Noise Suppression in Parallel Fluxgate Magnetometers by DC-Biased Excitation Method

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We experimentally revealed that a direct current (DC) biased excitation method can reduce the noise in parallel fluxgate magnetometers composed of a permalloy ring core. The noise suppression was achieved by decreasing the Barkhausen noise and increasing the open-loop sensitivity using the nonlinearity of the $B-H$ curve with the DC-biased excitation. The noise performance depends on the excitation parameters: frequency, amplitude, and DC-bias. We proposed that the parameters should be determined based on the evaluation of the sensitivity and noise level in both open-loop and closed-loop modes. Specifically, a contour map of the closed-loop noise is useful for understanding the noise decrease with different values of the amplitude and DC-bias. We also demonstrated the effectiveness of the DC-biased excitation method using a commercially available fluxgate magnetometer (APS520A, Applied Physics Systems). Using the DC-biased excitation method, the noise level was approximately one-fourth compared to that of the original electronics.

Key words: parallel fluxgate magnetometer, DC-biased excitation, noise suppression

1. Introduction

Fluxgate magnetometers are widely used in magnetic measurements, such as geomagnetic fields, magnetic exploration, magnetic metal detectors, buried objective surveying, and permeability measurements. The advantage of the fluxgate magnetometer is that it can obtain high sensitivity from a direct current (DC) to several kHz bandwidth without any cryogenics.

The sensor heads of fluxgate magnetometers are usually composed of a core with an excitation coil and a sensing coil. The core is made of a soft magnetic material and excited by applying an alternative current (AC) magnetic field. High sensitivity can be achieved by detecting the modulated AC magnetic field corresponding to the external magnetic field via the sensing coil. There are two types of fluxgate magnetometers according to the direction of the magnetization of the core: parallel or orthogonal to the external magnetic field to be observed.

Sasada et al. developed an innovative orthogonal fluxgate magnetometer by applying a DC-biased excitation current to the amorphous wire and demodulating the detected signal using the fundamental frequency of excitation. The sensitivity (noise performance) of the fluxgate sensor was dramatically improved, and they successfully measured a magnetic signal from a human heart with 36 channel orthogonal fluxgate magnetometer array.

On the other hand, a low noise magnetic sensor named "differentially dc biased type magnetic field sensor" was proposed by Sonoda et al. This sensor was composed of a pair of amorphous cores (wires or sheets) and its basic structure of the sensor head was same as the one of an amorphous core based parallel fluxgate magnetometer. The principle and optimization of excitation conditions were reported in 7) and 8).

Additionally, we found that the noise of the parallel fluxgate magnetometer composed of a permalloy ring could also be suppressed using a DC-biased excitation method, which applies the DC-biased excitation field to the core and demodulates the output signal of the sensing coil with the fundamental frequency, as based on Kado's idea. We developed a multi-channel parallel fluxgate sensor array for a motion detector system using the DC-biased excitation method. However, we have not yet confirmed that the noise can be suppressed by the DC-biased excitation method in parallel fluxgate magnetometers, although the basic concept of the sensor head are same as those of the previous studies. Therefore, the purpose of this paper is to reveal the effectiveness of noise suppression using the DC-biased excitation method in the permalloy ring core based parallel fluxgate magnetometer which has simple structure and is used widely compared with the amorphous core based sensors.

After describing the configuration of the fluxgate magnetometer and a setup for experiments in Section 2, we present our experimental results for revealing the mechanism and the effectiveness of the DC-biased excitation method in the parallel fluxgate magnetometer with the ring shaped permalloy core. In Section 3, the noise suppression mechanism is described. In Section 4, the optimization of the excitation parameters is discussed. In Section 5, we demonstrate the effectiveness of the DC-biased excitation method using a commercially available parallel fluxgate magnetometer.
2. Configuration of the Fluxgate Magnetometer and Experimental Setup

Figure 1 shows the configuration of our fluxgate magnetometer which is composed of a sensor head, an excitation circuit, and a sensing circuit. The ring-shaped magnetic core of the sensor head is made of permalloy and its thickness, inner- and outer-diameter are 0.3 mm, 13 mm, and 17 mm, respectively. The numbers of the excitation and sensing coils are 140 and 100, respectively.

