Electrical Interference with Pickup Coil in Induction Magnetometer

Kunihisa Tashiro , Hiroyuki Wakiwaka , and Shin-ichiro Inoue
Spin Device Technology Center,
Shinshu University,
Nagano, Japan
tashiro@shinshu-u.ac.jp

Abstract—**In this paper, we consider electrical interference with pickup coil in an induction magnetometer. By using a dummy load in place the pickup coil, we confirm that there is no significant electrical interference with a differential-input type current-to-voltage converter. In order to reveal electrical interference with the pickup coil, we investigate the output voltage of the magnetometer as grounding condition parameters. From the number of experimental considerations, we formulate a suitable condition to solve the electrical interference problem.**

Keywords: Induction magnetometer, current-to-voltage converter, pickup coil, electrical interference, grounding condition

I. Introduction

Although induction gradiometers (IGs) only require a pickup coil and a current-to-voltage converter (transimpedance amplifier), they show promise as magnetic sensors for detect weak, and low-frequency magnetic fields in close proximity to an object [1-3]. This kind of magnetic sensor, an induction magnetometer (IM), was proposed in several papers. A review may allow us to understand the advantages [4], however, the technical details are not usually described. Compared with a traditional voltage-detection-type magnetometer, the pickup coils for IMs or IGs have relatively low impedance so that they are very sensitive to undesired electrical interference. In a previous report [5], we considered stable operating conditions for a high-sensitivity IG. Through experimentations with our constructed faraday cage, we pointed out the importance of suitable grounding for the electronics.

In order to remove electrical interference, we proposed a differential-input type current-to-voltage converter [6]. A circuit simulation with LTSpice revealed that the output voltage does not have an offset voltage and a disturbance due to ground level perturbation. It should be noted that the output voltage is twice that of the conventional converter. We also confirmed the advantages of the new converter with our developed IM and IG [7]. The diameter of the pickup coil is as small as 2 cm, which is comparable to a SQUID sensor. From circuit simulation results, our developed IG can detect a magnetic field of 100 pT at 1 Hz. Because the corresponding amplitude of the output voltage is a few mV, it can observe the waveform with an oscilloscope.

However, we could not experimentally detect a magnetic field less than 1 nT. Compared with the conventional converter, the noise level was dramatically improved as low as 1/100 times. After the several considerations, we found that the output voltage of power-line frequency component was not reduced if the pickup coil was placed in our developed magnetic shielding system. The corresponding peak-to-peak voltage was a few hundred mV. This fact means that electrical interference may still remain in the IG.

In this paper, we study electrical interference in an IG with a differential-input type current-to-voltage converter. To provide an electrically shielded space, we used a Faraday cage. First of all, we confirmed electrical interference in the converter with a dummy load. In order to find a suitable electrical grounding condition, we defined several connecting points. Based on a number of experimental considerations, we propose a suitable condition to solve the electrical interference in the IG.

II. Experimental Setup

A. Induction Gradiometer

Fig. 1 shows a schematic design of our developed IG. The pickup coil consists of two Brooks coils. Table 2 shows the summary of the specifications. The resistance and inductance of the single Brooks coil are 70 Ω and 0.611 H, respectively. Due to the benefits of the coil shape [8], the measured coil parameters are in good agreement with estimated values within 3 % relative error [9]. If there is an imbalance of magnetic flux density in the pickup coil, it is transferred into electric current, and converted into output voltage. The pickup coil and the converter are connected with a metal shielded multi-conductor cable. The flux-to-current transfer ratio and the cutoff frequency are defined by the pickup coil. For this pickup coil, if the frequency is higher than the cutoff frequency of 18 Hz, the flux-to-current transfer ratio is 30 A/T [9]. Because the transimpedance gain of the converter is 2×10^6 V/A, the sensitivity of the IG is 60 mV/nT.

Fig. 2 shows our developed IG. The coil width is 30 mm, the inner diameter is 60 mm, the outer diameter is 120 mm, and the distance between the two coils is 300 mm. Although it was the same pickup coil which used in the previous report [5], an aluminum foil was wrapped around it to suppress electrical interference. In order to find a suitable electrical grounding condition, we defined connecting points as described in Figs. 1 and 2. Our considered combinations of the connecting points are summarized in Table 2. The output voltage of the IG was measured by a battery powered oscilloscope (TPS2014, Textronics).

