SNR enhancement for the second harmonics in fluxgate sensor

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Abstract. The fluxgate sensor uses the nonlinear characteristics of soft magnetic materials to measure the geostationary magnetic field, which has the characteristics of high sensitivity, wide magnetic measurement range and easy portability, and is widely used in geological exploration, navigation, space technology and other fields. In this paper, the research is based on the second harmonic method of the development of fluxgate sensor, since the second harmonic contains static magnetic field direction and amplitude information, so the second harmonic signal-to-noise ratio enhancement can effectively improve the resolution of the fluxgate sensor. In this paper, the induction signal is first resonated to the second harmonic frequency using a resonant circuit, and then filtered after an amplification circuit, the second harmonic signal-to-noise ratio is significantly enhanced by 13 times.

1. Introduction
The earth system is composed of different circles, and each component generates geomagnetic field due to internal movement, which carries information about the process of different parts of the earth system, and these information are important data for understanding the earth system and mineral resources, so geomagnetic field measurement results play an important role in basic research of earth science and practical engineering applications\cite{1}. Fluxgate sensors, due to their high resolution, large dynamic range, low power consumption, low noise, small size and other characteristics, are suitable for different slow-changing magnetic field measurement environments, such as vector detection of weak magnetic field in space, geological exploration, satellite magnetometry and other fields, especially in the field of address exploration\cite{2-3}. Fluxgate sensors can assist exploration equipment to identify the orientation, and meanwhile obtain the magnetic field distribution of the surrounding environment, through geophysical theoretical analysis to obtain mineral resource distribution.

The fluxgate sensor is a magnetometer developed by using the magnetic saturation characteristics of high permeability, low coercivity soft magnetic material. As the measured magnetic field is a slowly changing magnetic field, the core needs to work periodically in the saturation state under the alternating excitation magnetic field, and the even harmonics in the induced voltage contain the measured magnetic field information\cite{4}. The second harmonic amplitude is the largest among the even harmonics, so the static magnetic field can be measured by extracting and analyzing the second harmonic. Since the second harmonic characterizes the measured magnetic field information, the signal-to-noise ratio of the second harmonic directly affects the measurement resolution. However, due to the incomplete elimination of odd harmonics caused by the excitation magnetic field and the presence of Buckhausen noise in the magnetic core, the SNR of the second harmonic is reduced, resulting in a decrease in resolution. When the induction signal is weak, the noise near the second harmonic frequency cannot be completely eliminated by the filter circuit alone; the digital signal
processed by the algorithm may be superimposed with thermal noise and the noise of the circuit itself after the amplification circuit[5]. In this paper, designed a resonant circuit directly connected to the coil, analyzing the inductance and capacitance parameters in the induction coil equivalent circuit, adjusting the capacitance value in the resonant circuit according to the actual equivalent parameters of the coil, setting the resonant frequency of the circuit to the second harmonic frequency, and then filtering out the high frequency noise after the signal passes through the amplifier circuit. By establishing the mathematical model of the fluxgate sensor and the equivalent circuit of the induction coil of the probe, analyzing the characteristics of the induction signal in theory. The circuit designed in this paper which can significantly improve the second harmonic signal-to-noise ratio is verified by simulation and experiment.

2. Mathematical model of fluxgate sensor

The fluxgate sensor probes are composed of a core, an excitation coil and an induction coil. The core often made of permalloy with high permeability and low coercivity. The excitation coil generates an alternating excitation magnetic field and the induction coil senses an induced voltage in relation to the measured magnetic field according to Faraday's law of electromagnetic induction[6].

