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SQUID magnetometer using sensitivity correction signal for non-magnetic metal contaminants detection

Toshifumi Yagi*, Masaharu Ohashi, Ken Sakuta

Department of Electronic Systems Engineering, University of Shiga Prefecture, 2500 Hassaka-cho, Hikone-City, Shiga 522-8533 Japan

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ABSTRACT

Measurement methods with SQUID can accurately detect small magnetic metal contaminants based on their magnetic remanence. But, a high-frequency excitation is necessary to detect nonmagnetic metals, on the base of contrasts in electric conductivity. In this work, an open loop technique is introduced to facilitate this. The SQUID is negative feedback controlled (flux locked loop (FLL) operation) for the low frequency range, which includes significant noise due to the movement of the magnetic body or the change of the ambient magnetic field composed of the geomagnetic field and technical signals, and it operates in an open loop configuration for the high frequency range. When using the open loop technique, negative feedback is not applied to the high frequency range. Consequently, the V–Φ characteristic changes due to various causes, which leads to variations in the conversion factor between the SQUID output voltage and the magnetic field. In this study, conversion techniques for the magnetic field for open loop operation of SQUID in the high frequency range are examined.

1. Introduction

Various detection methods with SQUID for small metallic contaminants which enter into food or industrial products were studied [1–3]. Magnetic metals are detected by measuring magnetic remanence; however, a high-frequency excitation is necessary to detect nonmagnetic metals such as copper. High-speed FLL has been already examined a lot [4] and it is possible to expand the excitation frequency by using it. Also, it is possible to expand the excitation frequency more simply by introducing small signal mode [5]. However, it is difficult to lock a working point for the SQUID without negative feedback because the shielding factor of the magnetic shield box used in this work in the low frequency range is generally small, and significant noise of low frequency due to the movement of the magnetic body or the change of the ambient magnetic field composed of the geomagnetic field and technical signals is applied to the SQUID. One of the solutions is open loop technique [6] as shown as Fig. 1. The SQUID is negative feedback controlled (FLL operation) in the low frequency range which includes the noise, and it operates using an open loop configuration in the high frequency range. Using this method, it is possible to improve the detection accuracy of nonmagnetic metal contaminations by increasing the excitation frequency. But, the conversion factor between the SQUID output voltage and the magnetic field in open loop technique changes, for instance due to temperature fluctuations. In this study, we examine magnetic field conversion techniques for open loop operation of the SQUID in the high frequency range.

2. Estimation of conversion factor between voltage and magnetic field

2.1. Theory and experimental method

The relationship between the detection voltage V_{detect} produced by a magnetic flux Φ_{detect} with a preamplifier gain G_A in the FLL circuit and the gradient at the working point of the V–Φ characteristic V_φ in the small signal mode is given by $V_{detect} = V_\varphi G_A \Phi_{detect}$. This expression means the V–Φ characteristic varies due to various causes, which leads to a change in the conversion factor between the SQUID output voltage and the magnetic field. A system that determines the conversion factor by applying a weak interchange magnetic field as reference magnetic flux Φ_{ref} to the SQUID from a feedback coil in the open loop technique is introduced. Fig. 2 shows a schematic of the system used for estimating conversion factor $V_\varphi G_A$. The relationship between the function generator voltage V_{FG}, which produces a reference magnetic field and a reference voltage V_{ref}, generated by the reference magnetic flux in the circuit of Fig. 2, is given by $V_{ref}/V_{FG} = V_\varphi G_A M_f/R_f$ when the frequency of the signal is larger than the frequency band of the FLL. Here, R_f is the feedback resistance and M_f is the mutual

* Corresponding author.
E-mail address: sakuta.k@usp.ac.jp (T. Yagi).

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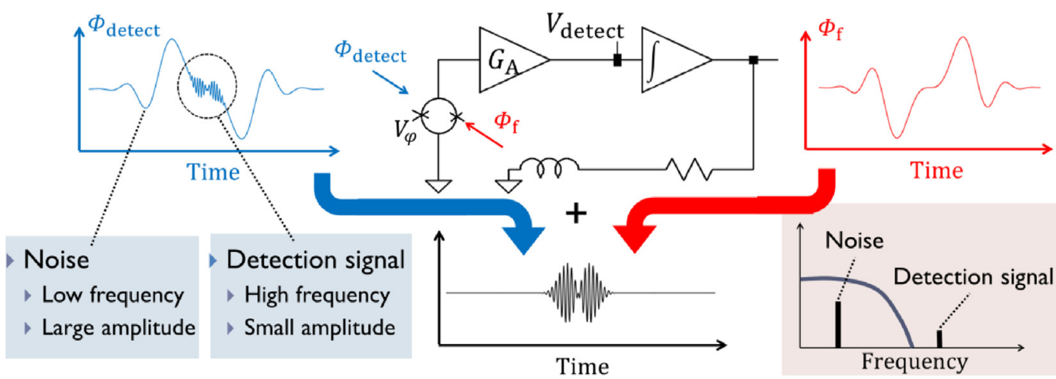

Fig. 1. Schematic of FLL with open loop technique.

