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Programmatic Sequence for the Automatic Adjustment of Double Relaxation Oscillation SQUID Sensors

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Abstract

Measuring magnetic fields with a SQUID sensor always requires preliminary adjustments such as optimum bias current determination and flux-locking point search. A conventional magnetoencephalography (MEG) system consists of several dozens of sensors and we should condition each sensor one by one for an experiment. This timeconsuming job is not only cumbersome but also impractical for the common use in hospital. We had developed a serial port communication protocol between SQUID sensor controllers and a personal computer in order to control the sensors. However, theserial-bus-based control is too slow for adjusting all the sensors with a sufficient accuracy in a reasonable time. In this work, we introduce programmatic control sequence that saves the number of the control pulse arrays. The sequence separates into two stages. The first stage is a function for searching flux-locking points of the sensors and the other stage is for determining the optimum bias current that operates a sensor in a minimum noise level Generally, the optimum bias current for a SQUID sensor depends on the manufactured structure, so that it will not easily change about. Therefore, we can reduce the time for the optimum bias current determination by using the saved values that have been measured once by the second stage sequence. Applying the first stage sequence to a practical use, it has taken about 2-3 minutes to perform the flux-locking for our 37-channel SQUID magnetometer system.

keywords : Auto-tuning, magnetoencephalography (MEG), sensorcontrol, superconducting quantum interference device (SQUID)

I. Introduction

We can detect very weak neuromagnetic fields generated by ionic currents flowing inside a bundle of neurons using superconducting quantum interference device (SQUID) sensors. The development of the multichannel SQUID sensor system had enabled us to determine locations of the current sources and we applied this technique to the noninvasive investigation of human brain function or heart diseases. We call the former magnetoencephalography (MEG) and the latter magnetocardiography (MCG). To achieve a high spatial resolution in these techniques, especially in MEG, simultaneous sensing at a number of sites is required. The number of sensors in a conventional MEG system reaches several dozens to hundreds. Such a multichannel SQUID system requires a careful design for preventing various problems like cross-talks among channels. Besides the design problem, measuring magnetic fields with a SQUID sensor is always in need of preliminary adjustment such as determination of the optimum bias current and searching a flux-locking point and we have to condition each sensor one by one for every experiment. For a multichannel SQUID system, it is a very cumbersome and time-consuming job that can

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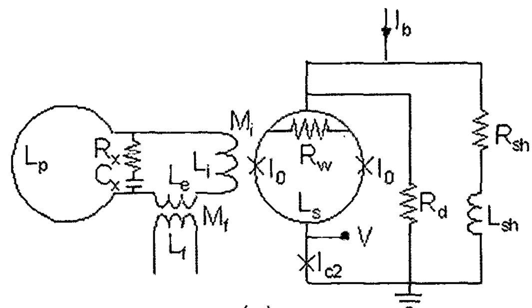
be conducted by only a person who has a professional knowledge on the SQUID, which is impractical for the use in hospital. To circumvent this problem, we have developed a serial communication protocol between SQUID sensor controllers and a personal computer in order to control the sensors automatically. However, the control based on the serial bus is too slow to adjust all the sensors with a sufficient accuracy in a reasonable time. In this paper, we introduce programmatic control sequence that saves the number of the control pulse arrays. Our sequences are designed for a double relaxation oscillation SQUID (DROS) sensor. Compared with the standard dc SQUID, the DROS provides a large flux-to-voltage transfer coefficient and a large modulation voltage. Therefore, simple flux-locked loop (FLL) electronics can be used for the DROS operation [1]. The first stage of our sequence is aimed to search a proper flux-locking point for the FLL electronics. By this stage, we can obtain the same polarity and the relatively uniform transfer coefficient after flux-locking process for a number of sensors. The second stage is for determining the optimum bias current with which a sensor operates in a minimum noise level. Generally, a DROS sensor has a feature that its noise level changes depending on a given bias current and we have to find the optimum bias current value of the minimum noise for sensitive field measurement. Here, we describe our DROS magnetometer and the programmatic sequence in detail.

