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Preliminary Study of MCG Measurement with Induction Gradiometer

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The purpose of our study is to demonstrate magnetocardiography (MCG) measurements from a human heart using our developed induction gradiometer. We have already reported the capabilities of our gradiometer, whose sensitivity at low frequency is comparable to that of a commercial SQUID sensor. However, we could not observe magnetic fields less than 1 nT because of electrical interference at the gradiometer. We solved this problem using a grounding technique and re-designed electronics. We modeled an MCG signal generated by PC-based instrumentation using LabVIEW software, and a magnetic field was generated with a one-turn coil. In order to generate an MCG field with an R-wave peak amplitude 100 $\mathrm{pT_{p\text{-}p}}$, we estimated the required current value for the one-turn coil. The experimental results obtained in our laboratory environment, we confirmed the observation of the R-wave with the induction gradiometer.

Keywords: MCG measurement, induction gradiometer, digital filter, LabVIEW.
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1. Introduction

The purpose of this study is to demonstrate magnetocardiography (MCG) measurements obtained from a human heart using our developed induction gradiometer. Magnetic field signals from the human heart were first detected by Bauel and MacFee in 1963[1-2]. Cohen detected magnetic fields outside the human scalp in a multilayer magnetically shielded chamber[3]. In recent years, biomagnetism measurements have received considerable attention for the early detection of heart diseases. SQUID sensors are mostly used in real-time MCG measurements. This sensor is highly-sensitive but requires liquid refrigerant during measurements. We have suggested induction gradiometers that do not need liquid refrigerant and can be transported.

Induction gradiometers detect the induced current in pickup coil when a magnetic flux crosses the pickup coil. This induced current detection model is similar to the induced voltage detection model. Current detection models have two characteristics. First, the sensor has low input impedance. Second, the pickup coil should have an optimal number of turns base on the inductance and resistance [4-5].

Induction gradiometers are designed to detect magnetic field fluxes of less than 1 pT. However, such sensors cannot detect fields smaller than 1 nT because of electrical interference affecting the induction gradiometer. We solved this problem using a grounding technique and re-designed electronics [6]. The new design resulted in, improved output voltages of the induction gradiometer in weak magnetic fields. However, we have not yet confirmed the feasibility of the design for demonstrating MCG measurements.

This paper aims to confirm the observation of a modeled MCG signal that was generated by PC-based instrumentation using the LabVIEW software. The magnetic field of a modeled MCG signal was applied using a one-turn coil.

The pickup coil was set 2 cm from the one-turn coil. The R-wave of the modeled MCG signal was set at 1 nT and 100 pT by the applied current in the one-turn coil. The output voltage was processed by a digital filter in the LabVIEW program. Experimental results, we successfully confirmed the observation of the R-wave in our laboratory using the gradiometer. We confirmed that the induction gradiometer is sufficiently sensitive to detect 100 $\mathrm{pT_{p\text{-}p}}$ magnetic fields from the human heart .

2. Experimental Setup

2.1 *Induction Gradiometer*

Table 1 shows specifications of the pickup coil. The pickup coil is shaped like a Brooks coil [4]. The self inductance L_s [H] of the coil can be defined by the following equation:

$$L = P_0 a n^2 \ \text{[H]} \ , \tag{1}$$

where P_0 [H/m] is the coil coefficient defined by the coil shape. If the ratio of the coil width, inner diameter, and outer diameter is constant, P_0 becomes constant. The Brooks coil ratio is 1 : 2 : 4. The value of P_0 for a Brooks coil can be described as follows:

$$P_0 = 1.699 \times 10^{-6} \ \text{[H/m]} \ . \tag{2}$$

Because the two Brooks coils are anti-parallel, the uniform magnetic field decreases to 1/100 of its original value. The pickup coil has a cutoff frequency f_i [Hz] of 19 Hz, which can be determined as follows:

$$f_i = R_s / 2\pi L_s \ \text{[Hz]} \ . \tag{3}$$

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Fig. 1 (a) shows a model of the induction magnetometer. The current-voltage converter circuit converts the induced current I into the output voltage V_{out}. The model is translated into an equivalent circuit as shown in Fig. 1 (b) because the product of the feedback resistor R_f and I is V_{out}.

