Mobile High- T_c SQUID System for MCG Measurement

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Abstract—We developed a mobile high critical temperature (high- T_c) superconducting quantum interference device (SQUID) system for a magnetocardiogram (MCG) measurement. The device is composed of a small cryostat, a high- T_c SQUID magnetometer, and digital flux-locked loop (FLL) electronics. A small commercially obtained vacuum bottle enables the device to be hand-held. Large dynamic range was achieved through the digital FLL processing. We also proved the feasibility of this mobile high- T_c SQUID system using simple construction. MCG measurements while holding a cryostat and also in unshielded conditions were successfully demonstrated.

Index Terms—Flux-locked loop (FLL), magnetocardiogram, mobile, SQUID magnetometers.

I. INTRODUCTION

LOW CRITICAL temperature (low- T_c) superconducting quantum interference devices (SQUIDs) are generally used for biomagnetic measurements. If their applications are to be expanded, the devices must be made easy to handle. The most eagerly desired features include operation by hand like a stethoscope, without liquid helium, unshielded operation, and low cost. A mobile high- T_c SQUID system is one way in which these operational features can be realized.

In recent years, some groups have demonstrated magnetocardiogram (MCG) measurements using specially designed high- T_c SQUID gradiometer chips [1]–[3] or electric gradiometer system [4]–[8]. They accomplished MCG measurements with good signal-to-noise ratio without magnetic shielding. In contrast, our aim is to achieve an MCG measurement with the cryostat held by the hand.

The mobile SQUID system which is to be hand-held must have a small cryogenic sensor part. We composed it of a high- T_c SQUID magnetometer and a small vacuum bottle. And moreover, they are commercially obtained ones in order to make the system simple and low-cost.

The mobile SQUID system needs a large dynamic range, which can allow movement in the geomagnetic field. Drung developed extremely high performance readout electronics which can achieve a large dynamic range through the working of a flux-locked loop (FLL) electronics with flux-quanta counting

Fig. 1. A block diagram of the mobile SQUID system. It is composed of a high- T_c SQUID magnetometer, a small vacuum bottle, digitally controlled FLL electronics, and a host computer.

[9]. Their devices were realized with state-of-the-art of electronics. On the other hand, the flux-quanta counting also can be executed by an ordinary electric circuit using a double-counter method [10].

We tried to develop a very simple, low-cost mobile SQUID system using a high- T_c SQUID magnetometer and FLL electronics. A dynamic range which is wide enough for mobile operation was achieved, and we have demonstrated MCG measurements with the mobile SQUID system.

II. COMPOSITION OF MOBILE SQUID SYSTEM

Fig. 1 is a block diagram of our latest mobile SQUID system. The system is composed of a high- T_c SQUID, a cryostat, a digitally controlled FLL circuit, and a host computer.

A general-purpose high- T_c SQUID magnetometer (Sumitomo Electric Industries Ltd., CL3508-1.2) was used. Its effective magnetometer area is 0.8 mm^2 , and the sensitivity B/Φ is $2.7 \text{ nT}/\Phi_0$, where B is the magnetic flux density in its sensitive area and Φ_0 is the flux-quantum. The maximum modulation voltage is $12.0 \text{ } \mu\text{V}$. Its intrinsic noise level is $0.2 \text{ pT}/\text{Hz}^{1/2}$.

A commercially obtained vacuum bottle (Sumitomo Electric Industries Ltd., K1-1.4) was used as a cryostat. It is made from stainless steel and can be held in the hand and its liquid nitrogen capacity is about 0.5 l . It was not custom-designed.

The digital FLL circuit is made of off-the-shelf electric parts: an 8-bit one-chip microcontroller, a 12-bit A/D converter, a 16-bit D/A converter, and some amplifiers. The electronics is controlled by a host computer through the microcontroller.