![Fluxgate sensor structure of dual core](image)

Figure 1. Fluxgate sensor structure of dual core

Fluxgate sensor structure of dual core as shown in figure 1. The external magnetic field is $E$. The permeability of the two magnetic cores is respectively $\mu_1$ and $\mu_2$. The excitation coils on the two cores are in inverse series connection. The direction of the excitation magnetic field on each core is opposite at all times. The external magnetic field has the same axial component in the two parallel cores. The strength of the magnetic field on the two cores is shown in equation (1).

$$
\begin{align*}
B_1 &= \mu_1(H_0 + H_m \cos \omega t) \\
B_2 &= \mu_2(H_0 - H_m \cos \omega t)
\end{align*}
$$

(1)

When the excitation magnetic field strength $H_m$ is greater than the core saturation magnetic field strength $H_s$, the permeability is an even function that varies with time, and the frequency is twice the frequency of the excitation signal[7]. The number of turns of the induction coil is $W$. The equivalent area of induction coil is $S$. Induction voltage and permeability function can be expressed as equation (2).

$$
\begin{align*}
E(t) &= -WS \frac{d(B_1 + B_2)}{dt} \\
\mu(t) &= \mu_d + \sum_{i=1}^{\infty} \mu_i \cos 2i\omega t
\end{align*}
$$

(2)

When dimensions and permeability of the two cores are exactly equal, the induced potential generated by the excitation field in the induction coil eliminates each other. The induced voltage contains only the even harmonic component, as shown in equation (3).
\[ E(t) = -W S \frac{d(B_1 + B_2)}{dt} = 2\omega W S H_0 \sum_{i=1}^{\infty} \mu_i \sin 2\omega t \]  

(3)

Since the two cores cannot be made identical in reality, the core permeability is different in reality [8]. The actual induced voltage contains odd harmonics generated by the excitation magnetic field[9]. Therefore, a resonant circuit is designed in this paper to resonate the induced signal to the second harmonic frequency as much as possible, and to eliminate the high frequency signal through lowpass filtering to enhance SNR of the second harmonic.

### 3. Resonant circuit design

Due to the inability to achieve identical core permeability, and the presence of Bachhausen noise[10]. In this paper, a resonant circuit is designed to pick up the second harmonic component of the induced signal to the maximum extent, ensuring that the amplification circuit maintains the accuracy of the signal without affecting the resolution of the fluxgate sensor.

#### 3.1. Principle of circuit

The inductor coil of the fluxgate sensor is essentially a wire-wound inductor, and its output impedance is mainly inductive[11]. Therefore, the equivalent shunt capacitor is placed in front of the differential amplification circuit to form a resonant network.

![Resonant network equivalence model](image)

Using a single axis as an example, the equivalent model of the resonant network is shown in figure 2. The capacitance between turns and cable bypass capacitance is \( C_0 \). It is negligibly compared to the external resonant capacitance \( C_r \). \( R_{e1} \) and \( R_{e2} \) are the matching resistors of the resonant network, used for impedance matching of the amplifier circuit to guarantee that no self-excited oscillation will occur. Adjusting \( C_r \) so that the resonant frequency is \( 2\omega \). The signal is amplified by op-amp differential amplification, and then the high frequency signal is eliminated by first-order filtering to enhance the second harmonic signal-to-noise ratio.

![Resonant network equivalence model](image)

#### 3.2. Analysis of circuit condition

First measuring the equivalent inductance \( L_s \) and resistance \( R_s \) of the induction coil. The bypass capacitor \( C_0 \) can be ignored for its small value. The resonant frequency is set to \( 2\omega \), and the resonant capacitance can be calculated from the series resonant circuit formula, as shown in the equation (4).

\[ C_r = \frac{1}{(2\omega)^2 L_s} \]  

(4)

Since differential amplification has a large common mode rejection ratio, most of the noise in the circuit is common-mode signal. The differential amplification circuit can greatly reduce the interference of noise caused in circuit[12]. After that resonant signal is amplified by differential
amplification of the op-amp chip, which can effectively amplify the second harmonic signal. The gain $G$ is selected according to the reference voltage of the ADC chip in the circuit. The amplification gain is calculated as shown in equation (5).

$$G = \frac{R_{e3} + R_{e4}}{R_{e5}} + 1$$  \hspace{1cm} (5)

