Research on magnetic field size and coil parameters based on non-contact magnetic induction detection of corroded rebars in infrastructure

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Abstract: Non-contact magnetic induction detection is widely used in infrastructure testing due to its advantages. How to choose the appropriate magnetic field and the corresponding coil parameters is very important for electromagnetic detection. Excessive magnetic field causes excessive coil power consumption, which leads to serious heating and affects the service life of the equipment; however, if the magnetic field is too small, the detection accuracy will be reduced due to the attenuation of the magnetic field. This paper first analyzes the principle of magnetic induction detection, then the simulation analysis is carried out based on the buried depth and type of rebar commonly used in infrastructure to choose the appropriate magnetic field size.

1. Introduction

With the rapid development of China's economy, the pace of modernization is accelerating, and the corresponding infrastructure is also in constant construction. However, due to differences in their application environments and lack of awareness of the protection of many infrastructures, it causes structural failure or even collapse due to insufficient durability before reaching the predetermined service life, which poses a huge threat to people's life and safety and also causes a lot of economic losses[1]. As rebar is the core part of supporting infrastructure, the testing of rebar in infrastructure can effectively assess the state of infrastructure. Scholars have done a lot of research on the testing of infrastructure[2].

At present, there are many methods to detect corroded rebar in reinforced concrete. According to the damage condition of the structure during the detection process, there are two categories: damage detection and non-destructive detection. According to the detection principle, there are three categories: analysis method, physical method and electrochemical method[3]. Non-contact magnetic induction detection is non-contact testing, does not require contact with the surface of the infrastructure, nor does it require couplings. It can realize high-speed and high-efficiency automatic detection of the state of rebar, and it is more convenient to operate and has higher detection accuracy than other methods[4], so it is widely used in infrastructure testing.

Because there is a certain distance between the embedded rebar and the concrete surface in most infrastructure, there will be obvious magnetic field attenuation in the reinforced concrete, which will have a significant impact on the final detection accuracy. Therefore, it is required to excite the magnetic field as large as possible, but excessive magnetic field will cause excessive power consumption of coils,
which will cause severe heat generation and affect the service life of equipment. So how to choose the appropriate magnetic field size and corresponding coil parameters is very important for electromagnetic detection. In this paper, a 20mm diameter rebar with 100mm embedded depth is studied, and the corresponding excitation magnetic field and coil parameters are selected.

2. Basic principle of magnetic induction detection
The basic principle of magnetic induction detection for non-contact corroded rebar is shown in Figure 1. By analyzing and processing the signals collected by Hall sensor, we can judge the state of rebar in infrastructure. The non-contact magnetic induction detection method is composed of an excitation source, an excitation coil, a Hall sensor, a signal processing circuit and a host computer. It is characterized in that the excitation signals of different frequencies, amplitudes and waveforms are generated through the excitation source. Then the excitation signal is input into the excitation coil, which generates a magnetic field in space under the action of the excitation source, the rebar in reinforced concrete is a kind of electroconductive and magnetic conducting material. Under the action of space magnetic field, eddy current effect and magnetization effect are produced, which have an impact on the original magnetic field. The specific impact is affected by the permeability, conductivity and material size of reinforcement, however, after the rebar is corroded, the parameters of the rebar as the medium change. By analyzing and processing the signal of the magnetic field, the degree of the steel bar corrosion in the reinforced concrete can be judged[5-6].

![Figure 1. The schematic diagram of non-contact magnetic induction detection of corroded rebars in infrastructure.](image)

The excitation source inputs the excitation signal into the excitation coil L1. The magnitude of the magnetic field generated directly below the excitation coil L1 is shown in formula (1):

\[ B = \frac{\mu_0}{4\pi} \int_0^1 \frac{Ia^2d\phi}{(z^2 + a^2)^{3/2}}e_z = \frac{\mu_0 Ia^2}{2(z^2 + a^2)^{3/2}}e_z \]  

(1)

In the formula, \( \mu_0 \) is the vacuum permeability, \( I \) is the current size in the coil, \( a \) is the coil radius, and \( z \) is the distance from the coil to the sampling point on the coil axis. When the rebar is in the magnetic field generated by the exciting coil, the rebar will produce a magnetization effect. The corresponding magnetic field \( B_m \) is shown in formula (2):

\[ B_m = \frac{\mu_0}{4\pi} \int_{V'} \frac{J_w \times e_R}{R^2} dV' + \frac{\mu_0}{4\pi} \int_{S'} \frac{K_m \times e_R}{R^2} dS' \]  

