Measurement of High-resolution Mechanical Contraction of Cardiac Muscle by Induced Eddy Current

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***Abstract*—There are many types of devices which help to manage a personal health conditions such as heartbeat chest belt, pedometer and smart watch. And the most common device has the relationship with heart rate or ECG data. However, users have to attach some electrode or fasten the belt on the bare skin to measure bio-signal information. Therefore, most of people want more convenient and short-ready-time and no-need to attach electrode. In this paper, we proposed the high-resolution measuring system of mechanical activity of cardiac muscle and thereby measure heartbeat.**

The principle of the proposed measuring method is that the alternating current generate alternating magnetic field around coil. This primary magnetic field induces eddy current which makes magnetic field against primary coil in the nearby objects. To measure high-resolution changes of the induced secondary magnetic fields, we used digital Phase-locked loop(PLL) circuit which provides more high-resolution traces of frequency changes than the previous studies based on digital frequency counter method.

As a result of our preliminary experiment, peak-peak intervals of the proposed method showed high correlation with R-R intervals of clinical ECG signals(*r*=0.9249). Also, from signal traces of the proposed method, we might make a conjecture that the contraction of atrium or ventricle is reflected by changing conductivity of cardiac muscle which is beating ceaselessly.

I. INTRODUCTION

In these days, cardiovascular diseases are common for those who live in modern life. Actually, according to the WHO's statistics the major reason of death of all around world is cardiovascular disease in 2011[1]. It is crucial point to live without illness to elevate quality of life. So that, there are a lot of devices to monitor health conditions with variety forms such as watches, belts, finger grips and insoles. U-health and Sports science system have grown gradually. And heart rate is the most useful information to manage our health for athletics and calorie estimation and so on [2]. However, a few people only used for the reason of that fact is for inconvenient to wear the device every day and some devices have to be attached on bare skin. It causes several problems such as skin irritation, hard to attach for all day, have to buy disposable accessories and so on. To solve these cumbersome problems, convenient and easier ways of measuring method are required.

In this paper, we proposed heart activity measuring system by measuring of mechanical movement of cardiac muscle without contact and consciousness. To measure the mechanical movement of cardiac muscle, we used time-varying magnetic field and detect the changes of inductance of virtual secondary coil which is caused by the induced eddy current in cardiac muscle. There are some related researches about this topic using magnetic field and eddy current [3-7]. However, those used frequency counter method showed low resolution of demodulated signals by inductance changes. The proposed method in this paper, we used digital phase-locked loop method, we could get more smoother, higher resolution demodulated signals caused by frequency changes.

II. PRINCIPLES

A. The Reflected Impedance by Alternating Magnetic Field

When AC current is applied to a coil, magnetic field $\vec{H}$ is generated and induces a magnetic flux ϕ_E. If a coil is placed adjacent to a living tissue which is considered as diamagnetic water [8]. Magnetic flux ϕ_E inside of a living tissue is also time-varying depending on the magnetic characteristics, especially electrical conductivity, of living tissues as in Fig.1.

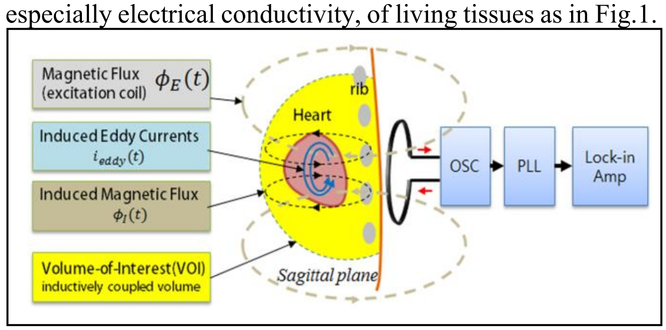

Figure 1. The principle of the proposed magnetic

B. Primary excitation Magnetic field

Any change in the magnetic field of the primary external coil will cause electromotive force (emf) in the body tissue by Faraday's Law of induction as in Eq. (1). In order to simulate this condition, we simulate the magnetic field near a living

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tissues as shown in Fig. 2 assuming 20 mA current at 1.8 MHz.

$$\nabla \times E = -\frac{\partial \mu H}{\partial t} \quad (1)$$

Fig. 2 shows the formation of magnetic flux ϕ_E density norm when a current is flowing along with simplified circular coil. In real implementation, the primary coil is configured as multi-turn coil and number of turns is 20.