After resonance and differential amplification, the induction signal $E'(t)$ still contains a small amount of high frequency even harmonic component. The high frequency signal will reduce SNR of the second harmonic and also cause waveform distortion[13]. It will lead to changes in the position of the sampling point of the ADC chip. There is a bias between the processed signal and the true magnetic field value. It makes resolution decrease of the fluxgate sensor. Therefore, a first-order passive low-pass filter is needed to filter out high-frequency signals. The cutoff frequency $\omega_c$ is set as $4\omega$, calculated as shown in equation (6).

$$\omega_c = \frac{1}{\pi(R_{e6} + R_{e7})C_1}$$  \hspace{1cm} (6)

After calculating the resonant equivalent capacitance $C_e$ according to equation (4), the resonant equivalent circuit was designed as shown in figure 3. Since there are deviations between the different probes of the fluxgate sensor. $C_{e1}$, $C_{e2}$, $C_{e3}$, $C_{e4}$ capacitors are used instead of resonant capacitance. $C_{e5}$, $C_{e6}$ capacitors are the coupling capacitance which can eliminate the DC component of the signal and change the phase of the second harmonic signal. It helps the ADC chip to accurately acquire the peaks of the second harmonic and makes the magnetic field measurement results more accurate. The equivalent resonant capacitance of the circuit can be calculated by equation (7).

$$C_{equat} = \frac{C_{e1}C_{e2}}{C_{e1} + C_{e2}} + C_{e3} + C_{e4}$$  \hspace{1cm} (7)

4. Simulation and experimental results

The resonant circuit designed in this paper can improve SNR of the second harmonic in principle. However, it needs to be verified experimentally that the resonant circuit can improve SNR of the second harmonic, and make the quantitative analysis of the SNR enhancement effect in the time domain and frequency domain. In this section, the feasibility of the designed resonant circuit is verified by simulation and experiment respectively, and the inductor coil parameters of the probe are measured parameters, $L_s = 3.2mH, R_s = 75.4\Omega$. And excitation frequency $f$ is 19.2kHz.

4.1. Simulation results

The designed resonant circuit is simulated by TINA-TI software. The simulation circuit includes a resonant circuit and a filter amplifier circuit. The resonant capacitance of the simulated circuit is calculated according to equation (4) and equation (7). The coil parameters in the simulated circuit are measured parameters. The simulated input signal imitates the actual induced voltage signal. The
second harmonic signal has the largest amplitude and also contains other even harmonics and high frequency even harmonics.

![Graph of frequency response of resonant circuit](image)

**Figure 4. Frequency response of resonant circuit**

The frequency response of resonant circuit in simulation is shown in figure 4. The resonant frequency is $2f$ by using the calculated resonant capacitance value, and the second harmonic frequency is also $2f$. And there is only a small phase delay at frequency $2f$. The simulation results show that the designed resonant circuit can maintain the maximum gain at the second harmonic frequency and there is almost no phase hysteresis at the $2f$ frequency. The resonant circuit also ensure the sampling accuracy of the ADC chip.

### 4.2. Experimental results

The open-loop fluxgate sensor was used for the experiment. The probe was placed in a shielded barrel to avoid introducing noise from external magnetic fields into the circuit. In this shielded barrel only the excitation field and the given magnetic field are present in the probe.

![Graphs of experimental results](image)

**Figure 5. Resonant circuit input and output signal comparison**

(a) induction voltage signal $E$
(b) induction signal $E'$ after resonance and amplification
(c) $E$ analysis in frequency domain
(d) $E'$ analysis in frequency domain
The resonant circuit’s input and output signal comparison is shown in figure 5. It shows that the input signal of the circuit contains noise and the noise of the output signal after the resonant circuit is effectively filtered out. By analysing the signal in the frequency domain, the resonant circuit can enhance SNR of the second harmonic by 13 times.

5. Conclusion
Magnetic fluxgate sensor obtains magnetic field data by extracting the second harmonic component of the induction signal. Therefore, the SNR enhancement of the second harmonic can improve the resolution of fluxgate sensor. This paper establishes the mathematical model of the magnetic fluxgate sensor and analyses the feasibility of the designed resonant circuit in principle. Simulation and experimental data show that this resonant circuit can works and improve the second harmonic signal-to-noise ratio by 13 times, and resolution of the fluxgate sensor is effectively improved.

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