The performance improvement of conductivity sensor via primary field compensation

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Abstract. In this paper we propose novel magnetic sensor architecture to estimate the conductivity distribution of sample. However, the magnetic field received by the sensor coil would be impaired by primary field (excitation field). For the biologic tissues measurement, the ratio between the primary and secondary components can be up to 10000:1. This could reduce the sensitivity of measurement system substantially. For improving the sensitivity of measurements, the aligning coil and differential technique were applied together to eliminate the component of primary magnetic field which is coupled on the sensor coil. To evaluate the performance of noise on the differential alignment gradiometer, we have compared the noise component of differential alignment coil with other measurement coils. By the aligning coil and differential technique, the component of primary magnetic field could be eliminated largely. So, the proposed contactless conductivity sensor not only can improve the measurement sensitivity but also reduce the undesired interference. This technique can be use to estimate low conductivity material, such as biologic tissue. We hope this technique can applied to the analysis of biologic material further

1. Introduction
The noncontact impedance measurement is a magnetic induction technique which could estimate the conductivity distribution in a target object. In order to assess the impedance of object in contactless, the magnetic probe excites the magnetic field and measure the response field on the target object. The eddy current would be induced on the surface of target object by excitation field. The magnitude of induced eddy current varies with the properties of the test material, such as electrical conductivity ($\sigma$), geometric dimensions and magnetic permeability ($\mu$). The eddy current also could induce a secondary field which proportion to properties of the test material. Then we put the sensor coil above the test sample to receive the magnetic field. The sensor coil would couple both the primary and secondary magnetic field and result a potential on the coil winding. Eventually, we can estimate the conductivity by measuring the voltage resulting on the sensor coil.

The method which measures the impedance by magnetic induction has been known for decades. It was applied in the field of geophysical inspection, examining the concentration of sea water and the test of impurity ration in semiconductor[1-3]. In recent years, many researchers used magnetic method for biomedical purposes [4-6]. Because of no physical contact when measuring the conductivity, the
magnetic measurement system could remove the effect of time-varying, pressure-sensitive contact impedance[6]. Without the contact interface, the contactless impedance measurement could decrease the influence of environment variation. In addition to eliminating the skin-electrode interface, the contactless conductivity measurement has the following advantages in impedance measuring. 1) The electromagnetic field can probe into deep-lying tissues without damaging the superficial tissues, such as skin and bone. 2) Compared to other medical imaging methods, the impedance image is lower cost and no known harm to body. So it is suitable to apply in the long-term monitoring application.

For the above description, we know the magnetic method can measure the conductivity of sample by coupling field without contact. However, it still exist some difficulties in practice. The magnetic field received by the sensor coil is composed of primary field and secondary field. The primary field is directly coupled from the transmitter coil and the secondary field is created by the eddy current induced on the sample. In non-contact impedance measuring, the induced eddy current is proportional to the sample conductivity. So we have to extract the weak secondary magnetic field from very strong primary field. For the biologic tissues measurement, the ratio between the primary and secondary components can be up to $10^7$[7]. In order to extract the part of eddy current, the primary voltage must be removed from the measured signal.

In this study, we provide a primary field compensation technique for improving the sensitivity of conductivity measurement. The coil alignment and coaxial differential technique were applied together to eliminate the component of primary magnetic field which is coupled by the sensor coil. The sensor noise and drift performance of the proposed coil structure was examined.

2. Method

2.1. Theoretical Background
The goal of primary field compensation is to subtract the strong primary field and to enhance the weak secondary field from measured signal. The theoretical background of this paper will be described here briefly. In a linear isotropic nonmagnetic conductive medium, the electric field can be expressed as follows[8]:

$$\vec{E} = -j\omega \vec{A} - \nabla \phi$$

(1)

where $\omega$ is the radial frequency, $\vec{A}$ is the magnetic vector potential, and $\phi$ is scalar potential. In order to calculate the scalar potential distribution ($\phi$) in certain conductive body ($\Omega$), we require the following differential equation:

$$\nabla \cdot (\sigma \nabla \phi) = -\omega \vec{A}_p \cdot \nabla \sigma \quad \text{in} \quad \Omega$$

