Optimization and design of wide-band and low-noise air-core coil sensor for TEM system

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Abstract. The effective bandwidth and background noise of the sensor are important factors to the performance of TEM, especially in the detection of urban underground space. The limitation of the size of coils further reduces the bandwidth and sensitivity of the sensor, resulting in the distortion of high-frequency signal from ultra-shallow and the loss of weak signal from deep. In order to solve this problem, by establishing the physical model of the induction air-core coil sensor, a method of winding wire which reduces the parasitic parameters of the air-core coil is proposed to improve the bandwidth and sensitivity of system. Combined with theoretical simulation, the components of noise and parasitic parameters of the air-core coil sensor were analyzed, and the system was optimized. An air-core coil sensor with an effective bandwidth of 783 kHz and an equivalent noise of about $2.45 \mu V/\sqrt{Hz}$ was obtained. The new sensor effectively improves the detection capability of TEM system for high-frequency secondary field signal, which has positive significance for the application of TEM in urban underground space.

1. Introduction

Transient electromagnetic method is a geophysical exploration method based on the law of electromagnetic induction, it is currently widely used in geological structure surveys and mineral resource exploration [6]. With the scale of urban construction land continues to expand and land resources decrease sharply, the development of urban underground space has become the future direction of land utilization. The use of transient electromagnetic method to investigate the condition of underground space on urban grounds can provide a foundation for the development and utilization of urban underground space.

For transient electromagnetic method, bandwidth includes the frequency characteristics of both magnetic sensors and hardware systems. Non-tuned air-core coil sensors are widely used in transient electromagnetic method [1], the inductive air-core coil sensors that mainly currently used for TEM include: MTEM-AL developed by Phoenix Corporation of Canada, which is use in Ground transient electromagnetic detection, and the wide-band aviation electromagnetic coil produced by Aeroquest Corporation of Canada. Lin et al. have studied deeply on the theoretical model of the air-core coil sensor and the source of noise, based on that, the receiving coil with a bandwidth of 71 kHz has been developed, which can be used for the helicopter time domain electromagnetic method [4]. Lin et al. found the law of sensor noise source changing with frequency and designed a low-noise electromagnetic sensor that can be applied to grounded electrical source air-ground transient electromagnetic detection [3]. The mentioned coil sensors are respectively applied to different electromagnetic methods, yet all have the defects of large coil volume and narrow bandwidth, which
cannot meet the needs of transient electromagnetic systems for urban shallow formation. Therefore, it is of great significance to develop a sensor with a small size, a wide bandwidth, and a high signal-to-noise ratio.

The urban shallow underground space is a place with dense and extensive human activities. The application of the transient electromagnetic method could assess and verify the underground geological structure of the city first. However, the transient electromagnetic secondary signal field has a large dynamic range, also the early signal has a high frequency. Therefore, it is required that the effective bandwidth of the receiving sensor should reach 200 kHz at least and the signal-to-noise ratio should be enhanced as much as possible.

2. Structure and equivalent model of air-core coil sensor

2.1. Structure of air-core coil sensor

The frame of the air-core coil is made of strong nylon material, which is non-magnetic, light and easy to process. In order to reduce the common-mode noise, differential winding with middle tap is adopted, which is divided into two sections in structure, as shown in Figure 1.

![Figure 1. Structure of differential air-core coil](image1)

![Figure 2. Equivalent circuit of air-core coil](image2)

2.2. Equivalent circuit model of air-core coil sensor

The equivalent circuit model of air-core coil sensor is shown in Figure 2. In this figure, R is the equivalent internal resistance of air-core coil. L is the equivalent distributed inductance of the coil; C is the equivalent distributed capacitance of the coil; \( R_m \) is matching resistance; \( U_i \) is the voltage generated by the electromagnetic field and \( U_0 \) is the voltage passing the equivalent RLC network of coil.

The internal resistance of the air-core coil can be calculated by the following formula:

\[
R = \rho \frac{l}{S} = 4\rho n D \frac{d_0^2}{S}
\]  

where \( \rho \) is the resistivity of the wire used, \( D \) is the average diameter of coil, \( n \) is the number of turns in coil, and \( d_0 \) is the diameter of the inner core of the wire used.

The inductance of the coil itself determines the resonant frequency [8]. The smaller the inductance, the larger the resonant frequency [2]. The inductance of the air-core coil can be calculated by the formula:

\[
L = \frac{2\pi N D n^2}{l} \left[0.088 \pi D - 0.713 h \right] \times 10^{-7}
\]

where \( l \) is the width of the single-segment coil, \( h \) is the laminated thickness of the coil, and \( N \) is the number of segments of the coil.
The resonant frequency of the air-core coil is negatively correlated with the distributed capacitance [7]. The distributed capacitance of the coil can be divided into the inter-layer distributed capacitance and the inter-segment distributed capacitance. The empirical formula of the distributed capacitance of the coil is as follows:

$$C = C_a + C_\delta = \frac{4D\pi\varepsilon_0\varepsilon\delta}{3\varepsilon N^2}(N_i - 1) + \frac{\varepsilon_0\varepsilon\pi}{16\varepsilon}(2D + \delta(N_i - 1)(N_i - 1)\delta)$$

(3)

where $N_i$ is the number of tiers, $\varepsilon_0$ is the dielectric constant of air, $\varepsilon_\pi$ is the relative dielectric constant of poly tetra fluoroethylene (PTFE), and $\delta$ is the distance between layers.

