Fundamental Mode Orthogonal Fluxgate Gradiometer

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A new method based on the fundamental mode orthogonal fluxgate (FM-OFG) mechanism is proposed to build a gradiometer of flexible base line and a minimum set of electronics. A pair of thin sensor heads and an electronic circuit designed for a magnetometer can be used, in which pickup windings of a sensor head pair are connected in counter series to respond to the field gradient between two locations of the sensor heads. Furthermore, a fine tuning to get a good balance in sensitivity between two sensor heads can be made by adjusting a dc bias current to one of the sensor heads. Developed gradiometers show a high suppression performance to the uniform magnetic field, where the suppression ratio (gradiometer output)/(magnetometer output), reaches below 1/40 000 with the resolution of 100 pT/m/$\sqrt{}$Hz at 10 Hz.

Index Terms—**Fundamental mode orthogonal fluxgate (FM-OFG), gradiometer, magnetometer.**

I. INTRODUCTION

THE gradiometer is a sensor to detect the gradient of the magnetic field. There are two methods to make the gradiometer. The one is electronic where two identical magnetometers are used and the output for the gradient is obtained by subtracting one magnetometer's output from others. Gradiometers built in this method are often used in a archaeology to find buried historical buildings via anomalies in the magnetic field distribution [1]. In this method, the distance between two magnetometers (base line) can be flexibly adjusted to change the sounding depth, however, an obvious drawback with the electronic gradiometer is that two complete magnetometers are needed and that a wide dynamic range with a good linearity is needed for the high-resolution measurement, especially when a tiny gradient magnetic field is present in a large uniform magnetic field. The other uses a single sensor head able to obtain the difference of magnetic fields at two specific points [2]. A common structure of this type of gradiometer heads uses two pickup coils wound on a single core. The system becomes compact and can be built with a single driving and detection electronic; however, the base line is fixed and making a good balance between two pickup coils in order not to respond to the uniform magnetic field is not easy.

In this paper, a new method based on the fundamental mode orthogonal fluxgate (FM-OFG) mechanism [3] is proposed to build a gradiometer having positive aspects of the two methods mentioned above; flexible base line and a minimum set of electronics. Furthermore, a fine tuning to get a good balance in sensitivity between two sensor heads can be made by adjusting a dc bias current to one of the sensor heads. Developed gradiometers show a good suppression ratio to the uniform magnetic field with the resolution a few pT/5 cm.

II. OPERATING PRINCIPLE

The basic configuration of the proposed gradiometer is shown in Fig. 1. Two identical sensor heads made of a hairpin-shaped amorphous wire (120 μm diameter, UNITIKA) core with a pickup coil wound on it are used in which the pickup coils are connected in counter series and also used as a feedback coil. The ac excitation current is biased by a large dc current to establish FM-OFG operation and fed directly to the thin amorphous wire core, therefore the gradiometer fully takes advantages of the fundamental mode of operation, which are Barkhausen magnetic noises suppression [4] and high sensitivity. This gradiometer is configured with a feedback loop. The main building block of the electronics is the same as that used for the FM-OFG magnetometer. The induced voltage of the excitation frequency at the sensing coils is input to the preamplifier then sent to the phase-sensitive detector (PSD). The output voltage of the PSD is low-pass filtered (filter not shown) and used to generate a feedback current to the pickup coil via a resistor R_f. The output of the gradiometer is taken from the error amplifier output terminal through the low-pass filter to reject switching ripples due to the PSD.

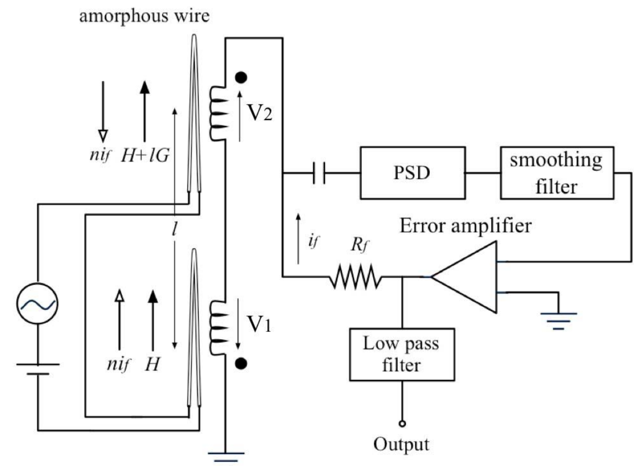

Fig. 1. Basic configuration of the gradiometer.