(2)

In the formula, \( J_w = \nabla \times M \), \( K_m = M \times e_m \), \( e_R \) is the unit vector in the \( R \) direction. Therefore, the magnetic field detected by the hall sensor is the overlap of the magnetic field \( B \) produced by the original coil and the magnetic field \( B_m \) produced by the steel bar magnetized by the original magnetic field, as shown in formula (3):

\[ B = \mu_0 (H + M) = \mu_0 \mu H = \mu H \]  

(3)

In the formula, \( B \) is magnetic induction strength of the space, unit: T; \( H \) is the original magnetic field strength, unit: A/m; \( M \) is the magnetization, unit: A/m; \( \mu_0 \) is the vacuum permeability, which is \( 4\pi \times 10^{-7} \)
H/m; \( \mu_r \) is the relative permeability of the medium, dimensionless. \( \mu \) is the permeability of the medium, unit: H/m. When the rebar is corroded or broken, the magnetic field produced by the corresponding magnetization effect will change. Therefore, the evaluation of the state of the rebar can be completed by using Hall sensor to detect the magnetic field[7-8].

3. Simulation Study

In order to select the appropriate magnetic field size and corresponding coil parameters, a model drawing of single steel bar is built in COMSOL. In the figure, the small ring is the excitation coil, the cuboid behind it is reinforced concrete, the long cylinder in the cuboid is rebar, and the largest cylinder outside is the boundary. Control variable method is used here to keep other parameters unchanged while studying the influence of one variable on electromagnetic signal. The diameter and length of reinforcing bars are 20mm, 150cm and the distance between coils and reinforcing bars is 10cm. Model drawing of single rebar, position of rebar and coil are shown in Figure 2 and 3.

3.1. Selection of magnitude of excitation magnetic field

Because of the large power loss of sine signal, the excitation signal selected in this paper is a pulse square wave signal with a certain duty cycle. Pulse signals are discontinuous signals and can significantly reduce power consumption. Because the change of the pulse signal is only reflected in the rising and falling edges, the eddy current is generated by an alternating magnetic field. When using pulse signal, the peak value of measured magnetic field signal is set as sampling characteristic value, which is less affected by eddy current. Most of the influencing factors are caused by magnetization effect of steel bar as medium. Figure 4 shows a pulse square wave signal.

![Figure 2. Model drawing of single rebar.](image1)

![Figure 3. Position of rebar and coil.](image2)

![Figure 4. Pulse square wave signal.](image3)

By adding a pulse excitation signal of amplitude 1A to the coil, the magnetic field at the point directly below the coil center changes with the thickness of the rebar, as shown in Figure 5. The corrosion degree of rebar can be judged by comparing the peak value of the collected magnetic field signal. As shown in Figure 5, as the rebar become thinner and thinner, the corresponding detected magnetic flux density is also smaller and smaller. By comparing the corresponding magnetic flux density, the status of the rebar inside can be determined. The corresponding coil current, voltage, power and other parameters are shown in Table 1.

| Table 1. Data of coil in different time. |
|----------------------------------------|


Time(s) | Coil current(A) | Coil power(w) | Coil voltage (V) \\
---|---|---|---
0 | 0 | 0 | 0 \\
0.05 | 0 | 0 | 0 \\
0.1 | 0 | 0 | 0 \\
0.15 | 0 | 0 | 4.3532 \\
0.2 | 0.5 | 7.0098 | 14.02 \\
0.25 | 1 | 19.762 | 19.762 \\
0.3 | 1 | 19.762 | 19.762 \\
0.35 | 1 | 19.065 | 19.065 \\
0.4 | 1 | 17.705 | 17.705 \\
0.45 | 1 | 17.705 | 17.705 \\
0.5 | 0.5 | 3.2197 | 6.4394 \\
0.55 | 0 | 0 | -3.2269 \\
0.6 | 0 | 0 | -0.14525 \\
0.65 | 0 | 0 | -0.011483 \\
0.7 | 0 | 0 | -0.0043274 \\
0.75 | 0 | 0 | -0.0019668 \\
0.8 | 0 | 0 | -0.0019668 \\
0.85 | 0 | 0 | -0.0010605 \\
0.9 | 0 | 0 | -0.0010605 \\
0.95 | 0 | 0 | -6.42E-04 \\
1.0 | 0 | 0 | -6.42E-04 \\

Figure 5. Magnetic flux density corresponding to rebars with different diameters. (r0 is the diameter of rebar)

From Figure 5, it can be seen that when the thickness of steel bar group changes by 2mm, the peak magnetic flux density changes between 0.02-0.1mT (0.2-1GS, 1T=10000GS), while under other conditions unchanged, the magnetic field is linearly related to the current. Most magnetic field detection equipment on the market can only be accurate to 0.1GS (0.01mT) now. Considering the measurement error, the magnetic field excited by 1A current will result in low measurement accuracy.