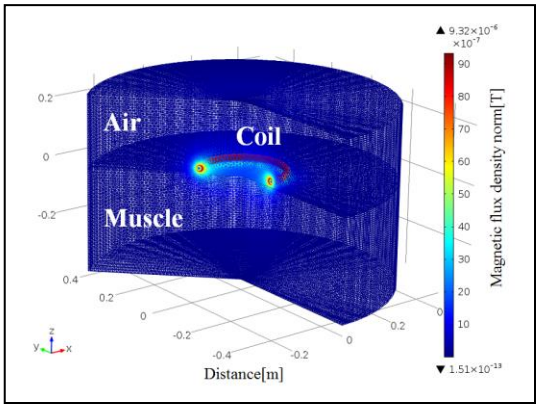

Figure 2. Simulated magnetic flux density of simplified primary coil near a living tissue

After the primary coil generates time-varying magnetic field by current, that induces eddy current i_{eddy} in the living tissue as in Fig. 3 and the amount of induced eddy current would depends on the conductivity of the living tissue as Eq. (2).

$$J_c = \sigma E \quad (2)$$

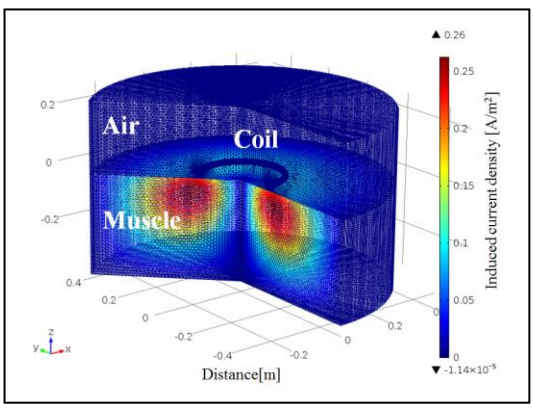

Figure 3. Induced current density in a living tissues by primary coil

C. Secondary Magnetic field

After the primary magnetic field generates electromotive force, it produces eddy current which producing secondary magnetic field against the direction of primary magnetic field as in Fig. 4. The eddy current would create a secondary flux ϕ_I . The strength of secondary magnetic field which is induced by the current is derived from Ampere's law as in Eq. (3).

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad (3)$$

So then, it affects the impedance of colpitts oscillator and the center frequency of oscillator is varied.

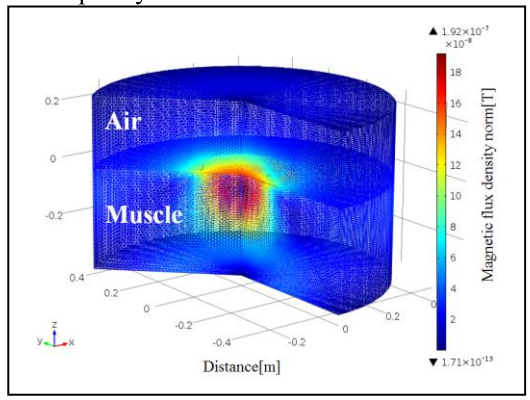

Figure 4. Magnetic flux density of multi-turn coil

With these principles, it can distinguish the material which is consisted of different electric characteristics. As the target is more conductive, more eddy current is generated and it is easy to detect. Fortunately, Cardiac muscle is the most conductive tissue in the body and the electric characteristics of body tissues considered in our simulation study are described in table 1 [9]. As heart is the most active part of thorax, almost change of thorax is considered as the contraction of heart.

The impedance of chest is magnetically coupled with inductor and reflected impedance affects the center frequency of oscillator and that is showed as peak signal [10]. What we have to note is that there is some time difference between R-peak of ECG and contraction of cardiac muscle [11]. After R-peak is generated, cardiac muscle starts to contraction. So that PLL output is shifted from the R-peak.

TABLE I. ELECTRIC CHARACTERISTICS OF BODY COMPONENTS

Body Component	Conductivity(σ) (S/m)	Permittivity(ε)	Permeability(μ)
Lung	*0.3*	*1000*	*1*
Skeletal Muscle	*0.3*	*900*	*1*
Cardiac Muscle	*0.8*	*1000*	*1*
Fat	*0.02*	*100*	*0.999*

III. IMPLEMENTATION OF MEASUREMENT SYSTEM

A. Colpitts Oscillator

We used colpitts oscillator to generate alternative current. Electrode which shapes like as planar coil is inserted on the L side in series. It seems like to be replaced original L component with summation of original L and inductive electrode.

B. Frequency Demodulation

To convert the frequency modulated output of the oscillator by the change of reflected impedance into analog amplitude signal, we used Phase-Locked Loop(PLL) instead of frequency counter. The most disadvantage of frequency counter is less sensitive, because it outputs the number of pulses per period. It means that we can't get the result of each pulse's variation. But, PLL outputs are reflected the phase difference at each pulse. It compares the difference between center-frequency which internally generated with external input frequency. Basic frequency counter diagram is described in Fig. 5 and basic PLL diagram in Fig. 6.