The operating principle to detect the gradient is straightforward. We assume that the magnetic fields comprise of the uniform field H and the gradient magnetic field lG, where l is the distance between the centers of two sensor heads (base

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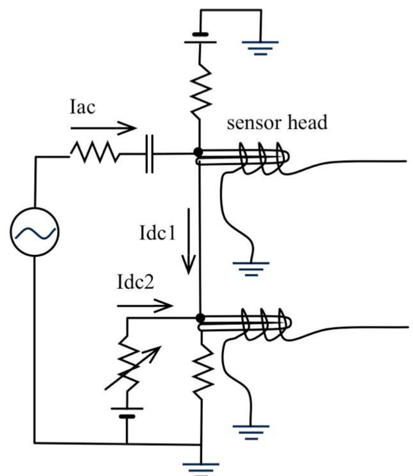

Fig. 2. Sensitivities of two sensor heads are balanced by the current I_{dc2}.

Fig. 3. Photo graph of the sensor head. The length of the coil is 30 mm and its outer diameter is 3 mm. Two of them are used for the gradiometer.

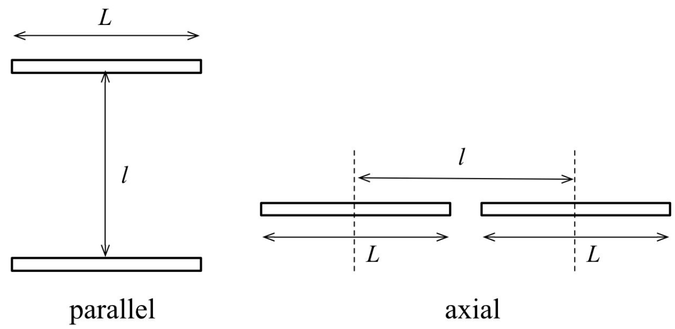

Fig. 4. Two configurations of the gradiometer head. The base line is l.

Fig. 5. Axial gradiometer head assembled in a plastic holder.

line) and G is the magnetic field gradient with the unit A/m^2. The winding density, measured in turns per meter, of the pickup coil is n. The carrier frequency component (typically 100 kHz) induced across the pickup coil V_2–V_1 for the inputs shown in Fig. 1 is fed first to the preamplifier (not shown) then to a PSD. The dc component from the PSD is then used to generate the feedback current to make V_2–V_1 null. When the sensitivity of two sensor head is well matched, one can use the same proportional constant K for two sensor heads. Assuming the gain of the error amplifier is large enough to make V_2–V_1 negligibly small by flowing the feedback current i_f, the output $V_o \approx lG \cdot R_f/(2n)$. It would be interesting to compare this expression with that for the magnetometer. For the magnetometer, one can obtain the expression for the output as $V_o \approx H \cdot R_f/n$ by simply omitting the sensor head at the top in Fig. 1 and removing the related values V_2 and lG and assuming $V_1 \approx 0$ in (1) due to the effect of the feedback. The sensitivity for the gradient is a half of that for the uniform magnetic field

$$\begin{aligned} V_1 &= K(H + ni_f) \\ V_2 &= K(H + lG - ni_f) \\ V_1 - V_2 &= K(-lG + 2ni_f) \approx 0 \\ V_0 &= R_f i_f \approx \frac{lG}{2n} R_f. \end{aligned} \tag{1}$$

III. Balancing Method

An interesting feature of this gradiometer is that the dc bias current can be used for a fine tuning of the sensitivity of sensor heads to get a high suppression for the uniform magnetic field. This feature is coming from the property of the FM-OFG, in which the sensitivity is a monotonically decreasing function of the dc bias current when the ac excitation current is kept constant [5]. The circuit for this tuning is shown in Fig. 2, where the dc bias current to the sensor head #2 is made to $I_{dc1} + I_{dc2}$ by a battery and a variable resistor. When the sensitivity K of the sensor head #2 is larger than that of sensor head #1, a slight positive I_{dc2} can make the sensitivity of two heads even or a slight negative I_{dc2} can make them even when the sensor head #1 has a larger sensitivity.

IV. Experimental Setup

Several gradiometer heads were prepared using sensor heads shown in Fig. 3, which were originally fabricated for the FM-OFG magnetometer. A pair of sensor heads was configured axially or in parallel, as shown in Fig. 4, where the base line is defined as a distance between the center of sensor heads. In this paper, the length of the sensor head $L = 30$ mm and the base line $l = 50$ mm. The gradiometer sensor head was packed in a plastic case to hold relative position stably. Fig. 5 shows the case for the axial gradiometer head, where the tube at the left contains sensor head #1 and sensor head #2 is located in the plastic body (not visible). The excitation condition for the gradiometer heads is 100 kHz ac excitation of 12 mA in root mean square, and dc bias current about 40 mA.