If the frequency $f < f_i$, the sensitivity of the induction gradiometer can be described as follows.

$$V_{out}/B = -(R_f/R_s)\times j2\pi^2 fna^2 \quad [\mathrm{V/T}] . \tag{4}$$

If $f > f_i$, the sensitivity of the induction gradiometer can be described as follows.

$$V_{out}/B = -\pi a R_f/(P_0 n) \quad [\mathrm{V/T}] . \tag{5}$$

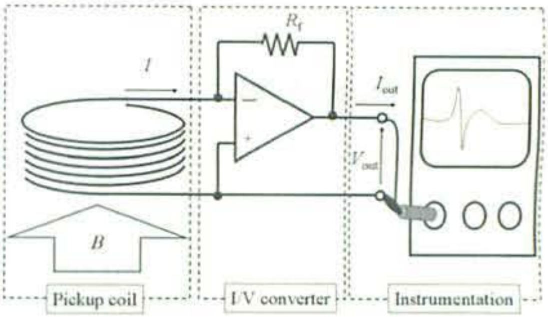
The designed induction gradiometer consists of a pickup coil, a current-voltage converter, a high-pass filter, and an instrumentation amplifier. Fig. 2 shows the equivalent circuit of an induction gradiometer.

The differential input type current-voltage converter has a feedback resistance of 10 MΩ. The transimpedance gain of this current-voltage converter is 20,000,000 [V/A]. The differential input type converter isn't affected by variations in the ground level[7]. If the detected frequency exceeds 19 Hz, the I-V converter has a sensitivity of 0.147 V/nT. However the I-V converter generates the undesirable offset voltage of a few ten mV.

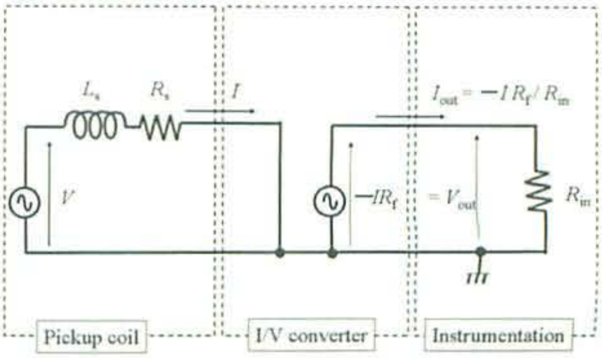
We positioned the high-pass filter after the I-V converter. Because high-pass filter has a cutoff frequency of 0.3 Hz, it can eliminate the offset voltage.

Finally, we positioned the instrumentation amplifier (IA) after the high-pass filter. The gain of this IA is 110. In addition, IA has a cutoff frequency of 1 Hz to eliminate the offset-voltage.

If the detected frequency exceeds 19 Hz, the induction gradiometer has a sensitivity of 32 mV/pT.



(a) Model



(b) Equivalent circuit

Fig. 1. Induced current detection model.

Table.1 Specification of the Pickup coil

Property	Value
Number of turns n	2827×2
Outside diameter $4c$ [mm]	120
Coil width $2/3a$ [mm]	30
Inductance L_s [H]	0.61×2
Resistance R_s [Ω]	71×2
Cutoff frequency f_i [Hz]	19
Coil distance [m]	0.3

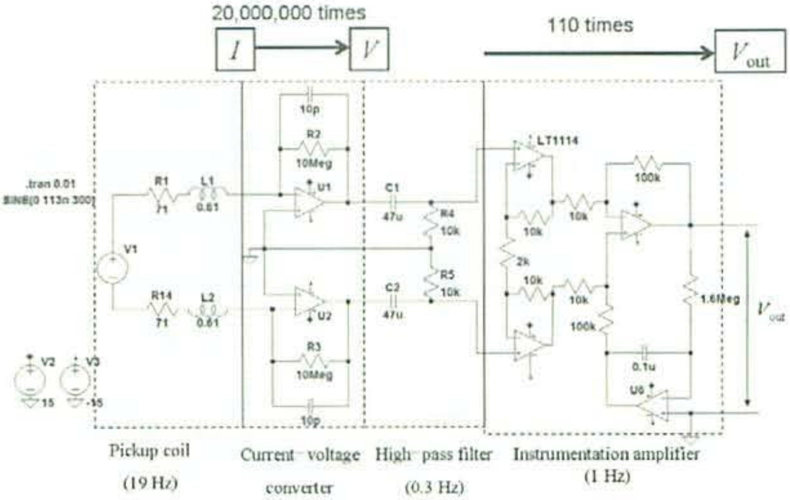


Fig.2. Equivalent circuit of induction gradiometer.