B. Faraday cage

Fig. 3 shows our constructed Faraday cage. It consists of copper mesh and wood, and is 2.0 m × 1.8 m × 1.8 m in size. The copper mesh size is 2 mm, and the diameter of the copper wire is 0.45 mm. No magnetic materials were used for avoiding magnetic noise. While all materials are the same as those used in the previous report [5], we reconstructed the cage in another room. For evaluating electric noise in this new environment, we measured electric fields as was done before. As a result, the environment noise was similar. Inside the Faraday cage, the measured value of the electric field was less than 20 $mV_{p\text{-}p}$. It should be again pointed out that the magnetic shielding performance of the faraday cage was almost negligible.

If an IG consisted of a conventional current-to-voltage converter with a high transimpedance gain, it could not operate stably outside the Faraday cage due to the electrical interference [5]. In contrast, the new current-to-voltage converter allows us to operate the IG in a normal laboratory environment.

III. RESULTS

A. Dummy load

In order to estimate electrical interference with the converter, we used a dummy load instead of the pickup coil. The waveform of the output voltage was also analyzed by FFT.

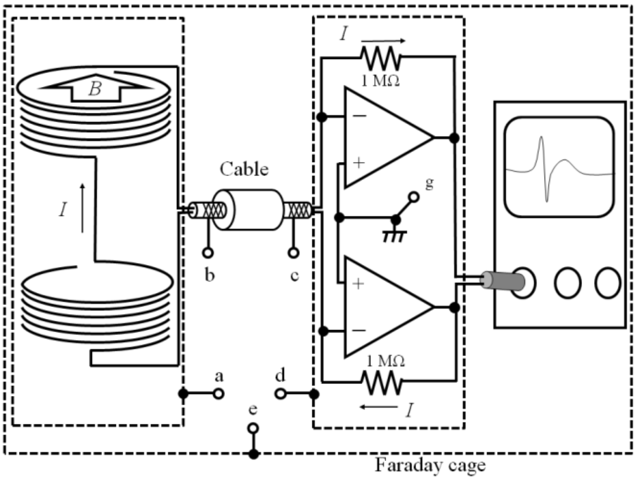

Figure 1. An schematic design of our developed induction gradiometer. Dotted lines represent conducting material for electrical shielding. The pickup coil and the different-input type current-to-voltage converter are connected by a metal shielded multi-conductor cable. When a uniform magnetic flux crosses the differential structured detection coil, a current is not induced. However, an induced current appears in the detection coil if the balance of the magnetic flux is disturbed. The converter transforms the weak current into voltage signal.

TABLE I
SPECIFICATION OF THE IG

Property	Value
(Pickup coil)	
Diameter	120 mm
Full length	360 mm
Resistance	76 Ω ×2
Inductance	0.611 H×2
Cutoff frequency	18 Hz
Flux-to-voltage transfer ratio	30 A/T
(Current-to-voltage converter)	
Transimpedance gain	2×10^6 V/A
(IG)	
Sensitivity	60 mV/nT

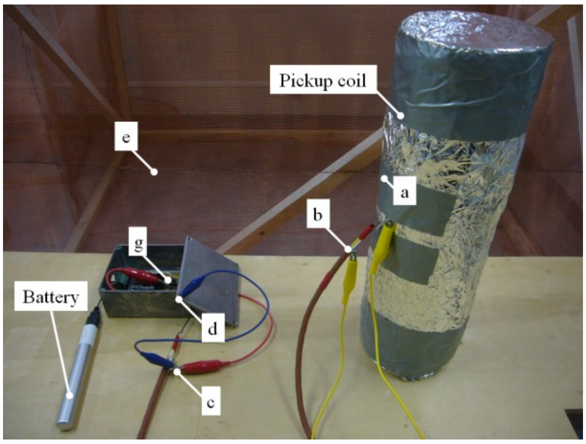

Figure 2. A photograph of our developed IG. A battery is used for the DC power supply to the current-to-voltage converter. The points "a" and "d" represent the contacting points on the electrical shield for the pickup coil and the converter, respectively. The points "b" and "c" represent the contacting point on the cupper mesh layer of the cable. The point "e" represents the contacting point on the Faraday cage. The point "g" represents the grounding point of the converter. The resistance values of the cables, used for the connecting points, are less than 0.2 Ω.

