Construction of HTS multi-channel SQUID system

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Abstract

We have constructed a multi-channel SQUID magnetometer system. The system is designed to operate normally with 10 high temperature direct coupled SQUIDs. The main features of the system include a remote control by serial communication, low noise with wide bandwidth and high slew rate by several MHz modulation, signal conditioning and calibration by digital signal processing.

Keywords : SQUID, multi-channel, magnetometer

I. Introduction

SQUID is the most sensitive device among currently available magnetic field sensor devices[1]. SQUID also exhibits outstanding frequency response characteristics. One of its applications is the remote sensing of magnetic or metal objects, for example geological exploration, mine search, maritime surveillance[2].

However, the popular application of SQUID has been limited since the device needs cooling. The prerequisite of the coolant and dewar detracts the portability and the maintenance of especially a large-scale integrated or a distributed multi-channel system. Hence, depending on application, different systems have been developed aiming different merits. In this work we developed a multi-channel integrated system with high performance and compact volume for distant operation.

II. System hardware

Sensor probe The target application of our system

is to sense and locate the magnetic dipole of a remote source[3]. To do this, one needs a minimum of 5 magnetic gradient components. Since we are planning to use SQUID magnetometer sensors not the gradiometer sensors, we need more than 5 SQUIDs. In principle 3 axis magnetic components and 5 gradient tensors can be obtained from as few as 8 magnetometer SQUIDs in orthogonal system[4]. For this scheme, however, we cannot check *in situ* the consistency of the collected data because some SQUID channels are used twice for two different gradient components. Furthermore, if one of the sensors does not operate, we cannot get any meaningful information. Hence we have designed a 10-channel system where the 5 gradient tensors are calculable from 5 independent combinations of 2 channels without double use.

The photo of the probe is shown in Fig. 1. The sketch and the equation in Fig. 2 show how the gradient tensors are calculated from the labeled sensor channels. To avoid the signal degradation due to the metallic or magnetic particles, the low temperature part of the probe is made of FR-4, a fiber-reinforced plastic (FRP) material. The probe is designed to fit into a cryogenic dewar with an inner dimension of 500 mm(H) × 150 mm(ϕ). Due to the

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size of the sensor package, the baseline is different for the diagonal and the off-diagonal components of the gradient tensor. The SQUID readout electronics are mounted directly onto the top of the probe to make the connection to SQUID as short as possible. The longer wiring cause noise increase as well as signal delay which limits the system slew rate.

SQUID readouts The SQUID sensor is operated with a flux locked loop(FLL) circuit with several MHz flux modulation. One of the applications is to detect slowly moving object at distance so that the data are to be collected in open space and at negligible drift. The main reason why we use the modulation scheme is the low signal drift with low noise and better immunity against the external electromagnetic interference. For the outdoor application, most practically required feature of the FLL electronics might be the slew rate and the signal bandwidth. High slew rate is needed to maintain the locked state in the presence of large and relatively fast changing magnetic signal while the wide bandwidth is to avoid the distortion of the small but fast changing signals from the environments. To satisfy these requirements we employed normally 4-6 MHz flux modulation. The SQUID output is amplified by a toroidal transformer whose winding

ratio is 4:50. Since the shorted input noise of the following IC amplifier is 2 nV/Hz$^{1/2}$, the equivalent input noise of the circuit is less than 0.2 nV/Hz$^{1/2}$ which corresponds to 3.2 $\mu\Phi_0$/ Hz$^{1/2}$ for the SQUID with 20 μV peak-to-peak output. Higher winding ratio of the transformer provides better noise performance but it causes narrower signal bandwidth so that the system becomes unstable for wide bandwidth application. The FWHM(full width of half maximum)-to-center frequency ratio($\Delta f / f_c$) of the transformer is about unity for 50 Ω source impedance. Thus the FLL is designed to have signal bandwidth up to MHz.

