A Digital SQUID Controller

B. Limketkai [a], J. Granger [a], M. Weilert [a], Inseob Hahn [a,1]

[a] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*

Abstract

We describe the performance of an improved dc SQUID controller base upon a PC data acquisition board with a single digital signal processor(DSP). The main DSP algorithm that handles the flux-locked-loop, is optimally written in the assembly language. To improve the performance of the controller, we have added a custom built frequency converter circuit that matches the modulation frequency of the DSP system to that of a commercial SQUID sensor and preamplifier. The noise level of the dc SQUID controller system is comparable with a commercial analog system, $\sim 4\mu\Phi_0/\sqrt{Hz}$ at 100Hz. The current system could control up to 5 SQUID channels.

Key words: SQUID;DSP;flux-locked loop

1. Introduction

The superconducting quantum interference device has been instrumental for many years in applications requiring sensitive magnetic field measurements.[1] One of the most commonly used techniques to read out the sensor is the flux-locked-loop (FLL). The flux-locked-loop basically maintains the flux constant in the sensor by feedback of flux proportional to input signal. In our previous work we have reported a DSP software flux-locked-loop that utilizes commercial instruments. The DSP controller could control a single channel SQUID sensor and showed the noise level of $\sim 50\mu\Phi_0/\sqrt{Hz}$ at 1Hz without great care of optimization.[2] Main limiting factors in the performance were associated with the fact that the commercial SQUID sensor and the preamplifier were built to operate optimally at 500KHz modulation frequency. However, the DSP FLL system was limited by the speed of the Analog-to-Digital Converter (ADC) and Digital-to-Analog Converter (DAC) to a modulation frequency of only 25kHz. To improve the situation we choose to add a simple frequency up/down converter circuit instead of modifying the readily available existing commercial instruments; a SQUID sensor package, a preamplifier and a DSP based data acquisition board. In this work we improved the system in two ways: software optimization by coding with a machine language, and improving signal-to-noise ratio by adding a simple frequency up/down converter. The use of the machine language speeds up the execution time of the flux-locked-loop program more than factor of 4. This execution speed allows the system to control up to 5 SQUID channels. The noise level of the controller is greatly improved and now it is comparable with commercial analog SQUID controllers, $\sim 4\mu\Phi_0/\sqrt{Hz}$ at 100Hz.

2. DSP controller

The dc SQUID sensor has two Josephson junctions in parallel on a superconducting ring. With a constant bias current near the critical current of the junctions, the voltage across the SQUID oscillates with a periodicity of a single flux quantum as the total magnetic flux applied to the SQUID increases. The FLL for a SQUID electronics system maintains the SQUID at constant flux. Main functions in an FLL are: (1) function generation for the modulation, (2) mixing the signal, (3)

[1] Corresponding author. E-mail:Inseob.Hahn@jpl.nasa.gov

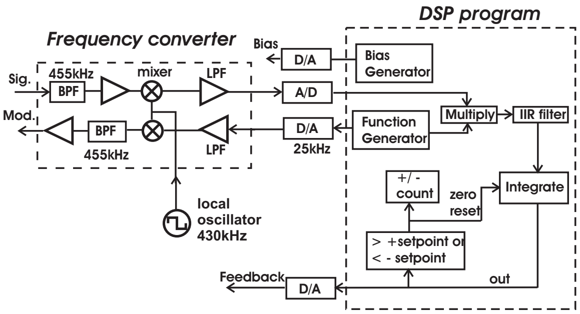

Fig. 1. Schematic drawing of DSP flux-locked loop and a frequency convertor. Connections to the SQUID sensor is not shown for simplicity.

filtering, (4) generation of the feedback by signal integration and reset, and (5) bias current generation. In our previous work we have successfully replaced all the functions listed above using a commercial ADC and DAC data acquisition PC board with a DSP.[2] The board was built around the Texas Instrument C32 digital signal processor. The board is equipped with 4 channel 100kHz, 16 bit, ADC and 4 channels of 200kHz, 16 bit DAC.[3] We have used a dc thin-film SQUID sensor and its preamplifier from Quantum Design Inc.[4] The input to the preamplifier is impedance-matched using a pair of transformers optimized for the 500 kHz modulation signal of the Quantum Design analog controller. However, the speed of the ADC and DAC limits the DSP system's modulation frequency to only 25kHz. This seriously limited the performance of the previous single channel DSP system. To improve the situation we added a frequency converter circuit to convert the modulation frequency of 25kHz to near 500kHz. Figure 1 shows a schematic drawing of the new system. In order to test the efficiency of the DSP program, we used debugging software to step through the program and count the number of DSP cycles needed to execute the program. The program reads the input ADC's, perform the required calculations and outputs values to the DAC's every 10 μs (time between two points of 25 kHz signal). We timed the number of cycles for the program to read each digital point and perform all the necessary calculations for the SQUID controlling (modulation, integration, filtering and feedback). We discovered that the code generated using the C-compiler was very inefficient. The compiled C code took approximately 140 DSP cycles (7 μs on our 40 MHz DSP) to handle one digital point of data. To improve the situation we have programmed directly in assembly langauge. This reduced the number of DSP cycles down to 35 cycles (1.75 μs) to process one digital point of data. With this enhancement, the DSP could control up to 5 SQUID channels. However, the number of ADC/DAC channels on our DSP board limited us to testing the simultaneous control of two SQUIDs.

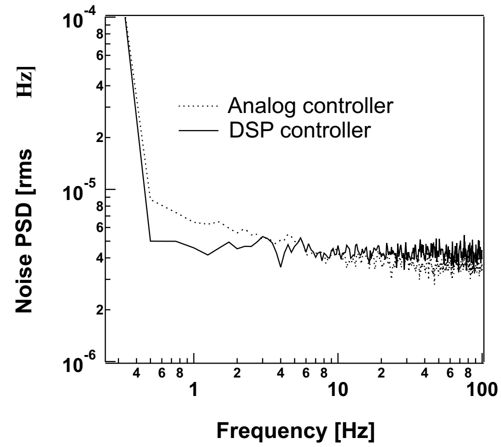

Fig. 2. Noise power spectral density vs frequency.

For a systematic comparison between the commercial analog controller and the DSP system, we used same components: SQUID sensor, the preamplifier and the cable. The input coil of the SQUID sensor was shorted with a superconducting wire to see the ultimate noise characteristic of the system. The Quantum Design commercial analog SQUID controller was first connected to the system for noise measurements. The dashed line in the Fig. 2 shows the power spectral density of the SQUID output in flux-lock mode after the proper tune of the controller. The noise at 100Hz is $3 \sim 4\mu\Phi_0/\sqrt{Hz}$. This is close to the value reported in the company's specification $\sim 3\mu\Phi_0/\sqrt{Hz}$. After taking the noise data of the commercial analog controller, we simply switched to our DSP unit without modifying the experimental set up. The solid line in the Fig. 2 shows the noise of the DSP system. The noise power spectral density measurement indicates that the DSP based controller performs similarly to the analog SQUID controller.

The authors have benefited from Dr. H. Cho's experimental support. The research described in this letter was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with National Aeronautics and Space Administration.

References

[1] J Clarke, in The New Superconducting Electronics, edited by H Weinstock, R. W. Ralston (Kluwer Academic, Dordrecht, Netherlands, 1993), p.123.

[2] Inseob Hahn, M. Weilert, Rev. Sci. Instr. 72, 2203 (2001).

[3] Model PCI32, Innovative Integration, Inc., Westlake Village, CA 91362.

[4] Quantum Design, Inc., Sandiego, CA 92121.