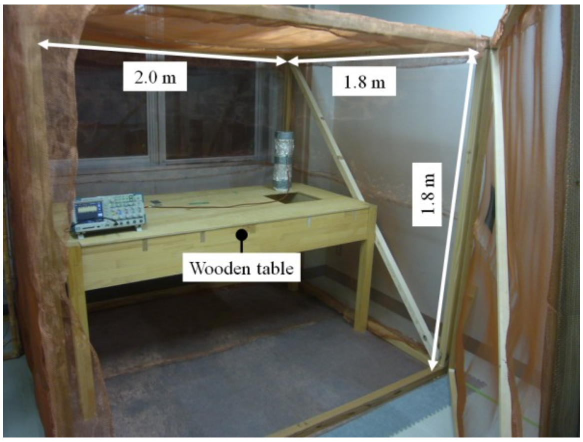

Figure 3. A photograph of our constructed Faraday cage. The wooden table is also used for measurement outside of the Faraday cage. The pickup coil is placed on the wooden table, and the sensing direction of the sensors is in the vertical direction. The door is closed when measurement are taking place inside it. Although the typical electric field under room light was larger than 200 $mV_{p\text{-}p}/m$, the measured value of the electric field inside it was less than 20 $mV_{p\text{-}p}$.

The ideal output voltage is, needless to say, zero. However, an increase in the resistance produces an increase in thermal noise (Johnson noise) [9].

Fig. 4 shows an example of the FFT analysis result of the measured output voltage. As a result, no typical peak value of 60 Hz, the power-line frequency, was observed. It should be noted that there were no significant differences if the converter was placed outside of the Faraday cage. The results indicated that there is no significant electrical interference with the converter.

If we can use an ideal converter whose equivalent voltage and current noise are zero, this would directly define the sensitivity limit of the IG. For example, the resistance of our pickup coil is 150 Ω, and the corresponding measured output voltage is 9 mV_{p-p}. Because the sensitivity of the IG is 60 mV/nT, the sensitivity limit under this measuring time condition is 150 pT_{p-p}. Because this kind of noise is white noise, the value will be small if the measuring time is long. We have already presented that the noise floor level of the IG is 665 fT/√Hz, and the experimental confirmation was done by IM using the single pickup coil [9].

B. Pickup Coil

In the previous report [5], we proposed that the Faraday cage is suitable as a grounding point. In this paper, we try to find a suitable grounding point without the Faraday cage for practical use. We measured the output voltage of the IG in relation to parameters of seven connecting conditions. The IG was placed inside or outside of the Faraday cage. We also focused on the 60 Hz component of the output voltage. In our experimental environments, the power-line frequency magnetic noise of 60 Hz was typically 5 nT. Because the pickup coil consists of two coils with a differential structure, the IG outputs the unbalance in magnetic flux density. If the unbalance due to the coil property is 3 %, the corresponding output voltage is about 10 mV.

Table 3 shows a summary of the results. Although the magnetic environment was similar inside and outside of the Faraday cage, there were some differences in output voltages. It was already known that the existence of electrical interference makes the differences large. Most large differences were found in condition 1. Because there are no connecting points, this case is the worst condition. The values measured outside of the Faraday cage was a few hundred mV_{p-p}, which were same as in previous situation [7]. From several experimental considerations, we finally found the candidates of the suitable conditions. In conditions 6 and 7, we find no significant differences between being inside and outside the Faraday cage. The typical output voltage and 60 Hz component were 20 mV_{p-p} and 10 mV_{p-p}, respectively.

IV. DISCUSSION

Based on our experiences, considerable electrical interference is caused by room light and static electricity of human. The typical electric field under a room light was larger than 200 mV_{p-p}/m [5]. In order to confirm this interference, we measured the output voltage of the IG when the room light was turned it off. Table 4 shows the summary of the results. The output voltages measured outside the Faraday cage dramatically decreased, and the values were less than 100 mV_{p-p}. It should be noted that there were no differences under conditions 6 or 7, which means that they worked effectively and the Faraday cage is not required to cut this electrical interference.