To characterize the gradiometer, we used our specially designed three-coil Helmholtz coil that can produce the uniform magnetic field in wider area than the normal Helmholtz coil [6]. By flowing 3.5 mA, the uniform magnetic field of 1.0 μT is produced. By reversing the direction of the current in the coils at one side, the gradient magnetic field of 2.25 μT/m is produced. Gradiometers of the parallel configuration and of the axial configuration were placed on the plane passing the axis of the coil system. To discriminate these magnetic fields from the environment magnetic noises, we used a 5 Hz ac. The tuning current I_{dc2} was supplied to one of the sensor heads from the battery through a variable

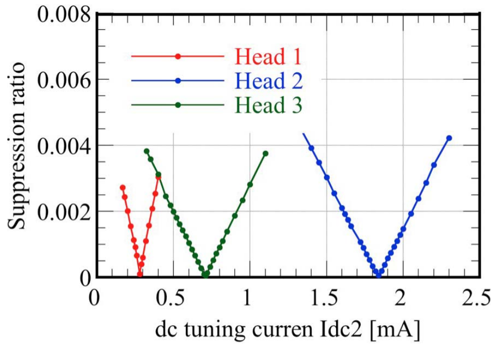

Fig. 6. Suppression ratio of the uniform magnetic field when the I_{dc2} is adjusted (axial configuration).

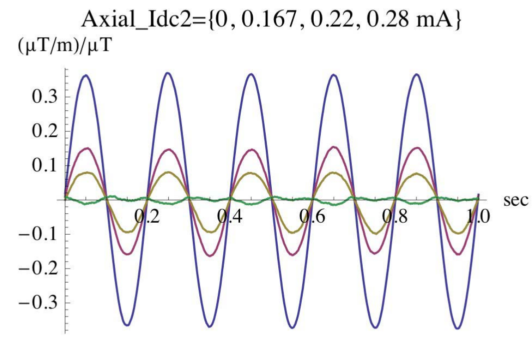

Fig. 7. Output waveforms of axial gradiometer for various I_{dc2} under the 5 Hz uniform magnetic field (uniform field applied in this case was 1.5 μT). The output voltages are divided by the sensitivity 5.98 mV/(μT/m) and normalized by the strength of the uniform magnetic field. I_{dc2} are shown in the plot title.

resistor. To avoid the effect of the earth's magnetic field, the axis of the coil systems was aligned along the east–west direction.

V. Results and Discussion

The sensitivity measured for the axial gradiometer with the base line 5 cm was 5.98 mV/(μT/m). It is interesting to compare this value to the sensitivity 0.25 V/μT of the magnetometer made of one of the sensor heads in the gradiometer configuration and the sensor circuit. We have $lG = 0.05$ μT for $G = 1$ μT/m and $l = 5$ cm. From (1) and with 5.98 mV/(μT/m), one can calculate the effective $R_f/(2n) = 5.98$ mV/(0.05 μT) $= 0.119$ V/μT. Finally, we have $R_f/n = 0.239$ V/μT that is close to the sensitivity of the magnetometer. This is a validation of (1).

The suppression ratio of the gradiometer to the uniform magnetic field is examined for three gradiometer heads. The remaining output of the gradiometer for the uniform magnetic field of 1.0 μT was measured with I_{dc2} varied. The suppression ratio was determined by dividing the output from the gradiometer by the output of the magnetometer (one sensor head is shortened to convert the gradiometer to the magnetometer) for the same uniform magnetic field. The case for the axial configuration is shown in Fig. 6. All the plots are V-shape, because the only amplitude was measured from the FFT spectrum at 5 Hz. One can see that all the gradiometers can be well balanced by adjusting I_{dc2} in the range less than 2 mA. By considering the dc bias current about 40 mA, this tuning value is within 5% of the dc bias current.

The waveforms of the gradiometer output are shown in Fig. 7 with axial Head 1 in Fig. 6 for a series of I_{dc2} values. Waveform data are smoothed with a moving average filter having null points at 60 Hz and its harmonics. The waveform corresponding to the optimum value (0.28 mA) is smallest but has higher harmonics of 5 Hz, which is later found to be due to a steel desk located near the three-coil Helmholtz coil. Even considering all the frequency components included in the output waveforms, the residual output for $I_{dc2} = 0.28$ mA becomes 1/42 of that for $I_{dc2} = 0$ (no adjustment).