The excitation circuit is composed of a RC oscillator, a variable-gain amplifier, a DC-bias voltage adder, and a current driver amplifier. The frequency of the output signal \( f_{osc} \) is determined by the combination of the resistor and the capacitor of the oscillation circuit. The oscillator outputs the sinusoidal waveform with the amplitude of approximately 1 V. The variable-gain amplifier is designed to increase from 0.1 to 10 so that the amplitude of the excitation signal \( v_a \) varies from 0.1 V to 10 V. The amplified sinusoidal waveform was biased by the DC voltage adder circuit. The DC bias voltage \( v_b \) is variable from -6 V to +6 V. The current driver amplifier is connected to the excitation coil of the sensor head. We used a high current operational amplifier (NJM4556AM, New Japan Radio Co., Ltd.), which can output up to ±70 mA, as the current driver amplifier.

The sensing circuit is connected to the sensing coil of the sensor head. Only the higher-frequency component of the sensing coil output is amplified by the low-noise amplifier (OP37, Analog Devices Inc.). The lock-in amplifier circuit is used to detect the magnetic signal applied to the sensor head from the modulated signal with the carrier frequency of \( f_{osc} \). The reference signal of the lock-in amplifier is provided by the RC oscillator circuit, and its phase is tuned to maximize the open-loop sensitivity (OLS) in every measuring condition, which will be defined in the next section. The integrator and feedback circuit are used to linearize the input-output characteristics of the fluxgate magnetometer, which is also known as the null method. Two switches were inserted in the integrator and feedback circuits, which were used to evaluate the characteristics of the fluxgate sensors with the open-loop (SW1: close, SW2: open) and closed-loop (SW1: open, SW2: close) modes.

When the fluxgate magnetometer is operated in the closed-loop mode, the sensitivity coefficient (the input magnetic flux density of the sensor head vs. the output voltage of the sensing circuit) is fixed by the feedback resistor \( R_f \). We used a resistor of 1.1 kΩ for \( R_f \), and the sensitivity coefficient was calibrated as 9.5 \( \mu \)T/V using the calibration method \( 1^1 \).

During experimental measurements, the sensor head is fixed to the center of a solenoid coil that is placed inside a magnetically shielded box (MSB) made of two layers of permalloy. The solenoid coil is connected to a function generator and applies a sinusoidal magnetic signal with a frequency of 8 Hz and an amplitude of 1.7 \( \mu \)T when measuring the input-output characteristics of the fluxgate magnetometer. The electronics including the excitation and sensing circuits were placed outside the MSB. The output signal of the sensing circuit is recorded by a 16-bit analog-to-digital converter after amplifying (variable gain) and low-pass filtering (500 Hz).

3. Experiments for Principle Verification

In this section, we show the possibility of noise suppression by applying a DC-biased excitation in parallel fluxgate magnetometers composed of the permalloy based ring core, and then we discuss its mechanism based on the sensor characteristics depending on the excitation.

3.1 Noise reducing effect by applying a DC-biased excitation

First, we experimentally confirmed that the
Fig. 2  Noise level comparison between the DC-biases of the excitation. (a) Noise spectra and (b) noise level at 100 Hz.

Fig. 3  Open-loop noise (OLN) before lock-in detection.

DC-biased excitation method could suppress the noise of the parallel fluxgate magnetometer. We recorded the output signal $v_{\text{out}}$ of the fluxgate magnetometer that operated in the closed-loop mode without applying the magnetic signal from the solenoid coil. Here, the excitation frequency $f_{\text{osc}}$ and amplitude $v_a$ were fixed to 53 kHz and 1.0 V, respectively (a comparison of different excitation frequencies and amplitudes will also be discussed later). Figure 2(a) shows the noise spectra when the fluxgate magnetometer was excited by different DC-bias currents and Fig. 2(b) plots the noise level at 100 Hz. The noise floor decreases by increasing the DC-bias voltage for excitation. For example, the noise level was reduced to approximately 1/18 by increasing the bias voltage from 8.4 mA to 51.3 mA. The indicated values of the bias current were derived by measuring the voltage across the resistor $R_L$ (110 $\Omega$). These results clearly reveal that the DC-bias excitation method can reduce the noise of the parallel fluxgate magnetometer which is composed of a permalloy ring core and operated in the closed-loop mode.

3.2 Mechanism of reducing noise

In this subsection, we describe the mechanism of the noise suppression by investigating the characteristics of the sensor in the open-loop operation mode.

