主　論　文　の　要　約

論文題目　Development of high performance femto-tesla resolution magneto-impedance sensor system for bio-magnetic measurements
(フェムトテスラ分解能磁気インピーダンスセンサの開発と生体磁気計測に関する研究)

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論　文　内　容　の　要　約

Recently, the automotive field and bio-sensing field have created huge market for micro magnetic sensor. For nowadays magnetic sensor device, the limitations of superconducting quantum interference devices (SQUIDs) are needing cooling system and magnetically shielded room. the high cost and large scale of SQUIDs result in pressure to develop some miniature, low-cost, and highly sensitive magnetic sensor systems for bio-magnetic sensing. Meanwhile, the micro magnetic sensors such as Hall sensor and Anisotropic Magneto Resistive (AMR) sensor, are limited by detection resolution. Therefore, we would like to develop a low-cost, micro-size, and high-resolution magneto-impedance (MI) sensor for bio-magnetic sensing. In this study, we have newly developed a high-performance MI sensor system which has achieved a femto-tesla resolution, for measuring extremely weak magnetic field. Meanwhile, we have investigated the sensitivity of MI element by controlling anisotropy, and analyzed noise components of amorphous wire. Moreover, for canceling out uniform environment magnetic noise, we proposed a Pk-pk VD-type MI gradiometer, which can suppress uniform magnetic noise with a shielding factor of – 60 dB, without causing attenuation of target magnetic signal. For measuring bio-magnetic signals and investigating distribution of Magnetocardiography (MCG) and Magnetoencephalography (MEG), we have developed a multi-channel programable oversampling MI sensor system with anti-aliasing filter system. Finally, we have demonstrated real time MCG measurement at room temperature via new MI sensor. Also, we have measured Spontaneous brain activity (mu/alpha rhythm), which can be utilized for investigating biological state of subjects. Meanwhile, the Event-Related Fields (ERFs) are evoked by visual and auditory stimuli which are connecting to Brain psychiatric disorders. We have significantly identified signals generated by human brain which are evoked by visual and auditory stimuli, via new MI sensor.

In the Chapter 1, we have introduced several magnetic sensors and some applications of magnetic sensor. The main applications for magnetic sensors are summarized with illustrating amplitude and frequency of target magnetic fields. The applications for high frequency upper than 1 MHz are Magnetic Resonance Imaging (MRI), functional Magnetic Resonance Imaging (fMRI), Detection of Plasma current, and antenna for microwave. These high frequency applications mainly utilize Magnetoresistance sensor and pick up coil as sensing device. According to recently market report, the automotive, industrial, consumer electronics, and aerospace are the four largest markets for magnetic sensors. Meanwhile, the 4 most popular applications with the largest market share are reported to be navigation, position sensing, rotation sensing, and current sensing. These applications are used to be dominated by Hall sensor, AMR sensor and GMR sensor. In recent years, with the rapid development of several new magnetic sensors, the markets are gradually taken by Tunnel Magneto Resistance (TMR) sensor and MI sensor. Moreover, there are several frontier applications for magnetic sensors, which require extremely high resolution of sensing device. Those frontier applications have attracted considerable attentions in bio-medical field, diagnosis of disease, and consumer electronics.

In the Chapter 2, we have introduced about MI effect. By applying a high frequency current to the amorphous wire to generate a skin effect, not only the inductance but also the electric resistance can be sensitively changed with the external magnetic field at the same time when excitation current flows through the amorphous wire. This is referred to as "MI effect". By applying high frequency pulse current, a strong skin effect occurs in the amorphous wire, and the current path and the magnetic flux path are limited to the surface layer. Meanwhile, we have investigated magnetic characteristics of amorphous wire and discussed about impedance mode of amorphous wire. Finally, we have introduced about pulse driven MI effect, which can achieve a highly sensitive MI sensor with lower thermal noise.