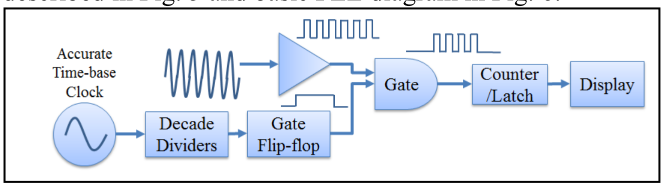

Figure 5. Basic frequency counter block diagram

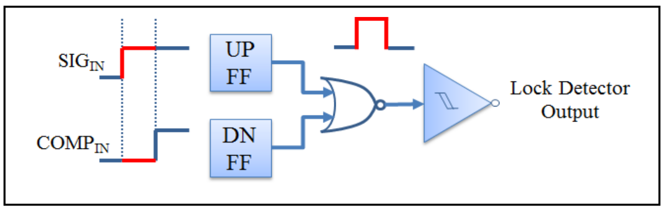

Figure 6. Basic concept of Phase Locked Loop

Fig. 7 describes the actual differences between PLL output and frequency counter output. For the PLL has a internal Voltage-Controlled Oscillator (VCO), it changes reference clock source according to the input clock. As frequency of input signal is decreasing, both outputs are decreasing also. When a period of frequency counter is 0.1 second, it changed 10 times per 1 sec. But, the PLL output is decreasing smoothly.

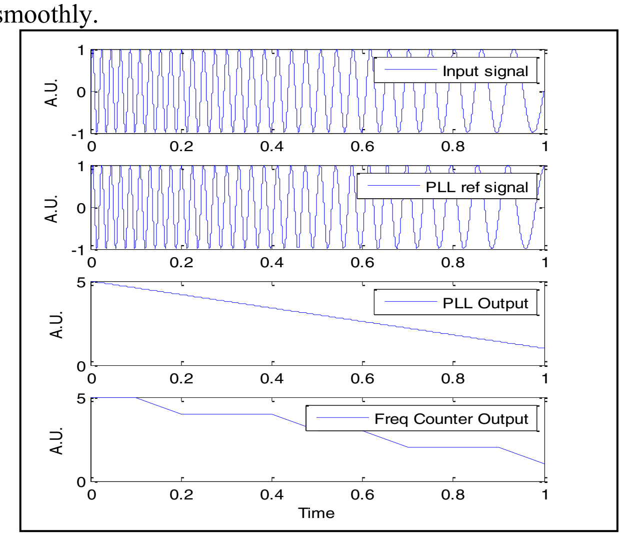

Figure 7. Comparison of resolution between PLL and frequency counter

C. Lock-in-Amp for end-processing

Lock-in amplifiers are used to detect and measure very small AC signal. But, in this application, we chopped the analog signal with reference clock source to convert DC to AC signal. The reference clock is configured as 10 kHz and it is generated by 555 timer. Block diagram of total system of Lock-in amplifier is described in Fig. 8.

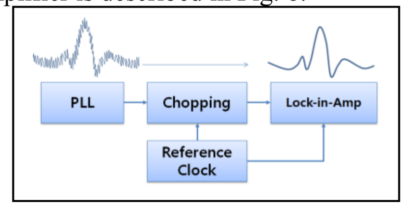

Figure 8. The function of Lock-in-Amplifier

We developed all system block for oscillation, PLL and Lock-in-Amp. Fig. 9 shows the hardware configuration.

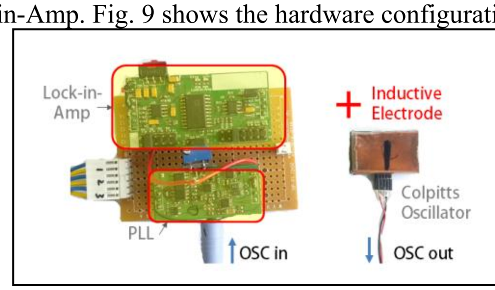

Figure 9. Hardware configuration of total system

IV. METHOD OF MEASUREMENT

Five subjects are healthy male and age is 25±5 yrs old. Textile electrode as a planar coil is placed on the subject's chest as shown in Fig. 10. The position is the center of the heart which is determined based on the X-ray film images of all subjects. Oscillator part is directly connected by textile coil electrode to reduce motion artifacts. It converts analog frequency signal to digital signal and transmits to the amplifier board. Data acquisition is performed with MP150(Biopac, USA) and wireless ECG module is used to get the reference heart beat signal. The protocol of experiment is sitting without any motion and with normal breathing for 20 seconds.

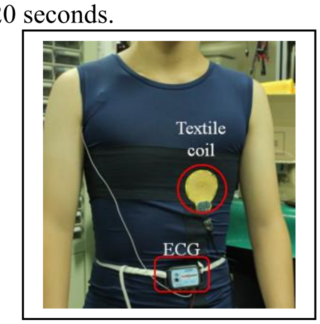

Figure 10. Placement of the textile coil electrode on front chest

V. RESULT

This system can measure the movement of heart and it has high resolution. Even though it contains other noise such as motion artifact and respiratory cycle, it can detect both of the effect of P-wave and R-wave. It means that PLL output represents not only contraction of ventricle as bigger positive peak but also contraction of atrium as smaller positive peak.

