Magnetic Induction Sensing with a Gradiometer Coil and Measurement Circuit

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***Abstract*—This paper focuses on the development and experimental test of a coil gradiometer sensor and the measurement circuit. The coil gradiometer, which is characterized as simple, flexible and low-cost, consists of one excitation coil and two sensing coils which are symmetrically arranged. The differential configuration of the sensor enhances signal conditioning and suppresses common-mode interferences. The measurement circuit is based on AD8302, an integrated chip for gain and phase detection. To verify the sensitivity measurement range of the gradiometer for magnetic sensing, experiments were carried out for saline solution concentration of 0%-10% and metallic plate displacement. These preliminary experiments demonstrate that the proposed coil gradiometer sensor has wide-ranging applications as a non-contact and non-intrusive method.**

I. Introduction

Magnetic induction sensing is a non-contact and non-intrusive measurement method that has been widely applied in many fields, such as biomedical measurement [1], metal detection, and non-intrusive testing in industrial scenarios [2]. Magnetic induction sensing [3] refers to a non-intrusive technique that applies an electromagnetic field to excite the measurement object and then measures corresponding changes in the electromagnetic properties–conductivity, permittivity, and permeability. Typically, such kind of systems consists of transmitter and receiver that are both made up of a coil. A sinusoidal current is applied at the transmitter to excite an alternating magnetic field, which consequently induces the eddy current in the object. The induced signal is sensed by receiver coil that is capable of picking up small induced voltage.

Different methods have been investigated to achieve magnetic induction sensing. One category is modulation, specifically there are frequency modulation (FM) [4] and amplitude modulation (AM) [5]. These approaches work without receiving antenna and thus only need a single coil. For example, the coil can be used as a sensing component of a Colpitts oscillator with a self-oscillation frequency between 4 and 10 MHz. Another category uses separate coil for excitation and detection. A general challenge of this kind of methods is that the output signal has a large common-mode offset induced by primary magnetic B_0. The secondary magnetic ΔB is weak compared to B_0. Especially in biomedical applications, the $\|\Delta B/B_0\|$ is $\ll 1$ because the conductivity is usually smaller than 2 S/m [6]. The output signal need to be amplified and the offset signal need to be eliminated so as to improve signal-to-noise ratio (SNR).

In this paper, a gradiometer that consists of one planar excitation coil and two planar sensing coils is presented. Due to the symmetric configuration of the coil gradiometer, large common-mode offset and interferences can be suppressed while in the meantime, sensitivity be enhanced. The gain and phase detection circuit is also described. To verify its performance in magnetic sensing, experiments were conducted for low conductivity saline solution and high conductivity metallic plates.

II. Measurement Principle

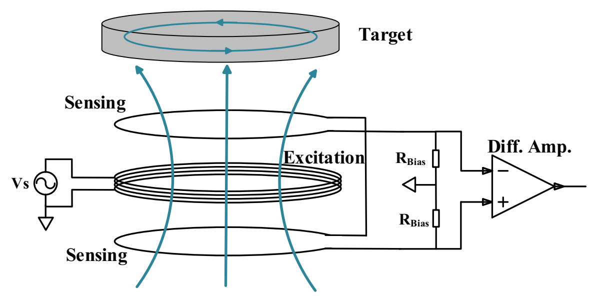


Fig. 1. The basic principle of the coil gradiometer measurement

In Fig. 1, two identical sensing coils are placed at equal distance from the excitation coil symmetrically. The excitation coil generates a primary magnetic field with an alternating excitation current. Inducing by the alternating magnetic field, eddy current occurs at the measurement target. Therefore, it would produce a secondary magnetic field which consequently leads to electromotive force in the sensing coils. To eliminate common-mode signal, two sensing coils are connected in anti-phase. With this configuration, the difference of the induced voltage in two sensing coils can be detected.

A quasi-static approximation can be derived [1]

$$\frac{\Delta V}{V} = Pf\mu_0(2\pi f\epsilon_0\epsilon_r - j\sigma) + Q\chi \tag{1}$$

where V and ΔV are the voltage induced by primary magnetic and secondary magnetic, respectively. σ,ϵ_r and χ are the electrical conductivity, relative permittivity and magnetic susceptibility of the sample, ϵ_0 and μ_0 are the permittivity and permeability of free space, f is the frequency of excitation and P and Q are geometrical factors that depend on the size and shape of the sample and its position relative to the two coils.