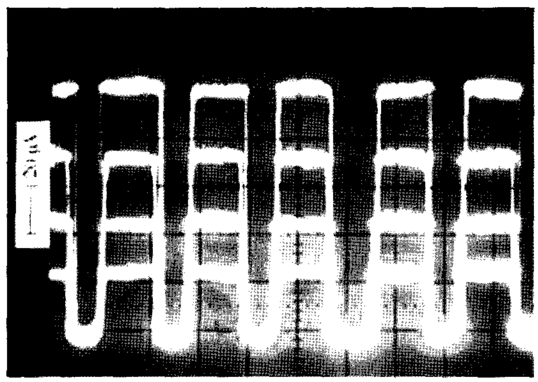
II. DROS Magnetometer

The DROS is based on the unshunted hysteretic Josephson tunnel junctions. The schematic circuit diagram of the DROS magnetometer is shown in Fig. 1a. A hysteretic dc SQUID (the signal SQUID) and a hysteretic junction (the reference junction) are connected in series, and shunted by a relaxation circuit of a resistor R_{sh} and an inductor L_{sh}. Though the original design of the DROS used a reference SQUID, we used the reference junction to remove the possibility of flux trapping by the reference SQUID and to eliminate the wires needed for the adjustment of the reference flux [2]. The critical current of the signal SQUID is determined by the flux signal applied to the signal SQUID through the input coil.

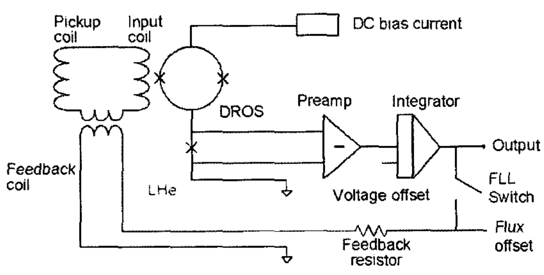
In a dc bias current I_b, relaxation oscillations can occur and persist if the operation condition is met, as in [1]. The relaxation oscillation frequency is of the order of R_{sh}/L_{sh}, which is typically 1 GHz. During the



(a)



(b)



(c)

Fig. 1. (a) The circuit diagram of the DROS magnetometer. (b) The voltage swing of DROS sensor as a function of the external magnetic flux at different bias current values. (c) The FLL circuit for DROS sensor.

relaxation oscillations, the DROS functions as a comparator of the two critical currents, $I_{c1}(\Phi)$ and I_{c2}. When the volatge output is measured across the reference junction, and if $I_{c1}(\Phi)>I_{c2}$, the reference junction oscillates between the gap-voltage state and the zero-voltage state periodically, generating periodic voltage pulses with the relaxation frequency. If the signal flux is changed such that $I_{c1}(\Phi)<I_{c2}$, the signal SQUID oscillates between the gap-voltage state and the zero-voltage state, whereas the reference junction remains in the zero-voltage state, resulting in no voltage output across the reference junction.

Since the room-temperature preamplifier has a bandwidth much narrower than the relaxation frequency, the measured output voltage is either zero-voltage or time-averaged voltage, depending on the relative magnitude of $I_{c1}(\Phi)$ and I_{c2}. The transition between the zero-voltage and the time-averaged voltage is very abrupt at the competing condition $I_{c1}(\Phi)=I_{c2}$, resulting in a large flux-to-voltage transfer coefficient.

In order to provide the stable operation condition of the DROS, some damping circuits were introduced. First, since the DROS has hysteretic junctions, a parasitic resonance due to the junction capacitance and the shunt inductance L_{sh} can occur. To damp this LC resonance, a damping resistor R_d was used across the signal SQUID and the reference junction [3]. Second, the signal SQUID washer acts a ground plane for the input coil, giving rise to a resonance. To damp this washer resonance, a damping resistor R_w was inserted across the signal SQUID loop. Third, a damping circuit made of a resistor R_x and a capacitor C_x was put in the flux transformer to damp the resonance in the input coil, and to filter out high-frequency noises from the pickup coil [4].

Our DROSs had reference critical currents of around 10 μA and the maximum modulation voltages of around 100 μV, depending on the bias current, which is about 2 times larger than that of dc SQUIDs. The flux-voltage curves showed almost a step function of the applied field (Fig. 1b). The flux-to-voltage transfers were around 1 mV/Φ_0, which is about 10 times larger than the transfer of standard dc SQUIDs. In order to eliminate the magnetic coupling between the adjacent pickup coils, external feedback scheme was used (Fig. 1c); when the FLL switch is on, the compensation field is applied to the SQUID loop by the feedback loop.