(2)

$$\frac{\partial \phi}{\partial n} = \omega A_{pn} \quad \text{on} \quad \partial \Omega$$

(3)

where $\sigma$ denotes conductivity and $A_{pn}$ is the normal component of the magnetic vector potential on the surface of conductive body. The flux $\Phi$ coupled in the detector coil can be determined by the current in the excitation coil and the induced current distribution in the conductive body. The flux $\Phi$ can be express as following:

$$\Phi = \frac{1}{I_R} \int \vec{A}_R \cdot \vec{J}_t \, dV_{\text{coil}} + \frac{1}{I_R} \int \vec{A}_R \cdot \vec{J}_i \, dV_{\text{body}}$$

(4)

where $\vec{A}_R$ is the magnetic vector potential created by the $I_R$ in the detector coil. Here, $\vec{J}_t$ is the current density in the excitation coil and $\vec{J}_i$ is the induced current density in the conductive body. The first term on the right-hand side of (4) is the primary flux directly coupled from the transmitter coil. The second term is created by the eddy current induced in the sample.

2.2. Primary field compensation
In many studies, the coaxial differential gradiometer has been applying to provide the basic primary field compensation [5;9;10]. Figure 1 illustrates the configuration of coaxial differential gradiometer. The differential gradiometer consist of two sensor coils placed below and above the excitation coil along the same axis. The sensor coils are connected with opposite winding directions for canceling the primary excitation field. The component of primary field in the sensor coil can be reduced largely by adjusting the distance between sensor coils and excitation coil. However, it is not possible to obtain complete primary field cancellation because of mismatch characteristics in both sensor coils. The residual primary field still remains on the sensor coil.

Alternative orientation configuration of coil is proposed to improve the primary field compensation [7;11-13]. The idea of orientation primary field canceling is achieved by aligning the sensor coil perpendicular to the primary excitation field such that no excitation flux cuts through the sensor coil. Figure 2 shows the sensor coil alignment for zero sensitivity to excitation field. The magnetic field produced by the excitation coil is normal to the secondary field produced by eddy current. The flux linkage of primary field can be minimized by exactly adjusting the direction of the sensor. This aligning coil configuration can be very simple to implement the primary field compensation and to yield a great sensitivity for conductivity perturbation. However, the aligning of sensor coil is easily sensitive to the interference from far RF source. The differential coil can eliminate the interference from far source efficiently. By combining the above two coil configurations, we can increase the sensitivity of receiver coil further. Figure 3 shows the newly differential and aligning coil structure. The new coil structure can improve the sensitivity substantially and apply to determine the small conductivity perturbation in biologic tissue.

![Figure 1. The configuration of coaxial differential gradiometer](attachment:image.png)
2.3. The Conductivity Sensor and Measurement System

As the above description, a conductivity sensor with differential and alignment structure is applied in this paper. This differential alignment sensor consists of three solenoidal coils, one excitation coil and two sensor coils. The excitation coil is fed by a constant current circuit which provides the sinusoidal current to generate the alternating field. The sensor coils would pick up the magnetic field perturbation. All the coils have the same ferrite rod cores which are 8 mm in diameter and 30 mm in length. The solenoid was wound 250 turns copper wire which is 0.08 mm in diameter. For canceling the strong primary field in differential configuration, both sensor coils are constructed with identical characteristics. The sensor coils one is 1.52 mH in induction and 16 in resistance and the other one is 1.516 mH in induction and 15.4 in resistance. The mismatch between the sensor coils is 0.26% in induction and 3.75% in resistance. The electrical characteristic of excitation coil is 0.2378 mH in induction and 1.07 in resistance. In order to allow large current flowing into the coil, excitation coils have fewer winding and larger wire gauge. Figure 4 illustrates the structure of the differential alignment conductivity sensor. Both differential coils are perpendicular to the excitation coil and placed below and above the excitation coil. The sensor coils have the same distance of 5 mm to the

Figure 2. The aligning coil for zero sensitivity to excitation field

Figure 3. The differential and aligning coil sensor
excitation coil. The excitation coil is fixed on the based broad with plastic screws which can be also use to adjust the alignment of coil. The alignment adjustment can be fulfilled by the angle of excitation coil by tuning the screws and checking the output voltage, repeatedly. This could reduce the mismatch of sensor coils and make the gradiometer achieve high sensitivity.