A flux-quanta counting method was used to achieve a large dynamic range [9]. This is based on the periodicity of the SQUID's voltage-flux characteristic. The integrator of an FLL is reset at every time the feedback flux exceeds $1 \Phi_0$ and the corresponding Φ_0 steps are then counted. Though this

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Fig. 2. Active area of a mobile high- T_c SQUID system with a preamps of 84 dB, 94 dB and 104 dB. Each system can measure magnetic signals in shaded areas.

process is usually executed by a high-performance digital signal processor, in our system the microcontroller covers it with a double counter method [10]. The integration and the reset are done by the microcontroller. The counter is separated into the microcontroller and the host computer. Therefore the flux-quanta counting processing can be accomplished by low-cost microcontroller.

III. EXPERIMENTAL PERFORMANCES

The designing of the preamp in the digital FLL electronics is a key fact for the performance of the system. The dynamic range and noise performance of the SQUID system depend on the preamp. In this paper, the preamp was determined by experimentally comparing of amplifications of 84, 94 and 104 dB.

Fig. 2 shows the active area for each case. The systems can measure magnetic signals only in these shaded areas. They were proportional to the amplification.

Fig. 3 shows noise spectra measured inside an MSR. White noise levels were $0.32 \text{ pT/Hz}^{1/2}$ with 84 dB, $0.33 \text{ pT/Hz}^{1/2}$ with 94 dB, and $0.88 \text{ pT/Hz}^{1/2}$ with 104 dB. The large peaks appearing around 100 Hz were suggested to be caused by power line noise (50 Hz) and its harmonics. They were increased by the preamp of 104 dB.

From these results, we chose the preamp of 94 dB as the most suitable of the three amplifications. Dung has theoretically discussed the design of an FLL [11]. However, experimental comparisons are also effective for fabrication of a low-cost system.

IV. MCG MEASUREMENTS

We demonstrated two examples of MCG measurements made with the developed mobile high- T_c SQUID system. First, an MCG signal was measured using this system with the small cryostat held by the hand near the subject's chest. Fig. 4 shows the measured waveform. The measurement was carried out inside an MSR. It is suggested that fluctuation of the signal was caused by vibration of the hand. Although the magnetic flux density was more than 10 nT, the system could maintain steady operation by virtue of its large dynamic range. Fig. 5 shows the MCG waveform analysed by a digital band-pass filter (5 to 40 Hz) and 15-times averaging (15 seconds).

Fig. 3. Magnetic noise spectra of a mobile high- T_c SQUID system measured inside a MSR. They were measured with preamps of 84 dB, 94 dB, and 104 dB.

Fig. 4. Magnetic signal measured using a mobile SQUID system with the hand-held cryostat.

Fig. 5. An analysed MCG waveform. This was obtained by applying a digital band-pass filter (5 to 40 Hz) and 15-times averaging. The measurement was carried out inside an MSR.

Hz) and 15-times averaging (15 seconds). The R wave which characteristically shows heart activity is observed.

Second, Fig. 6 shows a waveform measured outside an MSR. The cryostat was put on a table at this case. The position and height of the table were adjustable, to correspond a subject lying

Fig. 6. Magnetic signal measured using a mobile SQUID system which was set on a table in unshielded conditions.

Fig. 7. Analysed MCG (black line) and ECG (gray line) waveforms. They were obtained by applying a digital low-pass filter (40 Hz) and 63-times averaging. The measurement was carried out outside an MSR.

under the table. The power line noise of 50 Hz can be mainly seen in Fig. 6.

The dynamic range of our mobile high- T_c SQUID system also was effective for unshielded operation. Fig. 7 presents simultaneously taken MCG and ECG data. They analysed by a digital low-pass filter (40 Hz) and 63-times (1 minute) averaging. QRS complex is shown.

Our experiments demonstrated that the mobile high- T_c SQUID system can be used for MCG measurements. However, practical biomagnetic measurements require much higher noise performance. Some gradiometers [1]–[8] and digital signal processing methods [12], [13] have been investigated to cancel

magnetic noises. It is hoped that the applications of them to the mobile SQUID system will improve the noise performance.

V. CONCLUSION

We developed a mobile high- T_c SQUID system which is to be hand-held for MCG measurements. It has very simple cryogenic part and digitally controlled FLL electronics to obtain a large dynamic range. Experimental comparisons of preamps are effective for fabrication of a low-cost system. MCG signals were successfully measured while holding a cryostat and also in unshielded conditions. This system is effective in expansion of biomagnetic measurement application.

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