III. Serial Communication Protocol

We have developed a serial communication protocol for software control of SQUID controllers. The transmission bus consists of three wires: A clock pulse line (CLK), a data send line (DS), and a control send line (CS), respectively. The basic structure of the three lines is shown in Fig. 2. The communication consists of only one-way transmission from a personal computer to the controller. The controller reads the Boolean status of the DS and CS whenever the CLK signal is rising.

The first 8 bits of the DS indicate a channel number of the sensor system. The channel bits and the remaining control bits of the DS are classified by the CS status. The following 8 bits of the DS determine which function is to be executed, e.g., the power on-off, analog filter type selection, amplifier switching, integrator reset, and FLL on-off. The next 4 bits of the DS determine which value the next 12-bit resolution data are to be written for: the bias current value, voltage offset value, feedback coil current value, and offset field voltage.

Consequently, we give a command to the controller by three wires and each command contains a 32-bit length DS pulse array. The clock speed used in experiments was 500 Hz, i.e. it takes at least 64 ms for a command. For pre-adjustment, we should make numerous trials with changing the bias current value and the feedback coil current value for applying field. Each trial needs the 32-bit length pulse array and the time for that. In order to reduce the preparation time, we have to use as small a number of pulse arrays as possible. We describe the detail of the programmatic sequence using this protocol in the following

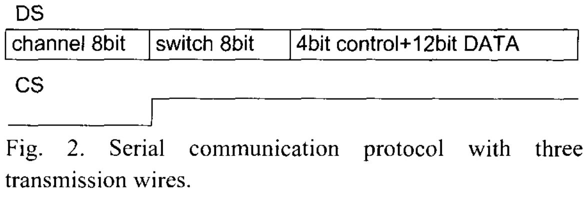


Fig. 2. Serial communication protocol with three transmission wires.

paragraph. All the sequence is conducted in a magnetically shielded room.

IV. Programmatic Sequence

The first stage : Flux-locking point search

Flux-locking point search means driving a FLL circuit at a proper external magnetic field. In a SQUID sensor the output voltage is not linearly varying with the applied magnetic field. The flux-to-voltage transfer coefficient changes with a period of the magnetic flux quantum Φ_0. Therefore, we have to use the FLL to obtain a linear voltage response to the applied field, which is operating a SQUID in a fixed magnetic field that gives the maximum flux-to-voltage transfer.

Practically, it works if we set the mean voltage value between the swing voltages as a reference value for the FLL feedback integrator. To find the mean voltage value, we must measure the maximum and the minimum voltage values of the voltage swing and take an average of them. In obtaining the maximum and the minimum, we should read at least three points having the same interval in one flux quantum Φ_0. In actual condition, the duty of the voltage swing varies with a given bias current and an external magnetic field; accordingly, we read the voltages at four different applied fields that have been written by pulse arrays for the feedback coil current (Fig. 3a). Each reading is the mean of voltage for 33 ms to average the line noise. The calculated mean voltage is to be set as the reference of the FLL integrator (zero offset). However, if we switch on the FLL when an applied field exceedingly deviates from a proper locking point, the FLL would fail in feedback locking because the integrator may be saturated. Therefore, we should turn on the FLL after the applied field approaches the locking point (the center of rising voltage). In searching the locking point, we take rather coarse intervals in applied fields ($\Phi_0/16$) and use extrapolation (Fig. 3b). When the point A in Fig. 3b is the first rising point that has the voltage value over the fluctuation level, we can estimate the proper applied field corresponding to the mean voltage value from the following approximation,

$$B = \frac{V_{mean} - V_A}{V_A - V_{min}}, \tag{1}$$

where B is the extrapolating shift and we can consider the sum of the shift and the field at point A as the proper applied field. Turning on the FLL switch at the estimated applied field makes some voltage offset because of the integration of a remaining difference between the estimated value and the exact value. The offset is adjustable by