It is well known that a periodic reversing of the bias current greatly reduces the low frequency noise of the SQUID due to critical current fluctuation at the Josephson junction[5]. The bias reversal is achieved by switching the bias voltage at a frequency obtained by dividing the modulation clock. The frequency is about 10-20 kHz depending on the modulation frequency. To reduce the ringing at the transformer output due to step voltage change across the SQUID, the voltage is partially balanced out by a bridge circuit. Since the bandwidth of the used transformer is quite large, however, the ringing is not so prominent as in narrow bandwidth system with lower
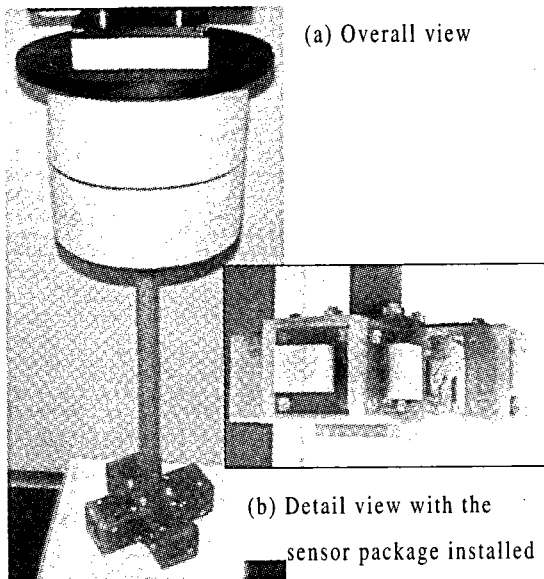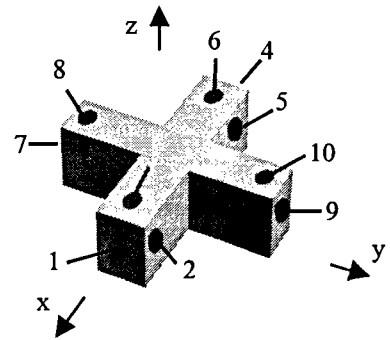

(a) Overall view

(b) Detail view with the sensor package installed

Fig. 1. Photo of the probe

$$\begin{bmatrix} \dfrac{\partial B_x}{\partial x} & \dfrac{\partial B_x}{\partial y} & \dfrac{\partial B_x}{\partial z} \\ \dfrac{\partial B_y}{\partial x} & \dfrac{\partial B_y}{\partial y} & \dfrac{\partial B_y}{\partial z} \\ \dfrac{\partial B_z}{\partial x} & \dfrac{\partial B_z}{\partial y} & \dfrac{\partial B_z}{\partial z} \end{bmatrix} = \begin{bmatrix} (1)-(4) & (2)-(5) & (3)-(6) \\ (2)-(5) & (9)-(7) & (10)-(8) \\ (3)-(6) & (10)-(8) & (4)+(7)-(1)-(9) \end{bmatrix}$$

Fig. 2. Relation between the magnetic tensor and the channel data. $\nabla \cdot B = 0, \nabla \times B = 0$ are used for the simplified formula.

modulation frequency.

Since the system is to be operated in remote, all the controlling parameters of the readout circuit – bias current, modulation level and frequency, phase shift, adjust flux for bias reversal operation, preamplifier gain for stable flux lock at different flux lock range, integrator offset for the flux lock at most sensitive lock point – are adjustable by serial communication from the remote host computer. Since multiple FLL circuits are used at the same time, we employed RS-485 serial communication. For the serial communication and the generation of the analog and digital control levels, a commercially available PIC module[6] is used as a CPU for each FLL circuit. For the tuning process where we optimize the FLL parameters such as bias current and modulation amplitude, a test flux is also required if the environment is magnetically calm. The test flux is generated inside the readout circuit by programming the PIC module.