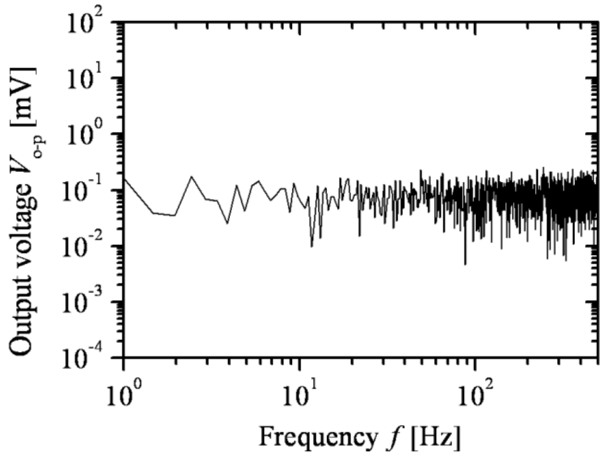

Figure 4. FFT analysis result of measured output voltage of the converter with a dummy load of 150 Ω.

TABLE II
COMBINATIONS OF CONNECTING POINTS

Number of condition	Connecting points
1	No connecting
2	c+g
3	c+d
4	a+b
5	c+e
6	a+b+c+g
7	a+b+c+d+g

TABLE III
OUTPUT VOLTAGE OF IG

Number of condition	Inside Faraday cage		Outside Faraday cage	
	V_{p-p} [mV]	V_{60Hz_p-p} [mV]	V_{p-p} [mV]	V_{60Hz_p-p} [mV]
1	26.0	7.62	388	156
2	24.8	7.56	376	11.6
3	25.6	8.67	440	15.6
4	23.6	9.33	148	18.2
5	20.0	9.86	484	4.40
6	19.2	11.2	25.6	15.3
7	18.4	11.4	20.0	14.0

TABLE IV
OUTPUT VOLTAGE OF IG (TURN OF THE ROOM LIGHT)

Number of condition	Inside Faraday cage		Outside Faraday cage	
	V_{p-p} [mV]	V_{60Hz_p-p} [mV]	V_{p-p} [mV]	V_{60Hz_p-p} [mV]
1	26.0	7.62	27.2	14.3
2	24.8	7.56	28.0	14.7
3	25.6	8.67	32.8	16.7
4	23.6	9.33	27.2	12.0
5	20.0	9.86	24.0	10.3
6	19.2	11.2	25.6	15.3
7	18.4	11.4	20.0	14.0

In order to check the robustness of the grounding conditions, we demonstrated a measurement of a weak magnetic field from a watch. Fig. 5 shows the relationship between the pickup coil and the watch. Fig. 6 shows an example of the observing waveform of the output voltage under the condition 6. Although the field from a watch was clearly observed, the baseline fluctuated with a range of a few ten mV. Fig. 7 shows an example of the observing waveform of the output voltage under the condition 7. We can see that there is an offset voltage of a few ten mV caused by the unbalance in the converter's element. In contrast, the baseline was stable compared with the results under the condition 6. Under the both conditions, there were no significant differences in the magnetic environments. This fact pointed out that the output voltage still contained a non-magnetic signal. From these observations and results, we concluded that the best condition is condition 7.

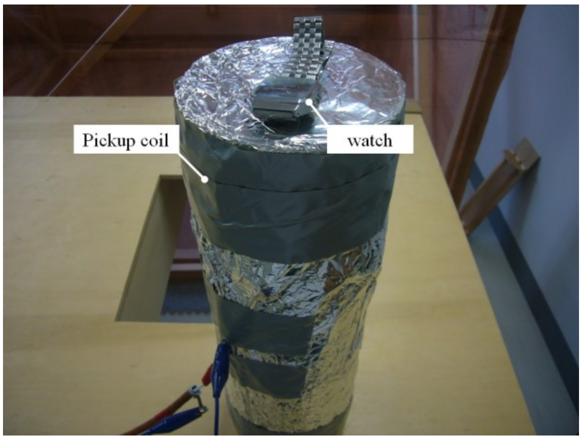

Figure 5. A photograph to explain the relationship between the pickup coil and the watch.