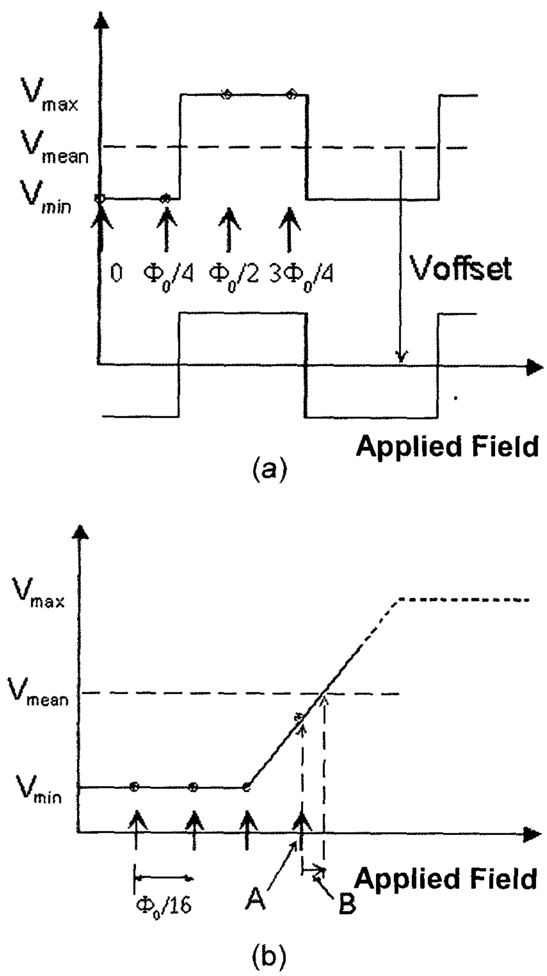


Fig. 3. (a) Measuring voltages at four different applied fields for searching the maximum and the minimum. (b) The point A means the first rising point over the fluctuation level and the point B is the extrapolating shift for the proper applied field corresponding to the mean voltage.

adding extra flux-coil current proportional to the offset when the FLL is working.

The second stage : Optimum bias current determination

The noise level in a DROS sensor changes depending on a given bias current. In order to measure the feeble neuromagnetic field, we have to operate the sensor in minimum noise condition, i.e., the optimum bias current. We should measure the white noise levels while scanning the bias current to find the optimum bias current; however, dense scanning requires enormously long time because the white noise measurement at a bias current value contains the first stage sequence, the flux-locking point search. Therefore, the range of the bias current scanning is preliminarily restricted within the range showing a finite voltage swing width (Fig. 4a). The sequence finding the swing width is similar to that of Fig. 3a. The lager bias current, the wider voltage swings and it gets disappeared. Especially, just before the disappearance, the flux-to-voltage transfer is too high to operate the FLL circuit having fixed time parameters. Thus, we limit the range to the bias current value showing 70 % of the maximum voltage swing width (B in Fig. 4a). When we refer to the maximum value and the minimum value of the bias current range as Ib_{max} and Ib_{min}, respectively, we start from Ib_{max} and decrease the bias current value to Ib_{min} measuring the rms white noise (measured field through a digital high-pass filter; 200 Hz cut-off frequency) at those current values. As the flux-to-voltage transfer is too high for the FLL when the bias current near the Ib_{max}, the controller fails to catch the flux-locking point and the output shows overload (Fig. 4b). After recording white noise as a function of decreasing bias current, we stop scanning current value. One stop condition is that the bias current value reaches Ib_{min}, and the other stop condition is when the voltage swing is too small to operate the FLL circuit (the output is overload).

Once the optimum bias current value with the minimum noise is determined by the sequence, it hardly changes about because the noise characteristics depending on bias current is determined by the manufactured structure. Therefore, we save the determined optimum bias current values of all the sensors to a data file, next time use those recorded data. Practically, all we have to do for pre-adjustment is the first stage sequences for the flux-locking of sensors. We perform the flux-locking for our 37-channel SQUID magnetometer system in about 2-3 minutes although the required time depends on magnetic noise environment. As the result, Fig. 5 shows the superposed magnetic fields measured from all the channels (7-Hz sinusoidal function current on a small solenoid below the sensor system). Although the differences in sensor location

