were traced to least significant bit errors in the phase matching of the SQUID output and feedback signals. Only 8 bits were devoted to phase matching and this observation points to the need of greater timing precision in the cancellation loop.

IV. Discussion

A DSP controlled FLL system with feedback cancellation has been successfully demonstrated for a HTC SQUID sensor system that is easily portable and has a cryogen hold time of more than two weeks. More than 99% of simulated background or primary flux was cancelled by a feedback flux at the SQUID generated by the DSP SQUID control system. The primary limiting factor for the cancellation is the granularity in the feedback gain. More precisely matching the dynamic range of the feedback ADC to the input signal (from the signal generator) will substantially improve the cancellation factor. The cancellation can be further improved by increasing the gain of the preamplifier and reducing the noise introduced by the preamplifier. Although the dynamic range of the ADC is approximately 10^5 for input signals of 10V, input signals of 0.5V reduce the available dynamic range to approximately 10^4. Improving the performance of the preamplifer is in progress.

Finally, although powerful DSP units are relatively expensive, the per-channel cost can be dramatically reduced by controlling multiple SQUID channels with one DSP or by implementing the relatively simple algorithms in far less expensive and faster programmable logical gate arrays (PLGAs).

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