Development of high resolution programmable oversampling MI sensor system with 32-bit ADC for multi-channel bio-magnetic measurements

Cite as: AIP Advances 9, 125243 (2019); https://doi.org/10.1063/1.5129842
Submitted: 02 October 2019 . Accepted: 25 November 2019 . Published Online: 30 December 2019

J. Ma, Z. Yang, and T. Uchiyama

AIP Conference Proceedings
FLASH WINTER SALE!
50% OFF ALL PRINT PROCEEDINGS
ENTER CODE 50DEC19 AT CHECKOUT
Development of high resolution programmable oversampling MI sensor system with 32-bit ADC for multi-channel bio-magnetic measurements

J. Ma, Z. Yang, and T. Uchiyama

AFFILIATIONS
Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan

Note: This paper was presented at the 64th Annual Conference on Magnetism and Magnetic Materials.

Corresponding author: Jiaju Ma (e-mail: ma.jiaju@i.mbox.nagoya-u.ac.jp)

ABSTRACT
In order to further improving noise performance and achieving higher spatial resolution for bio-magnetic sensing, there is a tendency to develop a multi-channel integrated system for micro magnetic sensors. In this study, we have developed a high resolution programmable oversampling MI sensor system, as a unit module for multi-channel integrated bio-sensor system, based on Pk-pk VD-type MI magnetometer. We have achieved a high field detection sensitivity with good linearity, and a noise level lower than 1 pT/Hz^{1/2}, by utilizing the time-differential measurement in each MI element for suppressing the low frequency noise components and increasing the stability of sensor system. Meanwhile, the proposed MI sensor system can be easily enlarged into multi-channel system, and is more suitable for integration and mass production. Furthermore, we have successfully achieved the real time R peak and T wave measurements of magnetocardiography (MCG) via new MI sensor system, with a high real time signal-to-noise ratio (SNR) of about 20 dB. We have at the first time achieved the clear P wave measurements of MCG using MI sensor, in an unshielded environment. The real time MCG measurements via new MI sensor system at room temperature, in an unshielded environment, will contribute to the diagnosis of heart disease.

© 2019 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5129842

I. INTRODUCTION
As a high-performance magnetic sensor, magneto-impedance (MI) sensor has attracted considerable attention and has wide prospects in geomagnetic detection and bio-sensing. Comparing with other magnetic sensors, MI sensor has very high sensitivity, and pico-tesla resolution which is coming up with Superconducting Quantum Interference Devices. Meanwhile, pulse driven MI sensor has good linearity by using pick-up coil and change rate of impedance in amorphous wire is more than 100% 
. Moreover, MI sensor has high frequency response from tens to hundreds of MHz with low power consumption lower than mW and of smaller size. In recent years, MI sensor has been used for measuring bio-magnetic fields in living cell tissue preparations and Magneto-encephalogram (MEG).

However, there are still some limitations for utilizing MI sensor into medical diagnosis. First is noise performance. In order to detecting MCG and MEG signals for diagnosis of heart and brain diseases, via MI sensor, it’s necessary to further improve noise performance into fT level. The second limitation is spatial resolution. For achieving MCG and MEG mappings, there is a tendency to develop a multi-channel integrated MI sensor system with high spatial resolution, which is a main advantageous of MI sensor. Furthermore, comparing with previous system, proposed MI sensor system is programed by Python and controlled by field-programmable gate array (FPGA) which are low development cost and convenient to be developed for various experiments and application. In this study, we have developed a high resolution programmable oversampling MI sensor system, as a unit module for multi-channel integrated bio-sensor system, based on Pk-pk VD-type MI magnetometer.