For cardiac muscle reacts after R-peak of ECG signal, the time of peak is different and PLL output shifted about 0.2 sec from the R-peak. This phenomenon is described well in Fig. 11. And the results for subject #1 and #2 are shown in Fig. 12 and Fig. 13.

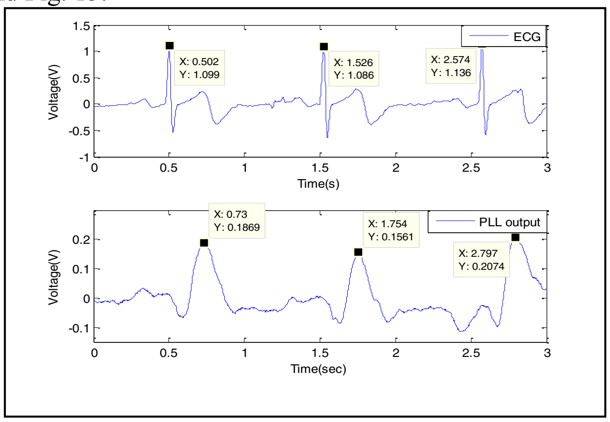

Figure 11. Comparison of peak time between ECG and PLL output

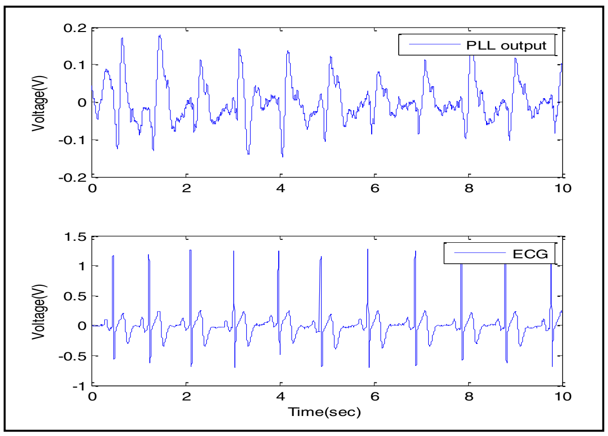

Figure 12. PLL output and ECG signal of subject #1

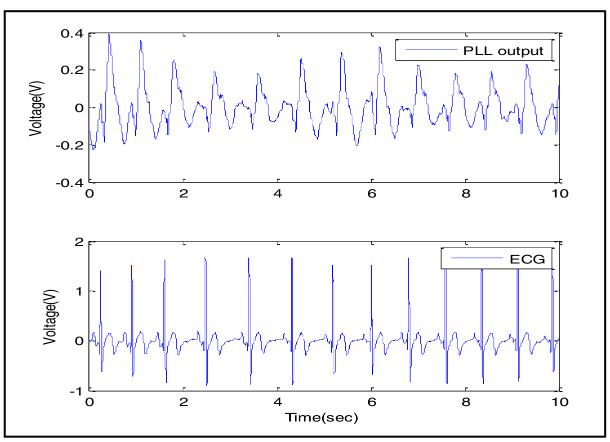

Figure 13. PLL output and ECG signal of subject #2

Feasibility is evaluated by the correlation between R-peak intervals and PLL output intervals. Result of interval time and correlation coefficient is described in table 2. This data is analyzed for 10 seconds and subjects are forced to be stable condition. Total correlation coefficient is 0.9249 and it is considered to deserve to be a representative signal for Heart rate analysis such like HRV.

TABLE II. CORRELATION OF ECG R-PEAKS INTERVAL AND PLL OUTPUT INTERVAL

# of subject	*R-peak interval mean(SD)[sec]*	*PLL out interval mean(SD)[sec]*	*Correlation(r)*
1	*0.8859(0.1100)*	*0.8667(0.1618)*	*0.9295*
2	*0.7548(0.0401)*	*0.7547(0.0439)*	*0.8405*
3	*0.5670(0.0152)*	*0.5679(0.0218)*	*0.9057*
4	*0.8017(0.0435)*	*0.8021(0.0442)*	*0.9523*
5	*0.7840(0.1069)*	*0.7822(0.1046)*	*0.9966*
Mean			***0.9249***

VI. CONCLUSION

This study has shown that we can measure the heart activity by principle of eddy current. Using PLL is more preferred than frequency counter for high resolution. This system can be applied to various applications. But, a limitations to this pilot study need to be acknowledged. The subject must be stabled and there was no electromagnetic interferer around it.

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