The Chapter 3 talks about Pk-pk VD-type MI magnetometer which is composed of pulse generation circuit, MI element, time-differential measurement circuit, and high stability reference potential circuit. The rising time of excitation pulse applied to amorphous wire is 5 ns which is corresponding to a 60 MHz sine wave, which can induce impedance change of amorphous wire with more than 200%. Meanwhile, we output difference between positive and negative peaks in pick up coil by time differential measurement circuit for suppressing low frequency noise components. The MI element output is natural balanced signal with a positive peak Vp1 and negative peak Vp2. The Vp1 and Vp2 directly and inversely proportional to the external magnetic field. The signals at positive peak and negative peak are differential mode signals depending on external magnetic field. However, because they are picked up from one same signal, the noise at positive peak and negative peak are common-mode signals. All noises are correlated. Depending on the Correlated Double Sampling (CDS) circuit, it is possible to obtain an output with significantly reduced electronic noise from MI element such as thermal noise due to pick up coil, noise caused by excitation current and interference of electromagnetic waves. Moreover, by utilizing the time differential measurement, we can suppress low frequency noise components and reduce common-mode noise due to fluctuation of frequency in oscillator, voltage variation at coil termination, fluctuation of reference potential. The noise level we achieved here is lower than 1 $pT/Hz^{1/2}$ which is 1/100 of conventional MI magnetometer. Moreover, bio-magnetic fields, such as MCG, and MEG, are extremely weak magnetic field in a pico-tesla or femto-tesla level. we have to cancel the background uniform noises such as geomagnetic field. The geomagnetic noise and laboratory noise are approximately 3 orders larger than bio-magnetic fields at low frequency range. We have developed a high-performance MI gradiometer with peak-to-peak voltage detector by synchronized switching, based on pk–pk VD-type MI magnetometer. In order to cancel uniform magnetic noise, magnetic field detection characteristics of sensing and reference sensors need to be approximately the same. The difference in sensitivity of sensing and reference elements is within 0.1%, which means geomagnetism and common model magnetic noises can be significantly suppressed with a shielding factor of 60 dB. On the other hand, the target magnetic signal in longitudinal direction is almost no attenuation caused by gradiometer configuration.

In the Chapter 4, for further improving MI sensor, it's necessary to demonstrating highly sensitive MI element and analyzing intrinsic magnetic noise in amorphous wire. However, the noise level of conventional MI sensor is too high to identify intrinsic noise of amorphous wire. So, in this study, we used new MI sensor circuit, which has an extremely low circuit noise for investigating MI element. The noise of MI sensor is considered to be mainly due to circuit noise, fluctuation of wire magnetic moment (thermal magnetic noise), and irreversible movement of domain wall trapped by impurities and scratches on wire surface (Barkhausen noise). The noise level of Pk-pk VD-Type MI sensor circuit is approximately 20 nV. The noise level we achieved here is getting close to the input conversion noise level of the differential amplifier used in this circuit. It is a strong proof that Pk-pk VD-Type MI sensor circuit has been well designed. With this extremely low circuit noise we achieved here, we can investigate the intrinsic magnetic noise of amorphous wire via proposed MI sensor circuit. We have considered the loss due to the BH loop, and dealt with fluctuation of magnetic moment according to the general theory of fluctuation. When magnetic moment fluctuates due to thermal energy, it becomes noise of magnetic sensor measuring this magnetic moment. The fluctuations of magnetic moment of amorphous wire are simultaneously detected by MI sensor with external magnetic field. The effective value of the fluctuations of magnetic moment measured by MI sensor can be considered as a noise part for adding into output of MI element. The thermal noise of MI element can be expressed as a function of permeability. It increases with anisotropy field. However, when anisotropy is 3 Oe or more, the value tends to be saturated. Moreover, it is considered that the magnetic noise due to irreversible movement of domain wall increases with the number of domain walls. If the number of pinning sites such as scratches and impurities on the wire surface is constant, the greater the number of domain walls, the greater the probability of being trapped at pinning sites. According to measurements results, noise due to irreversible movement of domain wall is linearly proportional to the -0.25 power of the anisotropy field, which is same with number of domain walls. Therefore, we can reduce magnetic noise of amorphous wire by controlling anisotropy field and improving surface structure of amorphous wire. In conclusion, thermal noise of amorphous wire is extremely weak comparing with other noise components, which is lower than 1/15 of measured MI sensor noise. The circuit noise is about 20nV which is 1/10 of measured MI sensor noise. The noise level we achieved here is getting close to the input conversion noise level of the differential amplifier used in this circuit. It is a strong proof that the Pk-pk VD-Type MI sensor circuit has been well designed. Of note is that, the noise due to irreversible movement of domain is dominant in all noise components of MI element. Since changing trend of noise due to irreversible movement of domain with anisotropy is dominated by sensitivity of MI elements, which is proportional to -1 power of anisotropy. Therefore, the smaller the anisotropy is, the lower the noise of MI element will be.