II. PROGRAMMABLE OVERSAMPLING MI SENSOR SYSTEM
The new developed MI sensor system is combined with Pk-pk VD-type MI gradiometer, FPGA system and programmable...
oversampling analog to digital converter (ADC) & digital filter system. Fig. 1 shows block diagram of new programmable oversampling MI sensor system. We program ADC configuration, down sampling factor, and Filter configuration by Python; and communicate to FPGA with these programed ADC & Filter systems. After receiving configuration programs from PC, FPGA will setup ADC & Filter systems and control the ADC by supplying controlling and configuration signals. The new MI sensor system is composed of a pair of MI element: a sensing element and reference element. We utilize 25-um diameter CoFeSiB amorphous wire, equipped in a pick-up coil, to realize a highly linear magnetic sensor by off-diagonal MI effect. The high frequency excitation pulse, with a 5 ns rising and falling times which corresponds to a 50 MHz sine wave, induces pulse current MI effect resulting from skin effect in amorphous wire, which insures there is no magnetization in the inner core for achieving a single domain and significantly reducing the magnetic noise and hysteresis of magnetic field sensing. The new MI sensor system utilizes time-differential measurement in each MI element for suppressing low frequency noise components and increasing stability. It detects both positive peak and negative peak of induced waveforms in pick-up coils for enhancing sensitivity and reducing noises. Meanwhile, we output difference between sensing and reference elements for reducing uniform magnetic noise. Then, the output of MI gradiometer is converted by utilizing low noise, low power consumption 32-bit ADC. After receiving configuration programs from PC, FPGA will set up and control ADC by sending control & setup signals with parameters of sampling frequency, down sampling factor and Filter configuration. For general sensor system, during conversion stage, the high frequency noise components greater than the Nyquist frequency (half the sampling frequency) will distort as a frequency shift and attenuate the SNR in interested bandwidth due to aliasing. For improving noise performance, we utilize the integrated digital filter cooperated with ADC in combination with an analog filter, for suppressing interference of high frequency noises shifted into interested frequency range, and avoiding aliasing. With this proposed system, we can achieve a shielding factor more than 80 dB for the noise exceeding interested bandwidth, even though using a simple first or second order analog filter with a gradual roll-off in circuit, which is friendly to design and lower noise level in interested frequency range. Therefore, the filter system can suppress out-of-band noise power, thereby lowering overall noise and increasing the dynamic range. The highest sampling frequency is 1 MHz. We can adjust output data rate by setting up down sampling factor without causing spectral interference in bandwidth of interest. We utilize oversampling measurement for enhancing resolution and reducing noise. As illustrated in Fig. 1, the dynamic range of this new sensor system increase when output sampling frequency decreases. Meanwhile, RMS noise decreases with output sampling frequency. Finally, sampled date is sent to computer by utilizing FPGA. Both down sampling processing and filter configuration can be programed, with controlling and communication by using FPGA. This proposed MI sensor system has been designed as a unit module for multi-channel integrated bio-sensor system, aiming to room temperature bio-magnetic measurements. Comparing with conventional MI sensor gradiometer, this proposed system achieves a higher sensitivity, and an extremely low noise level about 700 fT, with a high compatibility for extremely weak magnetic field measurements. Also, it can be easily enlarged into multi-channel system, and is more suitable for integration and mass production.

A. Field detection characteristics

The length of wire is 10 mm and number of coil turns is 700. Both of sensing and reference MI elements illustrate good linearity. The field detection sensitivity of sensing and reference elements are $1.642 \times 10^6$ V/T and $1.6398 \times 10^6$ V/T. The difference in sensitivity of sensing and reference elements is within 1% (about 0.15%), which means geomagnetism and common model magnetic noises can be

| SAMPLING FREQUENCY | DYNAMIC RANGE (dB) | NOISE (\(\mu\)VRMS) |
|--------------------|--------------------|---------------------|
| 8 kHz              | 129.7              | 1.2                 |
| 4 kHz              | 132.9              | 0.83                |
| 2 kHz              | 135.9              | 0.59                |
| 1 kHz              | 138                | 0.46                |
| 500 Hz             | 141.1              | 0.32                |
| 250 Hz             | 142.7              | 0.27                |
| 125 Hz             | 145.3              | 0.2                 |
| 62.5 Hz            | 147.6              | 0.15                |

FIG. 1. Block diagram of new programable oversampling MI sensor system.
significantly suppressed with a shielding factor of 56 dB, which corresponds to a two-shell permalloy magnetic shield. The geomagnetic noise is about 0.1 nT at 0.1 Hz, and decrease with the increase of frequency. Therefore, this new MI sensor system can significantly suppress geomagnetism noise.

B. Noise analysis

As illustrated in Fig. 2(a), we measure output noises in time domain of new MI sensor system with 30 Hz lowpass filter. The output RMS noise is lower than 10 pT. Fig. 2(b) illustrates magnetic noise spectral density of programmable oversampling MI sensor system and previous MI gradiometer, comparing with environment magnetic noise in our laboratory. The proposed MI sensor system utilizes time-differential measurement by detecting and output the difference between positive and negative peak of waveform in pick up coils, for suppressing low frequency noise components. The interval between these two peaks is about 100 ns, which is negligible comparing with periods of low-frequency noise. Meanwhile, the interference of high frequency noises shifted into interested bandwidth will be suppressed by using filter system described above. Also, output RMS noise will be reduced by oversampling measurement. The noise floor of new MI sensor system is lower than 1 pT/Hz$^{1/2}$ in the frequency range from 1 Hz to 100 Hz, which is less than 1/10 of noise level of previous MI gradiometer.

III. MAGNETOCARDIOGRAPHY MEASUREMENTS

In this section, we will illustrate MCG measurements via new MI sensor, with simultaneous measurements of electrocardiography (ECG). The room temperature MCG measurements are carried out on a male subject, in a sitting position. The MI sensor is perpendicularly placed to chest surface, with a distance of 10 mm. As illustrated in Fig. 3(b), measurement points are divided into two groups (A&D, B&C) for utilizing 2-channel MI sensor system unit module. Measurement point B is set at chest surface, 20 mm to the left of pit of stomach. The point C is 20 mm to the right of pit of stomach.

The interval between point A and B, also C and D are 20 mm. The magnetic signals measured by 2-channel MI sensor system are processed by 0.1 Hz high-pass filter and 40 Hz low-pass filter to eliminate interference of noise produced by power source at 60 Hz.