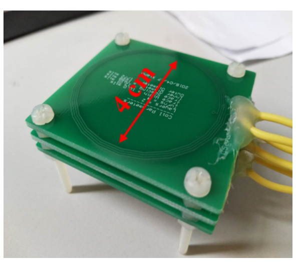
III. System Design

A. Gradiometer Coil Sensor

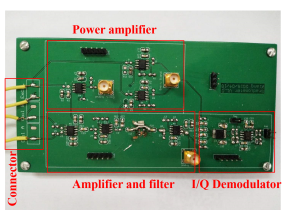
For magnetic induction sensing, different kinds of coils have been considered, including ferrite-core coil, air-core coil, and gradiometers [7]. Due to the non-linear characteristics over the megahertz range, ferrite core coils are usually unsuited for high-frequency usages.

The inductance and resonance frequency of the coil are two significant parameters. More turns of the coil have larger inductance and generate a stronger magnetic field, which can improve measurement sensitivity. However, larger inductance, in parallel with the parasitic capacitance, resonates at a lower frequency. Therefore, there is a compromise between the operation frequency and inductance value.

In this work, we use planar coil without ferrite (Fig. 2a). The coil has 8 turns with a trace width of 10 mils and a spacing width of 10 mils between adjacent traces. The average of the inner diameter and the outer diameter is 4 cm. The inductance of each coil is around 6 μH at low frequency and the parasitic capacitance is around 1 pF. The coil resonates at 32.2 MHz measured with an impedance analyzer (Keysight E4990A). The sensing coil and excitation coil are of the same design. They are placed 2.5 mm apart with plastic screws and nuts. Gaskets are used to adjust the spacing between coils slightly so as to eliminate the offset voltage. Printed circuit board (PCB) technology was used to fabricate the proposed coils in low-cost and simple manner.



(a) Gradiometer



(b) Measurement circuit

Fig. 2. Gradiometer and measurement circuit

B. Measurement Circuit

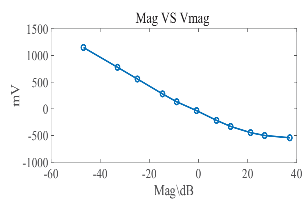
A signal generator (Tektronix AFG 3022B) is used to provide excitation signal source. To amplify the power of source signal, two current-feedback amplifier THS3091 (Texas Instruments) are configured in parallel to augment the drive current. THS3091 is well suited for gradiometer power amplifier because it has wide bandwidth up to 210 MHz (G=2) and can drive maximum 250 mA current.

An instrument amplifier AD8421 is used to differentially amplify the receiver signal. Two grounded resistors are connected at the non-inverting and inverting input pins to provide an appropriate bias current for the amplifier. They also create a closed loop for the induced current in sensing coils. Later, amplification with OPA842 enlarges the differential signal for gain and phase detection with AD8302. It is an integrated chip which ranges from low frequencies up to 2.7 GHz. The phase and gain output voltages are available simultaneously in the range of 0 V to 1.8 V.

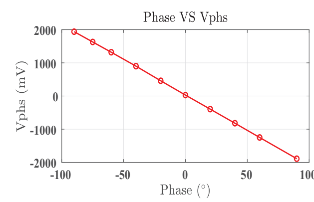
IV. Experimental Results

A. Characteristics of Measurement Circuit

To characterize and calibrate the measurement circuit, a 10-MHz sinusoidal signal was applied to the differential input of the circuit. Another channel of AD8302 required 10-MHz sinusoidal from the same signal generator (Tektronix AFG 3022B). The amplitude and the phase of two channel signals are adjusted to cover the gain and phase shift range of the AD8302, specifically, from -46.8 dB to 37.16 dB for gain measurement and from -75 ° to 90 ° for phase measurement. The output pins V_{mag} and V_{phs} are measured directly with USB-6003 (National Instruments). The test results are shown in Fig. 3.



(a) Magnitude charateristic



(b) Phase charateristic

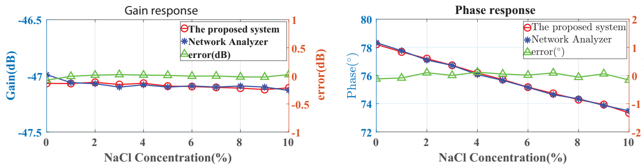
Fig. 3. Gain and phase detection characteristics

It is demonstrated that linear range of gain measurement is about -45dB$\sim$+20dB (Fig. 3a). The large gain region (over 20 dB) shows some nonlinearity because the signal amplitude might exceed the input range of AD8302. In the linear region, the sensitivity is 26mv/dB. For phase detection (Fig. 3b), the measurement range is +90° $\sim$ 90° and the sensitivity is 20mV/degree.