The suppression ratio for the three gradiometer heads is summarized in the Table I with the case where no tuning is made. From this table, one can see that better matched pair

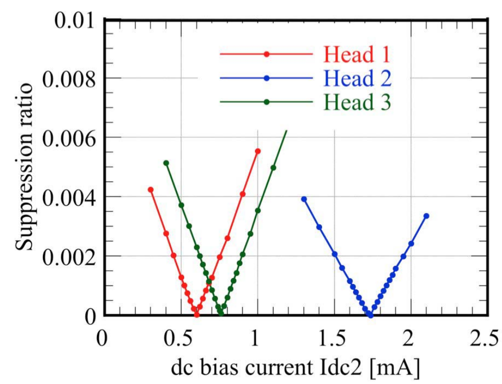

Fig. 8. Suppression ratio of the uniform magnetic field when the I_{dc2} is adjusted (parallel configuration).

TABLE I
Suppression Ratio for the Uniform Field (Axial)

	I_{dc2}	1/supp. ratio	I_{dc2} [mA]	1/supp. ratio
Head 1	0	154	0.28	9300
Head 2	0	61	1.84	14700
Head 3	0	150	0.71	18500

needs less I_{dc2}. Without tuning I_{dc2}, the suppression ratio is from 1/60 to 1/150.

The suppression ratio for the parallel configuration is shown in Fig. 8. By comparing Figs. 6 and 8, the tuning current I_{dc2} is slightly different but they are in the same range. We also investigated the dependence of I_{dc2} on the strength of the uniform magnetic field and found that the dependence is not strong. For example, in the range of the uniform magnetic field 1–5 μT, I_{dc2} increases about 5% with the uniform magnetic field.

Table II summarizes the suppression ratio and the tuning current for the parallel configuration. For the parallel configuration, the suppression ratio is fallen in the similar range as that for the axial one. This means that the gradiometer made by this method can provide a robust measurement method against the magnetic noises coming from distant locations. However, it should be noted that I_{dc2} have to be adjusted for each of the sensor heads pair. A gradiometer of the parallel

TABLE II

SUPPRESSION RATIO FOR THE UNIFORM FIELD (PARALLEL)

	I_{dc2}	1/supp. ratio	I_{dc2} [mA]	1/supp. ratio
Head 1	0	105	0.6	46000
Head 2	0	62	1.72	12000
Head 3	0	91	0.76	14200

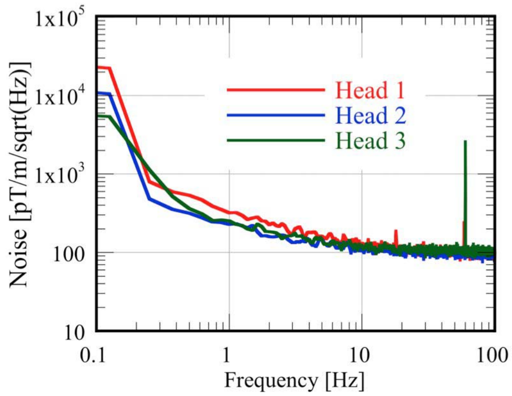

Fig. 9. Noise spectral density of the gradiometer measured for three sensor heads of parallel configuration.

configuration can be used to detect tiny magnetic sources, such as magnetic particles [7] by making the base line as small as 1 cm or less (diameter of the pickup coil is 3 mm). In this case, the tip of a parallel gradiometer heads should be put close to targets in the range less than 1 cm, preferably less than 5 mm.

The noise spectral density of the three gradiometer heads was measured with parallel configuration (base line = 5 cm) in a five-shell cylindrical magnetic shield. The result is shown in Fig. 9, where the vertical axis is scaled with pT/m/$\sqrt{}$Hz by dividing the noise spectral density in volt with the sensitivity 5.98 mV/(μT/m).

VI. CONCLUSION

A new method to build a fluxgate gradiometer having a large suppression capability to the uniform magnetic field has been proposed. By making a fine tuning of the dc bias current, the suppression ratio reaches below 1/40 000. The resolution of the gradiometer inherits that of the FM-OFG magnetometer that has the noise floor of 2 pT/$\sqrt{}$Hz above several hertz. Interesting applications of the gradiometer developed are fine magnetic particles detection using a parallel configuration and the magnetic field measurement from the human heart using an axial configuration in the unshielded or lightly shielded environment.

Influence of the operating temperature on the optimum I_{dc2} has not been studied yet. This important issue is left for our future work.

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