2.2 Calibration

Fig. 3 shows the calibration setup. A sinusoidal current is applied to a 14 cm diameter one-turn coil. A fluxgate magnetometer is positioned 2 cm away from the one-turn coil. We confirmed the relationship between the generated magnetic field and the applied current in the one-turn coil. From experimental results, a 120 mA_{p-p} current generated a magnetic field of 100 nT_{p-p}. Table.2 shows the relationship between the magnetic field and the current.

2.3 Setup of Demonstrated MCG Measurement

Fig. 4 shows the setup of the demonstrated MCG measurement, which was performed in a Faraday cage. The pickup coil is rolled in an aluminum foil to counter electrical interference. We applied a current to the one-turn coil using the LabVIEW. In order to generate an MCG field with R-wave peaks of amplitudes 1 nT and 100 pT, we set the current value to be 1.2 and 0.12 mA respectively.

Fig. 5 shows the block diagram used to demonstrate the modeled MCG measurement. It is a challenge to detect MCG signal without magnetically shielded environment. In order to observe the corresponding signal, we used digital filters and averaging technique. Their noise reduction methods are usually used in biomagnetic measurements [3]. The output voltage of the induction gradiometer is processed by the digital filter after the voltage was recorded by the LabVIEW. The digital filters used were a band-pass filter (BPF) and a band-elimination filter (BEF). A 60 Hz magnetic commercial frequency noise exists in our laboratory environment. The BPF allows the passage of 0.3-30 Hz signals, but BEF doesn't allow the passage of 60 Hz signals. The processed signal was averaged 20 times.

3. Experimental Result

We first confirmed the output voltage of the induction gradiometer. We were not able to observe the waveform because this induction gradiometer detected magnetic commercial frequency noise, and the modeled MCG signal was masked by 60 Hz noise. A digital filter was therefore required.

Fig.6 (a) shows the wave form of the 1 nT R-wave measured using the induction gradiometer. We could confirm R-wave in output voltage.

Fig.6 (b) shows the signal averaged 20 times. We were able to clearly confirm the measured wave form by averaging. However, the measured wave form was different from the original signal at some point. For example, the points (1) and (2) in the measured wave were distorted.

Fig. 7 (a) shows the R-wave of 100 pT measured using the induction gradiometer. We were not able to confirm the wave form because the noise voltage of 1 V_{p-p} is larger than the detected MCG signal.

Fig. 7 (b) shows the signal averaged 20 times. The result, showed that the detected R-wave was one-tenth that Fig. 6 (b), and the noise voltage decreased to 0.2 V_{p-p}. Because of the decrease in noise voltage, we successfully confirmed the observation of the R-wave in our laboratory environment using the gradiometer.

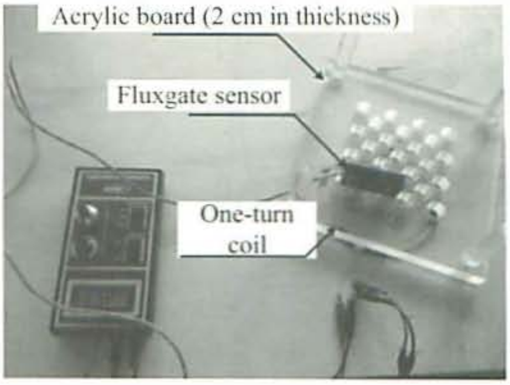


Fig.3. Calibration setup.

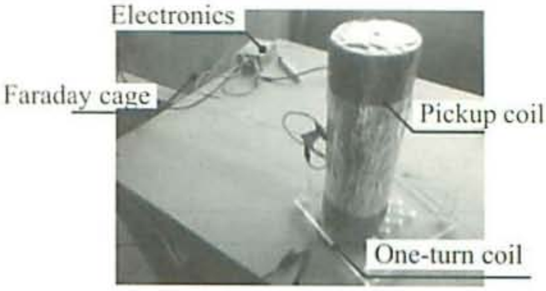


Fig.4. Experimental setup.