Another important factor for the remote operation of the system is the power consumption. Since the popular high speed IC's consumes larger current than the slow ones, we carefully selected the components with low quiescent current. As the result, at zero output level, the each circuit draws less than 120 mA from +5 V and –5 V.
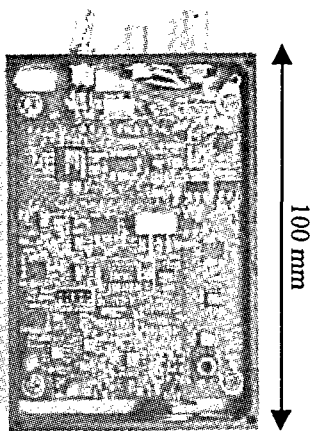
SQUID packaging The SQUID is mounted on a printed circuit board with a 20 turn feedback coil and an 1 turn modulation coil pattern. The board also accommodates two 50 Ω chip resistors for heating of the SQUID above its critical temperature in case a noise generating flux is trapped in the superconductor film. The wire bonded SQUID on the board are enclosed and sealed between an FR-4 cap and another FR-4 board to avoid water condensation as well as to heat up the device effectively when necessary. The size of the package is 21 mm(L) × 17 mm(W) × 10 mm(H) when mated to the holding adapter with several resistors and capacitors to prevent a low impedance coupling to EMI's. The adapter also provides rough balancing circuit for the bias reversal operation as previously described.

System wiring The wiring in the probe is made using twisted pairs of enamel-coated copper wires. The twisted pairs are placed inside the thin Teflon tubing. 5 twisted pairs – for bias, signal, modulation, feedback, heating - are used for each channel. The electrical power to the circuit is supplied from the remote host through a multi-conductor cable with ground shield. The cable also carries 2 lines for the serial communication. The power and the serial communication lines are shared by the readout electronics. The signal output from the SQUID

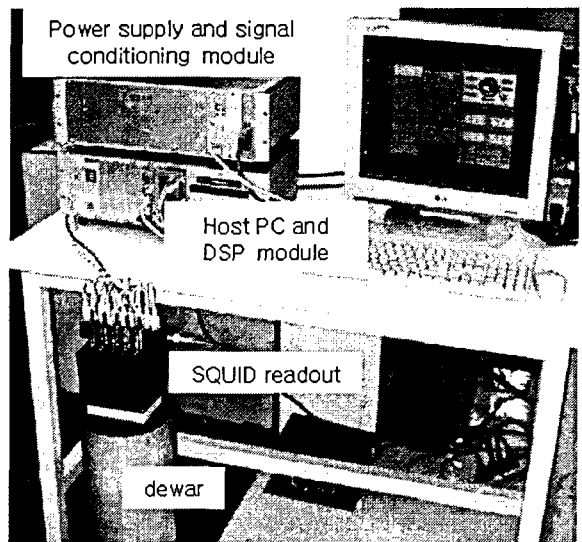Fig. 3. Photo of the SQUID readout electronics

Fig. 4. Photo of the overall system

readout electronics is driven by a differential driver IC to minimize the signal degradation over long transmission wires. Shielded two-conductor cables are used for the signal line.

Digital signal processing module The signals are first handled by a signal conditioning board where the differential signals are converted to single ended ones. The conditioning board also filters out high frequency components to avoid the aliasing in the analog-to-digital conversion. The conversion is achieved by 16 bit A/D modules controlled by a high performance DSP board which is commercially available and based on a DSP chip by Analog devices, inc.[7].

The mission of the DSP module includes (1) flexible frequency signal filtering, either low/high pass or band pass, (2) signal scaling and (3) an adaptive noise cancellation. The module continuously performs signal process and puts the outputs to a ring buffer memory shared by the host computer. Ultimately, the DSP module will be programmed to produce magnetic gradients with noise rejected so that the host computer is dedicated to the inverse problem and the dynamic display of the solved results.

Host computer The host computer is a Pentium III class system with single board feature to minimize the space usage. Both the main board and the DSP module are mounted on the same rack. The computer performs auto/manual tuning program, continuous monitoring and recording of all the channel or source motion by implementing inverse solution solver program. The graphical user interface is programmed using Labview/CVI software[8]. The main screen and the whole assembly of the system are shown in Fig. 4.

III. Summary

We have constructed 10-channel high temperature SQUID magnetometer/gradiometer system for the remote identification of a magnetic object in an open space. The performance test of the overall system is under progress.

Acknowledgement

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