B. Saline Solution Concentration Experiments

The saline solution experiment was conducted to test the measurement performance of gradiometer for low conductivity objects. Solution conductivity measurement can be used not only to measure the solution itself but also has important applications in low conductivity materials, such as biological tissue, fruits maturity, food testing and other similar electrical properties. In this experiment, sodium chloride solution with 0% $\sim$ 10% massed fraction concentration was used as the test object.

In the experimental set-up, the excitation signal was set at 2.5 V_{pp} and 10 MHz (smaller than the resonance frequency). The NaCl solution in plastic bottles with 50 ml was placed closely on top of the sensing coil. The bottom of the plastic bottom is 1.5 mm. When the experiment was conducted, the ambient temperature is 25 $°C$. As a reference and validation,



(a) Magnitude charateristic (b) Phase charateristic

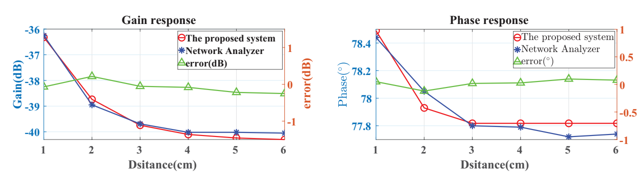
Fig. 4. NaCl concentration Measurement

network analyzer (HP 8752C) was used to measure the gradiometer responses.

The result of the solution concentration measurement with the coil gradiometer is shown in Fig. 4. The proposed circuit system, which has been calibrated in section IV-A, agrees well with network analyzer in gain and phase measurement. The maximum gain error is 0.02 dB and the maximum phase error is 0.16°. The phase and gain are monotonous with the saline concentration. In the whole measurement range from 0% to 10%, the amount of phase shift is 4.87° whereas the amount of gain change is negligible. This confirms that phase shift is the dominant information caused by conductivity perturbation because the imaginary part $Im(\Delta B/B)$ is more sensitive than the real part $Re(\Delta B/B)$ for conductivity. This result agrees with [8].

C. Metallic Plate Displacement Experiments

The metallic experiment was carried out to demonstrate the measurement performance of gradiometer for high conductivity objects (typically $> 10^6 S/m$). In this experiment, a 6 cm square copper plate was used as the target object, which is placed at the front of the gradiometer. The copper plate was moved along the coaxial direction of the coil to study the displacement response of gradiometer. The displacement is tested from 1 cm to 6 cm in steps of 1 cm. In this experiment, the excitation frequency is set at 10 MHz. The network analyzer is also used to measure the gradiometer responses.



(a) Magnitude charateristic (b) Phase charateristic

Fig. 5. Displacement Measurement

Fig. 5 displays the displacement response for a copper plate. In this experiment, the proposed circuit agrees well with the network analyzer, with the maximum gain error of 0.25 dB and maximum phase error of 0.12°.The phase decreases from -36.25 dB (at 1 cm) to -40.05 dB (at 6 cm). In comparison, the phase sensitivity is within 4 cm. The amount of the gain change is more obvious than the phase shift. The reason is that for high conductivity objects, the complex perturbation signal would mainly be a negative real quantity due to the skin effect. Therefore, the experimental results are in accordance with theoretical explanation.

In previous reported coil-based sensors, it is typical to reach 50 % of the coil diameter measurement. Some researchers reported one diameter measurement range [9]. However, in our work, the coil gradiometer was capable of sensing the metallic plate up to 6 cm, which is 1.5 times the coil diameter. This could be explained that compared to coil-based methods with only one or two sensors which detect the output voltage as the summation of the primary magnetic field and perturbation secondary field, the differential configuration of the coil gradiometer suppresses common-mode signal and enhances the measurement range greatly.

V. Conclusion

A coil gradiometer with one excitation and two symmetrically allocated sensing coils was present. To detect the induced signal, the measurement circuit based on the AD8302 was also described. The proposed gradiometer sensor has flexibility in canceling the common-mode signal, primarily generated by the excitation coil which can enhance the sensitivity of the sensor. Experimental results demonstrated that the coil gradiometer has good performance in saline solution concentration measurement and metallic plate distance measurement. Gradiometer can be used as an efficient magnetic sensing method for wide-ranging applications. These two preliminary experiments verify the feasibility of using gradiometer as a non-contact and non-intrusive method for low conductivity objects like biomedical tissues or high conductivity objects like metal detection.

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