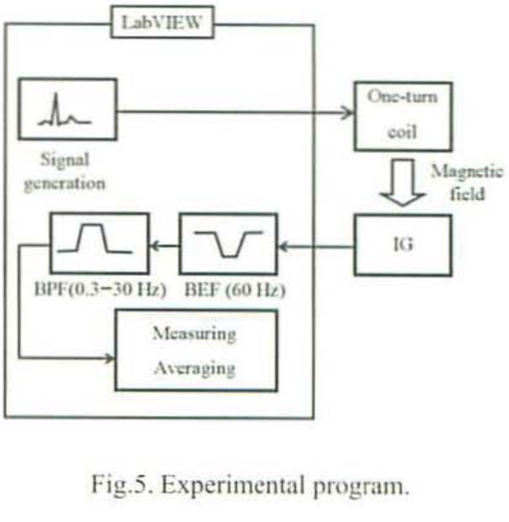
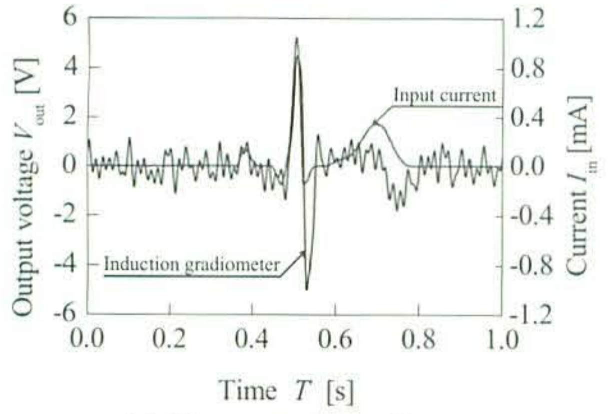
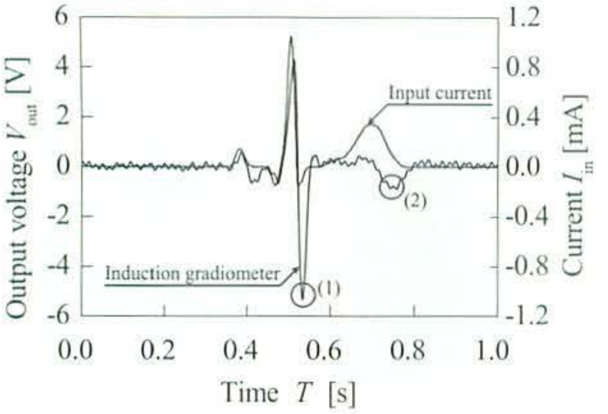


Fig.5. Experimental program.



(a) Measurement example



(b) Averaged 20 times

Fig.6. Experimental result (R-wave of 1 nT_{p-p}).

Table. 2 Relationship between magnetic field and current

Current [mA]	Magnetic field [nT]
120	100
12	10
1.2	1
0.12	0.1

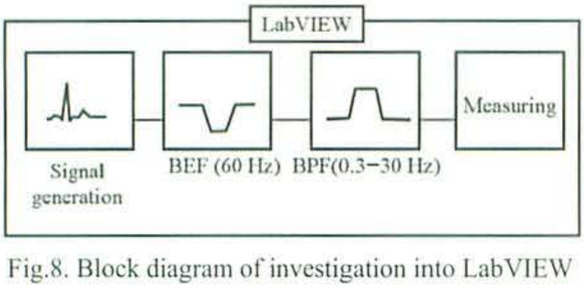
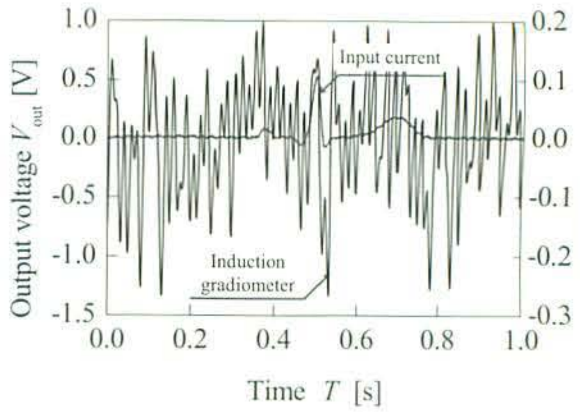
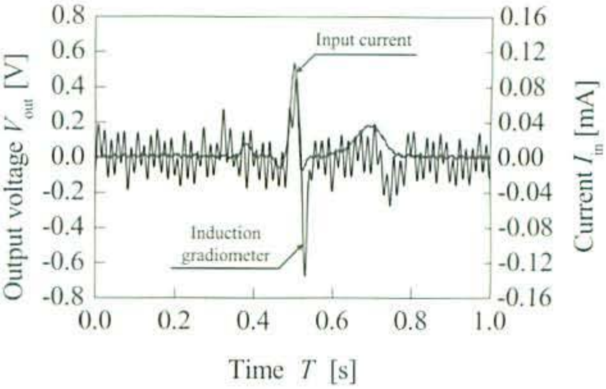


Fig.8. Block diagram of investigation into LabVIEW digital filter.