In Chapter 5, we have introduced multi-channel MI sensor system. We program ADC configuration, sampling frequency, down sampling factor, and filter configuration by Python; and communicate to field-programmable gate array (FPGA). FPGA will setup and control the ADC by supplying controlling and configuration signals. 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. The dynamic range of this new sensor system increase when output sampling frequency decreases. Meanwhile, RMS noise decreases with output sampling frequency. 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. and is more suitable for integration and mass production. 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 suppressing high frequency noise, we combined analog filter and digital filter. The shielding factor of this filter system is more than 80 dB. 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 dynamic range.

In Chapter 6, we demonstrated bio-magnetic sensing by using proposed multi-channel MI sensor system. As you may know, the Sustainable Development Goals for humankind until 2030, which was adopted at the United Nations Summit has 17 goals. The third one is good health and well-being. Ensure healthy lives and promote well-being for all at all ages. Especially this year, when we suffer from Covid-19, well-being seems very important. For achieving good health and well-being, there are several issues we have to solve. First is medical costs. Less than half of the global population is covered by essential health services, because of the high medical costs. The second one daily health monitoring. Remotely monitored patients are 36 million by 2020. Meanwhile, when facing Covid-19, the daily health monitoring become more and more important. The third, Cardiovascular disease (CVD) is the world's number 1 killer. 17.8 million per year more than cancer and HIV. 31% of all global deaths is because heart disease. Moreover, more than 75% of CVD deaths take place in low- and middle-income countries. So, we need to develop a cheap, convenient sensing device for heart disease. We have demonstrated real time MCG measurements via multi-channel MI sensor, and clearly identified the typical features of magnetic cardiogram signals, such as QRS complex and T wave, corresponding to the R peak and T wave of electrocardiogram (ECG). The P wave has been clearly identified by arithmetic average processing over 20 cycles. The room temperature MCG measurements, without any shielding equipment, will contribute to the diagnosis of heart disease. For Spontaneous brain activity (mu/alpha rhythm), simultaneous recordings of alpha rhythm are significantly attenuated when the subject's eyes are open and intensified when eyes are closed. The Mu rhythm related to motor action doesn't present over occipital cortex. However, during hands flexed condition, there are still remaining a little 10 Hz components over the motor cortex. In our opinion, the "suppression" or "block" of mu rhythm and alpha rhythm due to visual or motor action are also referred to as "desynchronization". Meanwhile, comparing with SQUIDs and electroencephalogram (EEG), MI sensor has higher spatial resolution. Therefore, MI sensor can investigate the "desynchronization" of spontaneous brain activity in detail. For auditory event related fields, there is a positive deflection with a latency about 120 ms obviously elicited by auditory stimuli. The polarity of deflections on the left and right temporal regions is opposite. The amplitudes of n100 signals decreases with the frequency of stimuli. Meanwhile, latency of all conditions is in the range from 80 ms to 120 ms. For visual event related fields, amplitudes of P300 component for all subjects in all task conditions are in a range of approximately 20 to 30 pT. The latency times of P300 component for all subjects in all 4 kinds of different diameter ratio conditions increase with the target/standard discrimination difficulty.

Finally, in chapter 7, we have summarized this study and discussed outlook and future challenges of MI sensor. In this study, we have developed a femto-tesla resolution MI sensor system for room temperature bio-magnetic sensing, and non-destructive Inspection. The noise level and resolution we achieved here is top level in the world. Meanwhile, the room temperature MCG and MEG measurements are dawn of hope for micromagnetic sensor. For future challenges, we would like to improve the structure and production process of MI element. Meanwhile, investigating noise superimposed on the induced voltage waveform in pickup coil, and developing a micro-MI sensor.

Furthermore, it’s necessary to demonstrate high frequency characteristics of MI sensor for high frequency applications more than 1 MHz. For bio-magnetic sensing, MI sensor is a highly sensitive, micro-size magnetic sensor with high spatial resolution, which is excepted for realizing high accuracy signal source estimation. In the next step, we would like to realize high accuracy signal source estimation by micro-MI sensor array. In addition, MI sensor is also expected to utilize in Magnetospinography (MSG) measurement, which is considered to be in high demand in the medical field. MI senor, which is expected to have flexibility in multi-channel placement unlike SQUID, can be expected to perform more accurate measurement by freely arranging it according to the subject's body.