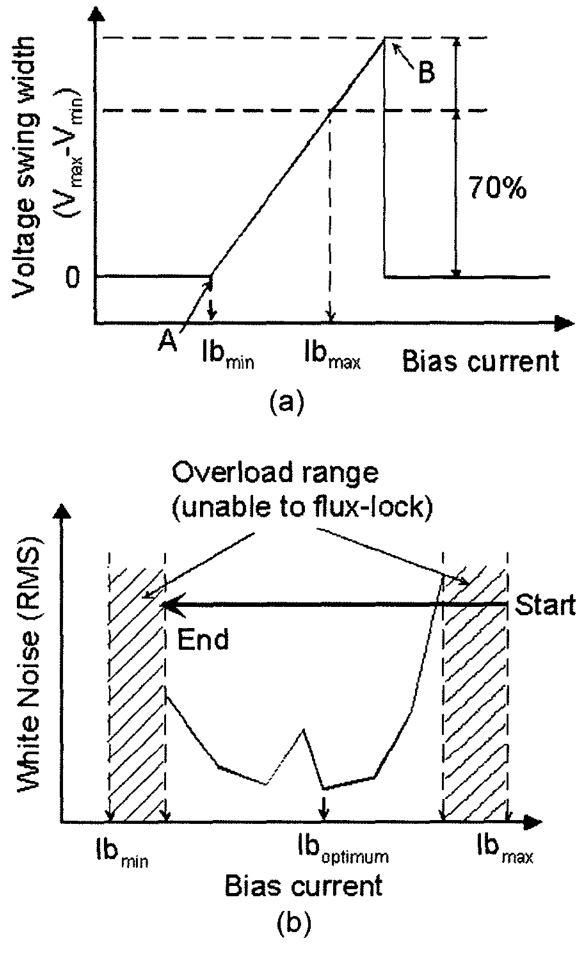


Fig. 4. (a) Limitation of bias current scanning range (Minimum; the swing-appearing value, Maximum; the value giving 70 % of the maximum voltage swing width, 70 % of the B in figure). (b) Record white noise as a function of decreasing bias current until the bias current reaches the minimum of the range or until the output is overload.

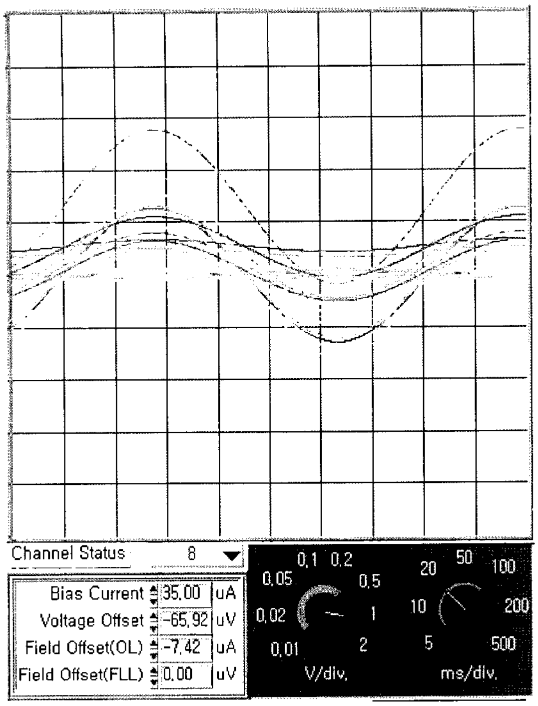


Fig. 5. Superposed graghs of measured magnetic fields from a small solenoid. The solenoid was located below the sensor system and we applied the current of 7-Hz sine-wave to the solenoid.

have made variation in the measured field amplitudes, every sensor had the same polarity.

V. Conclusion

We proposed the programmatic sequence for the automatic pre-adjustment of DROS Sensors using the serial communication protocol without any additional instrument generating a conditioning field for the adjustment, e.g., Helmholtz coil. We have separated the sequence to two stages, i.e. the flux-locking point search and the optimum bias current determination. Each stage was designed to save the number of pulse arrays in need. Using the saved values of the optimal bias currents, we have drastically reduced the time for the pre-adjustment. We expect that this automatic sequence will be very useful for clinical usage of MEG systems.

Acknowledgments

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