(a)Measurement example



(b)Averaged 20 times

Fig.7. Experimental result(R-wave of 100pT_{p-p}).

4. Discussion

4.1 Digital Filter of LabVIEW

The measured wave form was different from the original signal at some points. For example, points (1) and (2) in Fig. 6 (b) were distorted. If real MCGs are detected for the human heart, this distortion occurs because of vibration. There were no vibrations in experimental environment during measurement. Hence, this issue should be investigated further.

The experiments were performed because we believe that the wave form was affected by the digital filter. A modeled signal was processed directly to the digital filter in LabVIEW, and we confirmed that the original signal was processed by both BPF and BEF. Fig.8 shows the block diagram of the investigation into the LabVIEW digital filter.

Fig. 9 shows the experimental results. The digital filter's results differed from the originally modeled MCG signal. However it is not enough to explain the reason of distorted points in Fig. 6 (b).

4.2 Measured Frequency Response

We measured the frequency response of the induction gradiometer. A sinusoidal current was applied to a one-turn coil, and the pickup coil was placed at a distance of 2 cm from the one-turn coil. The applied current generated a magnetic field of 1 nT_{p-p}. The output voltage of the induction gradiometer was measured by an FFT analyzer. Fig. 10 shows the experimental block diagram of the measured frequency response. Fig.11 shows the frequency response. In experiment, the measured voltage less than 1 Hz, it may occur because of environmental magnetic noise and drift voltage in the electric. The dot and cross represent the maximum and minimum measured voltages of the measured voltage, respectively. The line represent the calculated result using the LTSpice. The output voltage was roughly constant for frequencies greater than 10 Hz and less than 1 kHz.

From the measured values, we found that the cutoff frequency of the induction gradiometer was 5-10 Hz. It should be noted that the measured voltage corresponded to magnetic flux density of 1 nT_{p-p}. In this calculation, a uniform magnetic flux crosses the one Brooks coil. In contrast, the generated magnetic flux density was 1 nT_{p-p} at the center of the one Brooks coil. This experimental results, pointed out that measured at the center.

4.3 Effect of High-Pass Filter on the Signal

Because the simulated frequency response is as similar as measured frequency response, we should consider the phase profile. The high-pass filter characteristics of the induction gradiometer were set in LabVIEW. Fig. 12 shows the program used to investigate the high-pass filter effect. The cutoff frequency of the high-pass filter is 5-10 Hz.

Fig.13 shows the original signal and the signal processed by the high-pass filter. In Fig. 13, it was observed became clear that the signal processed by the high-pass filter was different from the original signal. Frequency elements of the original signal that were smaller than 5 Hz were eliminated because the cutoff frequency of the circuit in the induction gradiometer was 5 Hz. Hence, the processed signal was distorted. In other words, the output voltage agrees with Fig. 6 (b). Therefore, we found that the distortion was caused by filter characteristic of the induction gradiometer.

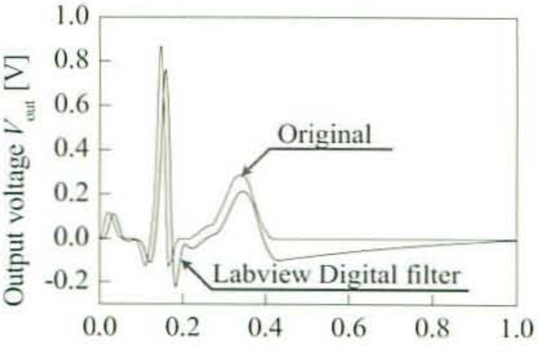


Fig.9. Experimental results.

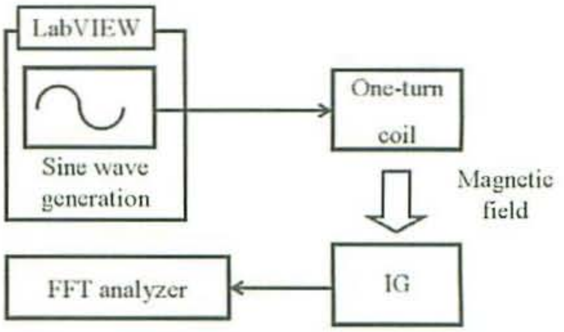


Fig.10. Block diagram of measured frequency response.