3.2.1 Noise performance in open-loop mode

In the orthogonal fluxgate sensors, reducing the Barkhausen noise by the DC-biased excitation is a main factor of the noise suppression\(^{(12)}\). To investigate the Barkhausen noise reduction in the parallel fluxgate, we measured the noise when the sensing circuit was operated in the open-loop mode. The excitation frequency and amplitude were fixed to 53 kHz and 1.0 V, respectively, and the DC-bias current was changed from 0.5 mA to 26.1 mA. Figure 3 shows the noise spectra of the output signal of the low-noise amplifier measured by a spectrum analyzer (35670A, Agilent Technologies). The largest peak at 53 kHz is the carrier signal with the excitation frequency $f_{\text{osc}}$. The noise floor level is suppressed by increasing the DC-bias current same as...
the result of the orthogonal fluxgate shown in 12). The Barkhausen noise is generated by randomly reversing the magnetic domain so that it appears when the magnetization of the core is not saturated. The magnetization of the core is shifted to the saturation area by adding the DC-bias to the excitation current, therefore, the Barkhausen noise can be suppressed by the DC-biased excitation method.

Figure 4 shows the measured noise spectra of the output signal of the fluxgate sensor operated in the open-loop mode with different DC-bias currents of the excitation. Because $v_{out}$ is the demodulation signal of the output signal of the preamp, we assumed that the noise reduction (presented in Fig. 4(a)) was due to the suppression of the Barkhausen noise via increasing the DC-bias of the excitation. Here, a peak of approximately 4 Hz of the spectrum measured with the DC-bias of 51.3 mA was assumed to be caused by a vibration from the floor of the laboratory or MSB. The noise levels at 100 Hz are plotted in Fig. 4(b). The dashed line indicates the noise level of the sensing circuit measured without connecting the sensor probe. The noise decreasing below the bias current of 25 mA is due to the suppression of the Barkhausen noise as described in the previous subsection, and the circuit noise was dominant above 25 mA of the DC-bias current. Here, the noise level reduction comparison between the DC-bias currents of 8 mA and 45 mA was about 1/5.

This result cannot fully explain the noise level reduction of 1/18 when the fluxgate magnetometer was operated in the closed-loop mode. In addition to the noise spectrum, we evaluated the sensitivity for the open-loop operation mode to investigate the mechanism of the noise reduction in the closed-loop mode, as described in the next subsection.

### 3.2.2 Open-loop sensitivity

We measured the open-loop sensitivity (OLS) of the sensor. The sinusoidal magnetic signal was applied to the sensor and output voltage $v_{out}$, which was obtained by demodulation using the fundamental frequency of the excitation, was recorded. The OLS was derived by dividing the amplitude of $v_{out}$ by the amplitude of the applied magnetic signal ($1.7 \, \mu T$).

The OLS measured with different DC-bias current is shown in Fig. 5. The OLS has a loose peak of around 45 mA. In principle, fluxgate magnetometers use the nonlinearity of the $B-H$ curve of the core, therefore, the output signal of the sensing coil becomes the largest at the shoulder of the $B-H$ curve. This result suggests that the magnetization of the core reaches the shoulder of the $B-H$ curve by applying the DC-biased excitation current of 45 mA. The OLS, which corresponds to the output voltage of the sensing coil, can be maximized by adjusting the amount of the DC-bias of the excitation. Here, we should note that measuring OLS is the same approach as measuring the effective permeability reported in 7) and 8). We decided to evaluate the output voltage in open-loop mode operation in order to simplify the discussion to design the excitation parameters of the fluxgate magnetometers. This allows us to apply the DC-biased excitation method to unspecified sensor heads even if its structure is unknown as described in section 5.

### 3.3 Estimation of the closed-loop noise

Figure 6 shows the equivalent closed-loop noise (CLN) calculated as

$$\text{Equivalent CLN} [pT/\text{Hz}^{1/2}] = \frac{\text{OLN} [\mu V/\text{Hz}^{1/2}]}{\text{OLS} [\text{mV}/\mu T]} \times 10^{-3}$$

where OLN and OLS are the noise level and sensitivity in the open-loop operation, respectively. The measured CLN is also plotted in Fig. 6 (same data as Fig. 2(b)), and the data is in accordance with the equivalent CLN. The noise level of the fluxgate magnetometer, which is usually operated in the closed-loop mode, was determined based on both the noise level and sensitivity in the open-loop operation mode in the same as the differentially dc-biased type magnetic field sensor. Therefore, we concluded that the noise suppression by the DC-biased excitation method was due to two factors: decreasing the Barkhausen noise and increasing the sensitivity using the nonlinearity of the $B-H$ curve.

### 4. Optimization of the Excitation Parameters

The results shown in previous section were measured with the fixed amplitude $v_0$ and frequency $f_{osc}$ of the excitation to 1.0 V and 53 kHz, respectively. In this
section, we present the results of the sensor characteristics measurements and discuss how to choose the optimal excitation parameters.