2.3. Parameter design of air-core coil

The air-core coil sensor receives the secondary magnetic field generated by eddy current attenuation on the geological body. Based on the law of electromagnetic induction, the induced voltage will be generated when the magnetic flux through the coil changes:

$$V_\delta = -n \cdot \frac{d\Phi(t)}{dt} = -n \cdot S_0 \cdot \frac{dB}{dt} = -n \cdot \frac{\pi}{4} \cdot D^2 \cdot \frac{dB}{dt}$$

(4)

where $\mu_0$ is the vacuum permeability, $S_0$ is the area of the single-turn coil, $B$ is the magnetic induction intensity of the secondary field passing through the air-core coil, and $\Phi$ is the magnetic flux of a single-turn coil.

The capacitance and inductance of the coil is affected by the way of winding wire, and the tightness of the coil also affects the parasitic parameters. In the equivalent circuit model of the air-core coil, the capacitance and inductance determine the range of pass-band frequency. Considering the height and size of the coil, the differential coil is divided into two sections and four layers to minimize the distributed capacitance and increase the resonant frequency. The noise of the coil itself is mainly the thermal noise generated by the resistance. In the equivalent model of shown in Figure 1, the thermal noise of the resistance is:

$$V_\delta = \sqrt{4 \cdot k_b \cdot T \cdot R} = \sqrt{4 \cdot k_b \cdot T \cdot \rho \cdot \frac{n \cdot \pi \cdot D}{\pi \left(\frac{d_\delta}{2}\right)^2}} = \frac{4\sqrt{k_b \cdot T \cdot \rho \cdot n \cdot D}}{d_\delta}$$

(5)

where $k_b$ is boltzmann constant, whose value is $1.38 \times 10^{-23} \text{ W} \cdot \text{s}/\text{K}$, $T$ is Kelvin temperature, whose unit is K.

The SNR of the coil can be calculated:

$$\text{SNR} = \frac{V_\delta}{V_n} = -\frac{n}{16} \cdot \frac{d_\omega}{\sqrt{k_b \cdot T \cdot \rho}} \cdot \sqrt{n \cdot D^2} \cdot \frac{dB}{dt}$$

(6)

Assuming that the induced voltage per square meter on the coil is 10nV, the relationship between SNR and the number of turns and the diameter D of the coil can be obtained, as shown in Figure 3. The resistivity of the wire was determined at room temperature (20 °C / 293.15k). When the diameter and winding method were determined, the SNR of the coil was only related to the number of turns and the diameter of the coil.
The resonant frequency of the air-core coil sensor is calculated from

\[
\frac{1}{f_0} = 2\pi \sqrt{LC}
\]  

(7)

Combined with the empirical formula of the inductance and the distributed capacitance, the relationship between the resonant frequency and the number of turns and the mean diameter of the coil can be obtained, as shown in Figure 4.

It is required that the SNR of the coil should not be lower than 20, and the bandwidth should be wider. In order to make sure that the 3 dB bandwidth of the air-core coil is wider than 200 KHz after matching resistance is added, the resonant frequency of the coil should be higher than 1 MHz. The new coil was designed according to the requirements above. The average diameter of the hollow coil was 0.2 m and the number of turns was 32. The inductance value was 480.6 μH, which measured by the Victory’s VC4080 LCR digital bridge. The distributed capacitance was 35.5 pF, and the resonant frequency of the air-core coil was 1.219 MHz. The simulation results were 1.261 MHz and the relative error was 3.4%, which were roughly the same as those calculated by the formula.

3. Noise analysis and optimization of differential coil sensor

3.1. Equivalent noise model of circuit

Due to the limitation of the size and the number of turns, the induced signal is weak, which need to be amplified. According to the difference structure of air-core coil, three operational amplifiers are used to form the amplifier structure for instrument. The equivalent noise model of the coil sensor is shown in Figure 5.
The instrument amplifier is divided into two parts, where the first amplifier uses two in-phase amplifiers and the second amplifier uses a differential amplifier. Because the two equivalent models of semi-coil and the amplifiers are symmetrical, the total noise of the sensor can be obtained by power superposition.

3.2. Noise analysis of coil sensor
The voltage noise of operational amplifier includes 1/f noise and white noise. The equivalent noise at the non-inverting input of the operational amplifier is

$$|e_{n0}|^2 = |e_n|^2$$

where $e_n$ is the input voltage noise of the operational amplifier.