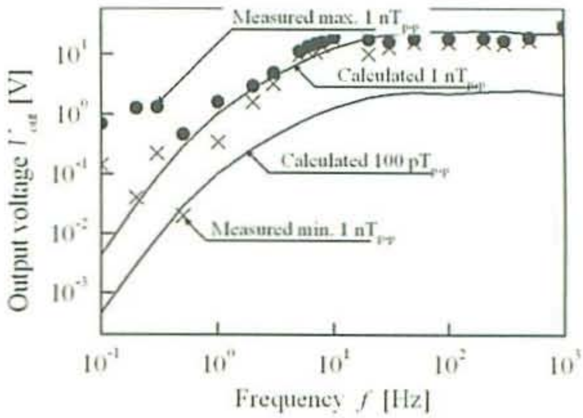


Fig.11. Frequency response.

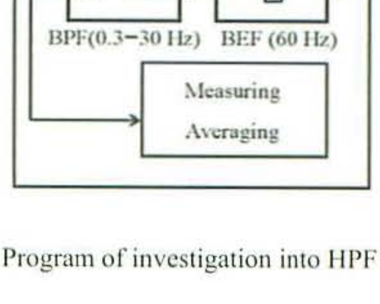


Fig.12. Program of investigation into HPF effect.

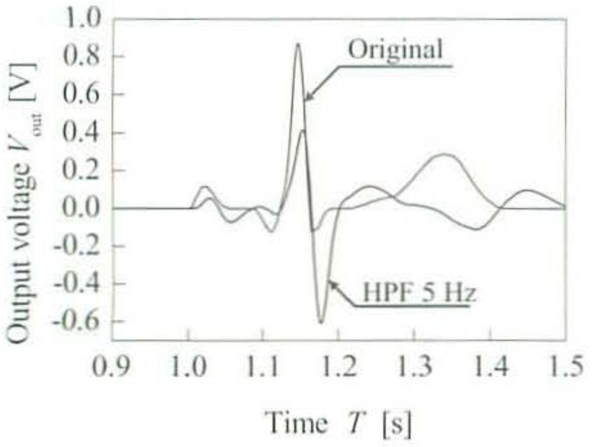


Fig.13. Original signal and the signal processed by the high-pass filter.

5. Conclusion

We investigated the sensitivity of an induction gradiometer for MCG measurement. A sample MCG signal was generated by applying current to a one-turn coil using the LabVIEW program. The signal detected by the induction gradiometer was processed by a digital filter using the LabVIEW and the processed signal was averaged 20 times. We setup an MCG field for which the amplitude of the R-wave peak was 100 pT. Our experimental results successfully confirmed the observation of the R-wave in our laboratory environment using the gradiometer.

However at some points, the observed wave form was distorted.

First, we used LabVIEW to investigate the influence of the digital filters (BPF (0.3-30 Hz) and BEF (60 Hz)). The digital filter made a distortion of a modeled MCG signal but Fig. 8 did not fully correspond to Fig. 5 (b).

Second, we measured the frequency response of the induction gradiometer. From the measured frequency response, the induction gradiometer showed that the cutoff frequency was 5-10 Hz.

Finally, we set the high-pass filter characteristic of the induction gradiometer using the program LabVIEW. From experimental results, we found that the strain was due to the filter characteristic of the induction gradiometer. Because frequency elements of the original signal smaller than 5 Hz were reduced because of by the cutoff frequency of the circuit in the induction gradiometer, the processed signal was distorted.

We found that the distortion in the detected wave form was probably not due to vibrations or electrical interference. However, more investigations are required to adequately explain this result.

References

[1] G. Baule and R. Mcfee, "Detection of magnetic field of heart," *American Heart J.*, Vol. 66, pp. 95-96, 1963.
[2] G. Baule and R. Mcfee, "The magnetic heart vector," *American Heart J.*, Vol. 79, No. 2, pp. 223-236, 1970.
[3] D. Cohen, "Magnetoencephalography: evidence of magnetic fields produced by alpha-rhythm currents," *Science*, Vol. 161, pp. 784-786, 1968.
[4] K. Tashiro, A. Kakiuchi, K. Moriizumi and H. Wakiwaka, "A consideration of the basis of an induction magnetometer," *The Papers of Tech. Meet. Magn., IEEJ*, MAG-09-32, 2009.
[5] K. Tashiro, "Proposal of coil structure for air-core induction magnetometer," *Proc. IEEE Sensor 2006*, pp. 939- 942, 2006.
[6] 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, pp. 2784-2787, 2009.
[7] K. Tashiro, S. Inoue, A. Kakiuchi and H. Wakiwaka, "USB bus powered induction magnetometer", *The Papers of Tech. Meet. Magn., IEEJ*, MAG-09-151, 2009.