4.1 Excitation frequency

We measured the OLS, OLN, and CLN with different excitation frequencies of 26 kHz, 78 kHz, and 103 kHz, respectively. The amplitude of the excitation was fixed to 1.0 V in the same manner as the experiment described in the previous section. Figure 7 shows the results with a changing DC-bias voltage in each excitation frequency. The results with 53 kHz are the same data plotted in Figs. 2(b), 4(b), and 5.

As shown in Fig. 7(a), the OLS was proportional to the square root of the excitation frequency, although the sensitivity of the sensing coil is theoretically proportional to the frequency. The effective area of the cross-section of the core is proportional to the reciprocal of the square root of the frequency due to the skin effect. The results suggested that the OLS was proportional to the square root of the excitation frequency $f_{osc}^{1/2}$ as the product of the sensitivity of the sensing coil (proportional to $f_{osc}$) and the effective area of the cross-section of the core (proportional to $f_{osc}^{-1/2}$).

Conversely, the OLN slightly increased with a higher excitation frequency. Potential white noise sources may have existed during this experiment, such as the Barkhausen noise and thermal noise of the sensing coil. These white noise appeared as a frequency proportional noise as shown in Fig. 3 because the induced electromotive force of the sensing coil is proportional to the signal frequency.

Consequently, suppression of the CLN via the DC-biased excitation method was evenly achieved with the excitation frequencies of 53 kHz, 78 kHz, and 103 kHz, but the suppression result with 26 kHz was slightly larger than others, as shown in Fig. 7(c). We observed that the improvement of the CLN is not proportional to the excitation frequency, so we had to consider both the OLS and the OLN to decide the excitation frequency.

To show additional criteria needed to choose the excitation frequency, we measured the frequency response when the DC-bias voltage was fixed to approximately 45 mA and the sensor circuit was operated in the closed-loop mode. The frequency response was measured using a frequency response analyzer (FRA5097, NF Corporation). The measured frequency responses are plotted in Fig. 8. The bandwidth (frequency at which the response is $-3 \text{ dB}$) became wider by increasing the excitation frequency. In general, the bandwidth of the closed-loop feedback system is proportional to the open-loop gain of the system. In the case of the developed fluxgate magnetometer, the OLS corresponded to the open-loop gain of the feedback; therefore, the bandwidth of the sensor was expanded corresponding to increase in the excitation frequency.

Based on the results of the CLN and frequency response, we decided to set an excitation frequency of 103 kHz to obtain both the low CLN and wide bandwidth.

4.2 Excitation amplitude

After choosing the excitation frequency of 103 kHz, we compared the sensor characteristics with different excitation amplitude (indicated as $v_a$ in Fig. 1) of 0.5 V, 1.0 V, 1.5 V, and 2.0 V. In this experiment, we measured the amplitude of the excitation current as shown in Fig. 9. Although $v_a$ was fixed in each
measurement, the current amplitude slightly changed according to the bias current. This result shows that the permeability of the core changed according to the bias current because the impedance of the excitation coil is proportional to the permeability of the core. These curves became almost flat above approximately 45 mA of the bias current, therefore, this result also supports that the magnetization of the core reached the shoulder of the \( B-H \) curve by applying the DC-biased excitation current of 45 mA as described in section 3.2.

Figure 10 shows the OLS, OLN, and CLN with changing DC-bias current in each excitation amplitude. The results with 1.0 V are the same data as those plotted in Figs. 2(b), 4(b), and 5.

Both the OLS and the OLN increased with the enlarged amplitude of the excitation signal. The OLS was proportional to the excitation amplitude; in contrast, the OLN showed a lower decrease limit. The convergence value was approximately the same as the noise level that originated from the electronics shown in Fig. 4(b). As plotted in Fig. 10(c), the measured CLN was suppressed by increasing the DC-bias voltage and appeared to be a function of both the DC-bias and amplitude of the excitation.

To facilitate the optimization of the DC-bias and amplitude of the excitation, we visualized the measured CLN, which is plotted in Fig. 10(c), as a contour graph in Fig. 11. The excitation current amplitude in the vertical axis was derived from the plots in Fig. 9. According to this contour graph, choosing large values for both amplitude and DC-bias achieves the noise suppression in the fluxgate sensor; for example, a noise level of less than 20 pT/Hz\(^{1/2}\) was obtained when the excitation amplitude and bias were set to the values included in the blue area.