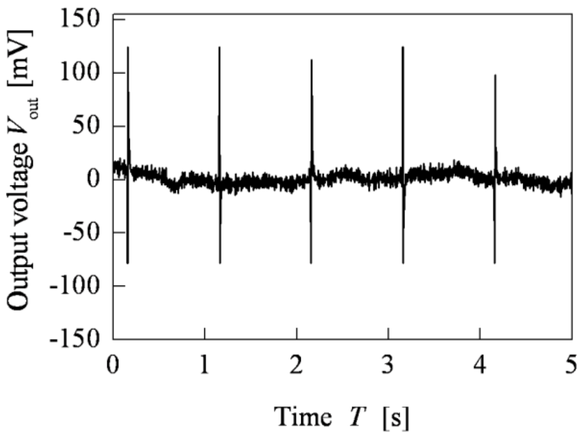

Figure 6. An example of the observing magnetic field from the watch measured with IG under the condition 6.

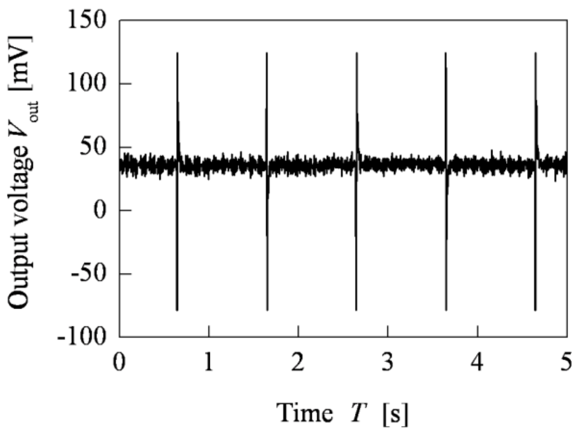

Figure 7. An example of the observing magnetic field from the watch measured with IG under the condition 7.

V. Conclusion

In this paper, we investigated electrical interference in an IG. From the experimental results with a dummy load, it was confirmed that there was no significant electrical interference with the differential-input type current-to-voltage converter. However, if we did not select a suitable grounding condition, the electrical interference appeared in the output voltage of the IG. From a number of experimental considerations, we have determined a suitable grounding condition.

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References

[1] K. P. Estola and J. Malmivuo, "Air-Core Induction-Coil Magnetometer Design," *Journal of Physics E-Scientific Instruments*, vol. 15, pp. 1110-1113, Mar 1982.

[2] R. J. Prance, T. D. Clark, and H. Prance, "Compact broadband gradiometric induction magnetometer system," *Sensors and Actuators a-Physical*, vol. 76, pp. 117-121, Aug 1999.

[3] H. Prance, R. J. Prance, and P. B. Stiffell, "Hardware comb filter enhances dynamic range and noise performance of sensors in noisy environments," *Review of Scientific Instruments*, vol. 78, 074701, Jul 2007.

[4] S. Tumanski, "Induction coil sensors - a review," *Measurement Science & Technology*, vol. 18, R31-R46, Mar 2007.

[5] K. Tashiro, A. Kakiuchi, K. Moriizumi, and H. Wakiwaka, "An experimental study of stable operating conditions for a high-sensitivity induction gradiometer", *IEEE Trans. Magn.*, Vol. 45, No. 6, pp. 2784-2787, June 2009.

[6] K. Tashiro, S. Inoue, K. Matsumura, and H. Wakiwaka, "A magnetic contamination detection system with a differential input type current-to-voltage converter", *The Fourth Japan-US Symposium on Emerging NDE Cabpabilities for a Safer World*, pp. 94-99, June 2010.

[7] S. Inoue, Y. Uchiyama, K. Tashiro and H. Wakiwaka, "Observation of weak magnetic field in low-frequency range with portable induction magnetometer", *Journal of Japan society of Applied Electromagnetics and Mechanics*, 6pages, 2011(To be published).

[8] F. W. Grover, Inductance Calculations: Dover Phenix Editions,pp. 91-133, 2004.

[9] K. Tashiro, H. Wakiwaka, A. Kakiuchi, and A. Matsuoka, "Comparative study of air-core coil design for induction magnetometer with current-to-voltage converter", Proc. of second international conference on sensing technology (ICST2007), pp. 590-594 , 2007