The equivalent noise of the thermal noise of the internal resistance of the semi-coil at the non-inverting input of the operational amplifier is

$$|e_{n_1}|^2 = \left[ 4kT R_0 \right]^2 \left( \frac{1}{1 + j\omega R_c + j\omega L_1 \frac{R_c}{R_{w1}} + R_e - \omega^2 L_1 C_1} \right)^2$$

The equivalent noise of the thermal noise of the semi-coil matching resistance at the non-inverting input of the operational amplifier is

$$|e_{n_2}|^2 = \left[ \frac{4kT/R_{w1}}{1 + j\omega R_c + j\omega L_1 \frac{R_c}{R_{w1}} + R_e - \omega^2 L_1 C_1} \right]^2$$

The equivalent noise of the thermal noise of the gain resistance of the operational amplifier at the non-inverting input of the operational amplifier is

$$|e_{n_3}|^2 = \left| e_{n_2} \right|^2 + \left| e_{n_1} \right|^2 = \left[ \frac{4kT R_1 R_0}{G(R_4 + R_6)} \right]^2 + \left[ \frac{4kT R_1 R_3}{2R_1 + R_3} \right]^2$$

The equivalent noise generated by the operational amplifier's current noise flowing through the equivalent semi-coil network can be expressed as

$$|e_{n_4}|^2 = \left| i_{n1} \right|^2 \left( \frac{R_e + j\omega L_1}{1 + j\omega R_c + j\omega L_1 \frac{R_c}{R_{w1}} + R_e - \omega^2 L_1 C_1} \right)^2$$

where $i_{n1}$ is the input current noise of the first amplifier.

The equivalent noise generated by the operational amplifier's current noise flowing through the gain resistance at the non-inverting input of the operational amplifier is

$$|e_{n_5}|^2 = \left| e_{n_4} \right|^2 + \left| e_{n_3} \right|^2 = \left| i_{n1} R_{w1} \right|^2 + \left| i_{n3} R_0 \right|^2 = \left[ i_{n1} R_1 R_3 \right]^2 + \left[ i_{n3} R_4 R_6 \right]^2 + \frac{i_{n3} R_4 R_6}{G(R_4 + R_6)}$$

3.3. Optimization and distribution analysis of noise
The air-core coil without matching resistance will generate time-domain oscillation when receiving high-frequency signal [5], and the amplitude-frequency characteristics of the coil will change after adding the matching resistance. The amplitude-frequency characteristics of air-core coil is shown in Figure 6.
Figure 6. Process diagram of finding minimum circuit

Figure 7. The noise source distribution of the air-core coil sensor

It can be seen from Figure 6 that the time domain oscillation occurs at the resonant frequency (1.219 MHz), and the 3dB bandwidth of the air-core coil reaches 783 kHz when the matching resistance is adjusted to the critical damping state ($R_m = 1.84 \, k\Omega$).

The total noise at the input of the operational amplifier is

$$\left[\epsilon_{\text{total}}\right]^2 = 2\left[\epsilon_{\text{in}}\right]^2 + \left[\epsilon_{\text{Ri}}\right]^2 + \left[\epsilon_{\text{Req}}\right]^2 + \left[\epsilon_{\text{Rm1}}\right]^2 + \left[\epsilon_{\text{Rm2}}\right]^2 (14)$$

Based on the noise analysis of the sensor and the structural design of the air-core coil, the low-noise amplifier LT1028 was selected to build the amplifier circuit. The parameters are as follows: $R_1 = R_2 = 820 \, \Omega, R_3 = 50 \, \Omega, R_4 = 300 \, \Omega, R_5 = R_7 = 10 \, k\Omega$, amplification is 1126, matching resistance $R_m1 = 920 \, \Omega$, the internal resistance $R_a = R_p = 2.928 \, \Omega$, the distributed capacitance is 71 pF, the parasitic inductance is 240.3 μH, and the matching resistance $R_m1 = R_{m2} = 920 \, \Omega$. The noise source distribution of the air-core coil sensor with critical damping can be plotted as shown in Figure 7.

According to the theoretical calculation, the voltage noise of operational amplifier occupied the main position, with the increase of the frequency of signal, noise increased. In the range of 10k-200 k Hz, the overall noise is about 2.45 nV/√Hz. The optimized air-core coil can receive high frequency secondary response produced from the urban shallow geologic body. The performance can satisfy the detection requirements of the shallow underground space.

4. Conclusions
In this paper, the physical model and hardware circuit of the air-core coil sensor are analyzed. In order to improve the resonant frequency and signal-to-noise ratio, a winding method to reduce the parasitic
parameters of the coil is proposed. The simulation results verify that the optimized air-core coil sensor has a larger bandwidth and a low background noise level at the same time, which can extract weak transient electromagnetic secondary field signal in the effective bandwidth. The optimized design proposed in this paper meets the actual demand of the electromagnetic detection system in the urban shallow underground space and improves the system's detection ability for weak signal.

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