When designing the fluxgate magnetometer in practice, there must be limitations to the electronics, such as power consumption and the slew rate of the current driver. We can choose the optimal excitation parameters for variable applications by referring to the experimentally obtained contour map of the CLN.

5. Demonstration Using a Commercially Available Fluxgate Sensor

We experimentally compared the noise performance between the conventional sensing and DC-biased excitation method to demonstrate the effectiveness of
Magnetically shielded room

Fig. 12 Block diagram of the comparative experiment

the DC-biased excitation method. We used two sets of a commercially available fluxgate magnetometer (APS520A, Applied Physics Systems). This fluxgate magnetometer has three orthogonally arranged ring-shaped sensor heads made of supermalloy in a single probe, which is operated by conventional method with the excitation frequency of 25 kHz.\(^\text{13}\)

Figure 12 shows the block diagram of the experiment. Two APS520A sensor probes were placed in a magnetically shielded room composed of two layers of permalloy and single layer of copper. One of the probes was connected to the original electronics of APS520A, and another one was connected to our electronics to operate with the DC-biased excitation method. We customized the electronics to have three-channel sensing circuits and a single-channel excitation circuit. We observed that the excitation coils of each core are connected in the sensor probe. Although the details of the connection in the probe were not available due to the confidentiality policy of Applied Physics Systems, we decided to supply the excitation signal from a single-channel excitation circuit. The frequency, amplitude, and DC-bias were fixed to 103 kHz, 8.1 mA and 19.5 mA, respectively, after evaluating the CLN of the sensor heads.

The output signals of both fluxgate sensors were simultaneously recorded by a data acquisition system via amplifiers (200 of gain) and low-pass filters (200 Hz of cutoff frequency).

Figure 13 shows the measured noise spectra of all outputs. The noise floor measured with the DC-biased excitation method is smaller than the floor measured with the original electronics. For example, the mean values of the three channels at 5 Hz and 100 Hz measured with the DC-biased excitation and conventional methods were 7.2 and 31.6 pT/Hz\(^{1/2}\), 4.9 and 12.2 pT/Hz\(^{1/2}\), respectively. We concluded that the DC-biased excitation method is effective in suppressing the noise of parallel fluxgate magnetometers.

6. Discussion

In this paper, we revealed the effectiveness of noise suppression using the DC-biased excitation in the parallel fluxgate magnetometers composed of permalloy based ring core. As demonstrated in section 5, this technique is effective even for existing sensor head which was originally designed for the conventional excitation. Many parallel fluxgate magnetometers have been developed so far, as introduced in 1), 2), and 3). Recently, Miles et al.\(^\text{14}\) developed low-noise permalloy ring cores for parallel fluxgate magnetometers which achieved noise level of 6 to 11 pT/Hz\(^{1/2}\). There is a possibility to reduce the noise level of those sensors using the DC-biased excitation method. Moreover, there is a possibility to achieve much lower noise level by optimizing the structure of the sensor head, including the core, the excitation coil, and the sensing coil, for the DC-biased excitation method. Approaching the noise level of sub-pT/Hz\(^{1/2}\) like the amorphous core based sensors\(^\text{10}\) is the topic of our further study.

Additionally, magnetic offset should be considered in fluxgate magnetometers. Unbalance of magnetization in the core often causes unexpected offset in the output signal.\(^\text{13}\) In case of the DC-biased excitation method, the unbalance of magnetization results in larger offset due to the DC-bias current. The magnetic offset can easily be compensated by adding the DC-current to the sensing coil in parallel to the feedback signal. Description of the offset compensation circuit was omitted to focus on the noise suppression in the fluxgate magnetometer.

7. Conclusion

In this study, we detailed the mechanism and effectiveness of the DC-biased excitation method for noise suppression in parallel fluxgate magnetometers.
We also revealed that the noise suppression was caused by both decreasing the Barkhausen noise and increasing the OLS using the nonlinearity of the B-H curve with the DC-biased excitation. The noise level was strongly dependent on the excitation conditions, especially the amplitude and DC-bias. The visualization of the CLN using the contour map provided a suitable combination of the excitation amplitude and DC-bias.

As demonstrated in Section 5, the DC-biased excitation method is applicable for existing parallel fluxgate magnetometers when changing the electronics. We believe that the DC-biased excitation method and its design described in this paper are not only effective for potentially developing a new magnetometer but can also be useful in improving the noise performance of conventional parallel fluxgate magnetometers composed of permalloy ring cores.

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