The Fig. 3(a) illustrates real-time recordings of MCG signals simultaneously measured at point A and D. We can clearly identify a shape magnetic peak corresponding to R peak of ECG. The amplitudes of R peak is approximately 120 pT at point A, and 50 pT at point D. There is always a gentle magnetic peak following R peak which is considered to be T wave at point A. As illustrated in Fig. 3(b), we have demonstrated MCG signals mapping via 2-channel MI sensor. We have performed arithmetic average processing in continuous MCG recordings by using synchronizing R peak of ECG as a trigger. The characteristic components of ECG, QRS complex and T-wave are all present in our magnetic data. The MCG signals in Fig. 3(b) have been averaged over 10 cycles. The spatial variation in signal shape is clearly identified between point A and C, also B and D, which is an advantageous characteristic of MCG measurement. Such high spatial resolution is important for diagnosis of diseases.

We also demonstrated MCG measurements via new MI sensor, with simultaneous measurements of ECG. Fig. 4(a) illustrates real-time recordings of MCG and ECG signals in an unshielded environment. The output superposing noise of new MI sensor system is lower than 10 pT, which is much lower than previous MI gradiometer. We have clearly identified typical features of magnetic cardiogram signals, such as QRS complex, corresponding to R peak of ECG. The amplitude of R peak is approximately 100 pT. There is always a gentle magnetic peak following R wave, which corresponds well to T wave of ECG. We have successfully achieved real time R peak and T wave measurements of MCG with a high SNR of 20 dB.

P wave represents depolarization of the atria. A clear P wave detection will be benefit for detection of ectopic atrial pacemaker and diagnosis of atrial enlargement. For achieving complete heart
health monitoring included P wave, we have performed arithmetic average processing in continuous MI sensor recordings. The MCG signals in averaging over 20 cycles is illustrated in Fig. 4(b). We have significantly identified a negative sharp magnetic peak followed with a gentle peak, which corresponds well to R peak and T wave of ECG. Meanwhile, there is a small magnetic peak in MCG signal at 290 ms, which is at the same position of P wave of ECG. Therefore, we have successfully measured R peak, T wave, and P wave of MCG signals, with a high SNR of 35 dB. According to these results, we have at the first time achieved clear P wave measurements using MI sensor, in an unshielded environment. The real time MCG measurements via new MI sensor system at room temperature, will contribute to diagnosis of heart disease. Especially, clear measurements of P wave via MI sensor will be a breakthrough for diagnosis of heart disease, such as complete atrioventricular block, and atrial fibrillation.
IV. CONCLUSION

We have proposed a high performance programmable oversampling MI sensor system as a unit module for multi-channel integrated bio-sensor system. The proposed system has achieved a high sensitivity with good linearity, and a noise level lower than 1 pT/Hz$^{1/2}$ in an unshielded environment. Also, it can be easily enlarged into multi-channel system, and is more suitable for integration and mass production. Meanwhile, we have achieved real time R peak and T wave measurements, and have at the first time achieved clear P wave measurements using MI sensor. These demonstrations of room temperature MCG measurements via MI sensor, are very significant advances in bio-magnetometry.

ACKNOWLEDGMENTS

This work was supported by A-STEP of Japan Science and Technology Agency (Grant Reference Number: AS2915024R).

REFERENCES

1. K. Mohri, T. Uchiyama, L. V. Panina, M. Yamamoto, and K. Bushida, J. Sensors 2015, 718069.
2. K. Mohri and Y. Honkura, Sensor Lett. 5(1), 267–270 (2007).
3. S. Sandacci, D. Makhnovskiy, L. Panina, K. Mohri, and Y. Honkura, IEEE Trans. Magn. 40(6), 3505–3511 (2004).
4. T. Uchiyama, K. Mohri, and S. Nakayama, IEEE Trans. Magn. 47(10), 3070–3073 (2011).
5. J. Ma and T. Uchiyama, IEEE Trans. Magn. 55(7), 4002706 (2019).
6. J. Ma and T. Uchiyama, IEEE Trans. Magn. 53(11), 4003404 (2017).
7. S. Gudoshnikov, N. Usov, A. Nozdrin, M. Ipatov, A. Zhukov, and V. Zhukova, Phys. Status Solidi A 211(5), 980–985 (2014).
8. T. Takiya and T. Uchiyama, IEEE Trans. Magn. 53(11), 4002804 (2017).
9. M. Pannetier-Lecoeur, L. Parkkonen, N. Sergeeva-Chollet, H. Polovy, C. Fermon, and C. Fowley, Appl. Phys. Lett. 98, 153705 (2011).
10. H. Karo and I. Sasada, Journal of Applied Physics 117, 17B322 (2015).
11. T. Uchiyama and T. Takiya, AIP Adv. 7(5), 056644 (2017).
12. R. Fenici, D. Brisinda, and A. M. Meloni, Expert Rev Mol Diagn. 5(3), 291–313 (2005).