Figure 4. The structure of the differential alignment gradiometer

The characteristics of measurement coil are very easy affect by the environmental variation, such as thermal noise, power line interference, and mechanical vibration. In order to eliminate the noise, the lock-in amplifier is applied to exact the component of interesting frequency. The lock-in amplifier can be see as a narrow band-pass filter (as narrow as 1 mHz) around the reference signal frequency. The output of the sensor coil is connected to the input of lock-in amplifier for detecting the phase and amplitude of measuring signal. Eventually, we can estimate the conductivity on measuring sample.

3. Experimental Result

3.1. Sensor Sensitivity and Linearity

In order to evaluate the sensitivity and noise of the measurement system, the proposed coil was applied to measure the conductivity perturbation of phantoms. The phantoms are made by saline solution with known conductivities. In this experiment, a 30 x 40 mm square vessel with a depth of 20 mm is filled with saline solution of conductivity 1.38, 6.93, 8.6, 13.47 mS cm$^{-1}$. The sensitivity was calculated using the voltage measured from different phantoms relative to air background, when the phantom was placed at the same position as used in the conductivity measurements. The measurement and sensitivity in different saline solution are list in table 1. The linearity in the conductivity measurements with respect to the object conductivity is shown in Fig. 5. The linearity of the system is found as 7.2% full scale.

| Table 1 the sensitivity in different saline solution |
|-----------------------------------------------|
| Sensor Performance | Phantom 1 (1.38 mS cm$^{-1}$) | Phantom 2 (6.93 mS cm$^{-1}$) | Phantom 3 (8.6 mS cm$^{-1}$) | Phantom 4 (13.47 mS cm$^{-1}$) |
| Voltage (mV) | 0.877 | 4.113 | 5.834 | 11.21 |
| Sensitivity (mV/mS/cm) | 0.635 | 0.593 | 0.678 | 0.736 |
Figure 5. The linearity in the measurements with respect to the object conductivity

3.2. Sensor Noise

To evaluate the performance of noise on the differential alignment gradiometer, we have compared the noise component of differential alignment coil with other measurement coils. The trial sensors include the alignment coil and the differential alignment coil. Then, the noise and drift was estimated from each coil. The noise is obtained by acquiring 1000 measurements and calculating the standard deviation, as defined in (5). The drift was obtained by finding the maximum-minimum value from measurements.

\[
SD_{\text{noise}} = \frac{1}{n} \left( \sum_{i=1}^{n} (V_i - V_{\text{avg}})^2 \right)^{\frac{1}{2}}
\]

where \( n \) is the total number of samples in each frame, \( V_i \) is the \( i \)th voltage measurement value and \( V_{\text{avg}} \) is the averaged value from \( n \) measurements. The significant performance indexes, noise and drift, are listed in table 2.

| Sensor configuration         | Noise V (%) | Drift V (%) |
|-----------------------------|-------------|-------------|
| alignment coil              | 5.89x10^-4  | 2.36x10^-3  |
| differential alignment coil | 3.69x10^-4  | 1.58x10^-3  |
4. Conclusion

By the coil alignment and differential technique, the component of primary magnetic field which is coupled on the sensor coil could be eliminated largely. The table 1 shows that proposed sensor could distinguish very small conductivity perturbation. It is not feasible for differential coil or alignment coil. From table 2 we can find that applying differential configuration into alignment coil could reduce the noise and drift.

So, the proposed contactless conductivity sensor not only can improve the measurement sensitivity but also reduce the undesired interference. This technique can be use to estimate low conductivity material, such as biologic tissue. We hope this technique can applied to the analysis of biologic material further.

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