Research on highly sensitive electromagnetic method based on balance coil for underground metal detection

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Abstract. In order to solve the problem of low signal-to-noise ratio and serious primary field interference of frequency domain electromagnetic system for urban underground metal, a balanced coil structure based on LC resonance technique is proposed in this paper. The proposed technique uses the balance coil to eliminate the interference of the primary field, and LC resonance technique is adopted to increase the signal amplitude and improve the signal sensitivity and signal-to-noise ratio. An experiment was conducted by the system built on this proposed technique. The results show that the primary magnetic field can be suppressed by the balance coil and the signal-to-noise ratio can be improved by LC resonance technique through experiments.

1. Introduction
At present, the detection of underground pipelines and underground unexploded substances is of great significance to the construction of cities and the development of the field, and the detection and investigation of these shallow underground metals have become the focus of our attention [2,4,6]. Ordinary electromagnetic detection technique is easy to be interfered by primary field, which will affect the accuracy of detection. Therefore a balanced differential underground metal detector based on the frequency domain electromagnetic method is used for the detection of these underground metal objects [5]. The detection sensor uses a balanced coil, which eliminates the interference of the primary field and most of the environmental electromagnetic noise. Because of the differential structure of the balance coil, we will perform differential operation on the collected secondary field signal, and the final output signal is relatively weak. The LC resonance circuit is formed by the external capacitor and the receiving coil to improve the amplitude and sensitivity of the collected signal.

2. System structure and principle
The structure of the balanced differential underground metal detector is shown in Figure 1. The balanced differential underground metal detector consists of five parts: hollow coil sensor, external capacitance, differential amplifier circuit, data acquisition and microcontroller. The detection sensor adopts a balanced coil structure, three coils are coaxial and parallel, the transmitting coil is located between two receiving coils, the distance between the transmitting coil and the two receiving coils is equal, the radius of the three coils is same, the first receiving coil and the second receiving coil are connected in differential parallel structure. The output ends of the two receiving coils are connected to a capacitor. The capacitor can form a resonant circuit with the two receiving coils. This output end of this resonant circuit is connected to the differential amplification circuit. Then it is transmitted to the microprocessor through A/D acquisition.
A sinusoidal excitation signal is introduced into the transmitting coil. According to the law of electromagnetic induction, the transmitting coil will generate a changing primary field. Since the first receiving coil and the second receiving coil are connected in differential parallel, the primary field induced by the two receiving coils is same. The primary field of one receiving coil is compensated by the primary field of the other receiving coil, that is, the primary field contained in the differential output signal of two receiving coils is completely cancelled, and the external electromagnetic noise is also compensated and cancelled [7]. When a metal object exists under the hollow coil sensor, the metal object induces the primary field to produce eddy current. Then the metal object generates the secondary field. Due to the different distances to the metal object, the two receiving coils will receive different signals, the receiving coils will eventually output a signal reflecting the metal position and property [1]. The metal position and attribute are different, and the amplitude and phase of the signal will also be different. By analyzing the amplitude and phase of the signal, the position and property of the metal can be determined.

3. Theoretical analysis of the system
Construct the model diagram of the metal ball and hollow coil sensor for theoretical analysis. The metal ball is located below the receiving coil 1, as shown in Figure 2. The center of the small ball is located at the coordinate origin, the center of the transmitting coil and the receiving coil is located at the Z axis, the radius of the transmitting coil and the two receiving coils are R, the radius of the small ball is r, the conductivity is \( \sigma \), and the permeability is \( \mu \), the distances from the origin to any point of the transmitting coil, receiving coil 1 and receiving coil 2 are \( r_s \), \( r \), and \( r_u \), respectively.
A sinusoidal excitation signal with an amplitude of I and an angular frequency of $\omega$ is introduced into the transmitting coil, and the corresponding eddy current will be generated in the conductor. The secondary field caused by the eddy current will be added to the primary magnetic. If the magnetic field produced by the transmitting coil is constant, the magnetic field produced by the eddy current in the ball changes with the change of the conductivity, permeability and size of the metal ball, and then the change of the induced electromotive force in the receiving coil is detected. According to the method of measuring the conductivity and permeability of the metal ball introduced in reference [8], the expression of the induced electromotive force of the receiving coil 1 is obtained:

$$V_1 = -j\omega \int A_1 \, dl = -j\omega 2\pi R A_{11}$$

Where $A_{11}$ is the vector magnetic potential of the receiving coil. $A_{11}$ is expressed as:

$$A_{11} = \sum_{n=1}^{\infty} D_n \frac{\mu_0 I}{2} \sin \frac{\alpha}{n(n+1)} r^{-n} P_n^m (\cos \alpha) r^{-n+1} P_{n+1}^m (\cos \beta)$$

The expression of induced electromotive force of receiving coil 2:

$$V_2 = -j\omega \int A_{22} \, dl = -j\omega 2\pi R A_{12}$$

Where $A_{12}$ is the vector magnetic potential on the receiving coil. $A_{12}$ is expressed as:

$$A_{12} = \sum_{n=1}^{\infty} D_n \frac{\mu_0 I}{2} \sin \frac{\alpha}{n(n+1)} r^{-n} P_n^m (\cos \alpha) r^{-n-1} P_{n+1}^m (\cos \beta)$$

$$D = r^{2n+1} \left( \frac{(2n+1)\mu I_{n+1/2} (\eta r)}{\eta I_{n+1/2} (\eta r) + n(\mu_0 - 1) I_{n+1/2} (\eta r)} \right)$$

The differential electromotive force of the receiving coils is

$$\Delta V = V_1 - V_2$$

Where $\eta = j\omega \mu \sigma$, $\mu_0 = \mu / \mu_0$, $P_n^m (x)$ is Legendre function, $I_{n+1/2} (x)$ is $n+1/2$ order modified Bessel function, $I_{n-1/2} (x)$ is $n-1/2$ order modified Bessel function, $\mu_0$ is vacuum permeability.

![Figure 3. Equivalent circuit of hollow coil sensor](image)

The model of two receiving coils can be equivalent to the second-order system model composed of resistance, inductance and capacitance [3]. The equivalent circuit is shown in Figure 3. R1, L1 and C1 are the equivalent resistance, inductance and capacitance of receiving coil 1. R2, L2 and C2 are the equivalent resistance, inductance and capacitance of receiving coil 2. V1 and V2 are the induced electromotive force of receiving coil 1 and receiving coil 2 respectively. C3 is a matching capacitor, which can form a resonance circuit with the receiving coil 1 and the receiving coil 2. The output voltage of the circuit is $U_0$.

Through the equivalent circuit of the coil, it can be found that the equivalent impedance of the coil is:

$$Z (j\omega) = (R1 + R2) + j\omega (L1 + L2) - \frac{1}{j\omega C}$$

(7)
Where \( C = \frac{C_1gC_2 + C_1gC_3 + C_2gC_3}{C_1 + C_2} \), \( \omega \) is the angular frequency. It can be seen that if the angular frequency is determined, only the external capacitor needs to be adjusted so that
\[
\omega_0(L_1 + L_2) = \frac{1}{\omega C}
\]  
At this time, the circuit is in resonance state, the expression of quality factor:
\[
Q = \frac{1}{\omega_0 C(R_1 + R_2)} = \frac{\omega_0(L_1 + L_2)}{(R_1 + R_2)}
\]  
Output voltage of coil:
\[
U_0 = Q \Delta V = Q(V_1 - V_2)
\]  
The output voltage of the coil is equal to \( Q \) times of the differential induction electromotive force, which improves the sensitivity of the output signal.

It can be seen from the equivalent circuit that the induced electromotive force which inputs to the amplifier is the output voltage of the equivalent circuit. According to the equivalent circuit in Figure 3, the transfer function of the coil is obtained as follows:
\[
H(\omega) = \frac{U_0}{V_1 - V_2} = \frac{1}{1 - \omega^2 (L_1 + L_2)C + j\omega(R_1 + R_2)C}
\]  
It can be found that the equivalent circuit of the coil can be regarded as a low-pass filter. It filters the noise whose frequency is higher than the cut-off frequency to reduce the interference of external noise and improve sensitivity.