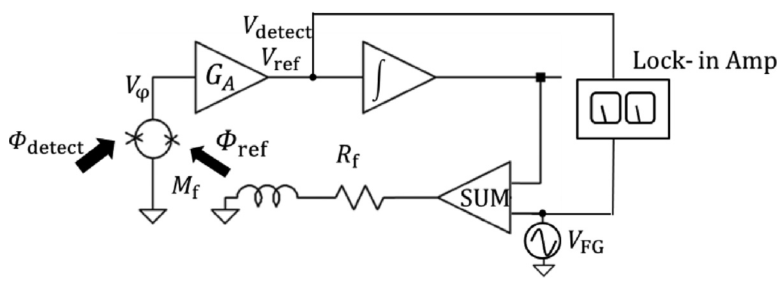

Fig. 2. Schematic of the system used to estimate the conversion factor.

inductance of the SQUID and feedback coil. Using this technique, the open loop operation conversion factor can be determined. This additional system is provided as an external circuit. Therefore, it is relatively easy to introduce this operational mode without depending on the used types of SQUID. The experiment in this article was carried out using rf-SQUID, but the notation of SQUID in the figures in this article transcribed it as dc-SQUID for simplification of schematic.

A conversion experiment using an open loop technique and applying the conversion factor estimation technique was performed. The system consisted of an automatic stage to move the sample, a HTS rf-SQUID module (JSQ rf SQUID Magnetometer and HTS-rf-SQUID Electronics V3.51 with Touchpanel Tiger Controller) provided by the Jülich SQUID Company (JSQ), a FLL circuit (open loop technique), an excitation WD coil, lock-in amplifiers for detection and reference, and a data logger. The feedback frequency band of the FLL circuit was set to 530 Hz when $V_\varphi G_A$ was 0.5 V/Φ_0. The excitation coil made with diameter 0.5 mm copper wire contained 10 turns of diameter 10 mm. The excitation signal is sinusoidal wave of 100 kHz. The excitation current is set at 42m$A_{p\text{-}p}$. The mutual inductance of the SQUID and feedback coil $M_f = 5$ pH, feedback resistance R_f=3 kΩ, and reference magnetic flux $\Phi_{ref} =$ 0.08 Φ_{0p-p}The frequency of the reference magnetic flux is 7 kHz. The magnetic shield is comprised of a permalloy (500 mm in width, 330 mm in depth and 700 mm in height). The shielding factor of the magnetic shield is 50 dB at 1 Hz. The metal sample was a copper ball of diameter 1.2 mm and was displaced by the automatic stage as shown as Fig. 3. When the sample followed the backward motion, the V–Φ characteristic was altered as $V_\varphi G_A$ was reduced (Fig. 4(a)). Though the magnetic field strength was identical for the two contaminant signals, V_{detect} in the backward motion was reduced compared with that in the forward motion (Fig. 4(b)). The graph of Φ_{detect} (Fig. 4(c)) was obtained by converting V_{detect} from Fig. 4(b) by $V_\varphi G_A$ determined from Fig. 4(a). Both contaminant signals were transformed by a conversion factor to equalize the signal strengths.

2.2. The range of the detection magnetic field strength can converting

The range of the detection magnetic field strength that can be estimated using a varying magnetic field at 100 kHz was measured. Fig. 5(a) shows measured data for V_{detect} and V_{ref} at detection magnetic flux Φ_{detect}. V_{detect} becomes nonlinear when the magnetic field has amplitude exceeding approximately 0.2 Φ_0 due to a nonlinear response from the unlocked SQUID. Thus, V_{ref} reduces with increasing magnetic field. Fig. 5(b) shows the relationship between Φ_{detect} and the conversion value of the detection magnetic flux Φ_{conv}, which was determined by converting V_{detect}. Φ_{ref} was converted into V_{ref} using a large V_φ value in the case of a small Φ_{detect} value. In contrast, Φ_{ref} was converted into V_{ref} by a small V_φ value in the case of a large Φ_{detect} value. The conversion factor $V_\varphi G_A$ is underestimated and Φ_{conv} does not agree with the Φ_{detect} value when a large detection magnetic field is applied.

3. Magnetic field conversion using the calibration curve technique

As discussed in the previous section, the conversion factor estimation technique tends to underestimate the conversion factor, especially when a large magnetic field is applied. In this section, a method to convert a large signal into an accurate magnetic field value by calibrating the nonlinear SQUID response will be introduced and discussed. Assuming that the V–Φ characteristic is varied similarly in the vertical axis direction, the ratio of V_{detect} and V_{ref} incorporate the same characteristics. A method to accurately convert this ratio into the detection magnetic field by deriving a calibration curve using this property is proposed.

Fig. 6(a), (b) and (c) show the measured V_{detect} and V_{ref} for Φ_{detect} with $V_\varphi G_A$ values of 0.60V/Φ_0, 0.67V/Φ_0 and 0.77V/Φ_0, respectively. The voltage value differs for each conversion factor because of the different gradients at particular working points. Fig. 6(d) shows the characteristic of the ratio of two output voltages V_{detect}/V_{ref} when the applied detection magnetic field. V_{detect}/V_{ref} depicts reasonable agreement for the different conver-

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