4. Experiment
The coil built in Figure 4 is used for verification. A sinusoidal signal with a frequency of 2KHz and an amplitude of 10Vp-p is given to the transmitting coil by the signal generator. Since the output impedance of the signal generator is 50 ohms, the signal in the transmitting coil is relatively weak, The signal sensed by the receiving coil is relatively weak because of the weak magnetic field signal. Connect the output end of the two receiving coils with the differential amplification circuit with a magnification of 100 times, and observe the output signal of the differential amplification circuit with an oscilloscope.

Figure 4. The model of balance coil

Figure 5 shows the signal observed by the oscilloscope when the metal abnormal body is not placed on the upper of the coil. The signal approaches to a straight line, and the primary field signal is very weak. The balance coil structure can fully reduce the primary field interference.
According to the equivalent inductance and resistance value of the coil, the capacitance value which needs to be placed in the resonance circuit composed of the receiving coil could be calculated. When a steel plate with an area of about 18 square centimeters is placed above the coil, as shown in Figure 6, as the distance from the steel plate to the coil increases gradually, the sensed signal will be gradually weak. Figure 7 shows the output signal of the differential amplification circuit when the output terminal of the receiving coil is not equipped with a capacitance, and Figure 8 shows the output signal of the differential amplification circuit when the output terminal is connected with an external capacitance. It can be seen that the signal amplitude is significantly increased after adding the capacitor, and the noise is also filtered out.

**Figure 5.** Signal observed by oscilloscope when metal body is not placed on the upper of coil

**Figure 6.** Schematic diagram of placing a steel plate above the coil

**Figure 7.** Output signal of the differential amplifier circuit when the receiving coil is not connected to the capacitor
Figure 8. Output signal of the differential amplifier circuit when the receiving coil is connected with an external capacitor

5. Conclusions
In this paper, the structure of balance coil and the technique of tuning and amplifying the output signal of the coil based on LC resonance are studied. The experimental results show that the structure of balance coil can reduce the primary field and external interference, and verify the amplification and filtering effect of LC resonance technique at the output of balance coil, which improves the SNR of signal and the sensitivity of sensor. The balance coil proposed in this paper meets the current detection demand of shallow metal objects and improves the detection capability of frequency domain electromagnetic system.

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References
[1] Bell, T., H., Barrow, B., J., and Miller, J., T., 2001, Subsurface discrimination using electromagnetic induction sensors: IEEE Transactions on Geoscience and Remote Sensing, 39(6),1286-1293.
[2] Carlson, N., R., Zonge, K., L., 2003, Minerals exploration methods modified for environmental targets: Exploration Geophysics, 34(2),114-119.
[3] Chen, X., D., Zhao, Y., and Feng, X., L., 2013, The development of an inductive sensor for TEM: Geophysical and Geochemical Exploration, 37(1),88-91.A reference
[4] Gui, X., Y., 1993, Detection of buried pipes and cable in urben areas: Earth Science Journal of China University of Geosciences, 18(03),362-368.
[5] He, J., S., 1997, Development and prospect of electrical prospection method: Chinese Journal of Geophysics, 40(9),308-316.
[6] Ou, G., F., Zhu, Z., Ch., and Yang, J., 2007, Research on the ground electromagnetic detection technique for the underground metal pipeline: Chinese Journal of Scientific Instrument, 28(2),258-263.
[7] Yamazaki, S., Nakane, H., and Tanaka, A., 2002, Basic analysis of a metal detector: IEEE Transaction on instrumentation and measurement, 51(4),810-814.
[8] Yamazaki, S., Nakane, H., and Tanaka, A., 1996, Simultaneous measurement of electric and magnetic properties of a spherical sample, 45(2),473-477.