In order to select the appropriate excitation magnetic field, we study the trend of peak magnetic flux density detected under 2-8A current excitation when rebar thickness (corrosion degree) changes. The specific data is shown in Table 2. Theoretically, before the magnetic saturation is reached, when the excitation signal is amplified N times, the magnetic field strength is also amplified N times, and the change of the peak magnetic flux density caused by the same change in rebar thickness (corrosion degree) is almost amplified N times, which improves the detection precision. For example, when the excitation is 5A and the thickness of the rebar changes by 2mm, the peak magnetic flux density changes from 0.1 to 0.5mT (1-5GS), which greatly improves the detection accuracy.

Table 2: Under the current excitation of 2-8A, the peak value of magnetic flux density (mT) at the
sampling point changes with the change of rebar diameter.

| Diameter (mm) | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|--------------|-----|-----|-----|-----|-----|-----|-----|
| 12           | 4.4165 | 6.6245 | 8.8323 | 10.6398 | 12.7687 | 14.8958 | 17.0251 |
| 14           | 4.5133 | 6.7698 | 9.0260 | 10.8930 | 13.0745 | 15.2505 | 17.4300 |
| 16           | 4.6098 | 6.9145 | 9.2189 | 11.1513 | 13.3822 | 15.6127 | 17.8437 |
| 18           | 4.7088 | 7.0630 | 9.4170 | 11.4087 | 13.6916 | 15.9715 | 18.2550 |

When the diameter changes by 2mm, the change of magnetic field (approximate value)

|                        | 0.099 | 0.149 | 0.198 | 0.257 | 0.309 | 0.359 | 0.411 |

The theory can be substantially validated from Table 2 data. Through observation and comparison, it can be found that when coil excitation is more than 3A, when the steel bar thickness changes by 2mm, the change of peak magnetic flux density is greater than 0.149 mT, and the detection accuracy is much greater.

The magnetic field at the positive center of the coil is about 10 mT (10000 μT) when the excitation current is 3A and without rebar. Therefore, it is required that the magnetic field in the positive center of the exciting coil must be greater than 10 mT (10000 μT) without rebar, and the upper limit value is 30 mT (30000 μT) considering the power loss of the coil.

3.2. Coil parameter selection

The input excitation signal of coil in simulation model is current signal. Coil current directly affects the magnetic field generated by the excitation coil (current is linear with magnetic field) [8]. Therefore, current-type excitation is better than voltage-type excitation. However, current-type excitation is not easy to be applied to actual test and its cost is too high. Therefore, positive pulse voltage-type signal can also be used.

In addition, considering that the coil inductance affects the rising and falling edges of the coil current, and the current directly affects the size of the magnetic field of the exciting coil, but because the sampling characteristic value is the peak value of the magnetic field during measurement. For the rising and falling edges of the coil current, the peak of the exciting coil current (the peak of the magnetic field) is required to satisfy the measurement requirements and the current can be restored to its initial state before the next pulse arrives. For the simulation model, because the sampling characteristic value is the peak magnetic flux density, whether current or voltage excitation is used, as long as the peak coil current (peak magnetic field) can meet the measurement requirements. Only because it is more intuitive to control the magnetic field of the excitation coil with the excitation current, it has no effect on the simulation results.

Considering that most of the excitation models in practical applications are voltage type, this paper studies the effect of coil inductance on coil current (magnetic field generated by coil). A simulation model is built in Comsol to study the coil separately, as shown in Figure 6. The coil is made of square coil with a side length of 25cm, a height of 5cm, a number of turns of 1000 and a enameled wire diameter of 1mm. The sample point of the peak magnetic flux density is the positive center of the coil.
Figure 6. Sampling point of peak value of magnetic field.

The excitation signal is a voltage-type pulse signal as shown in Figure 7. The pulse excitation amplitude is 20V, the pulse width is 0.2s, and the duty cycle is 50%.

![Figure 7. Voltage-type pulse signal.](image)

During a single pulse period, the coil current and the magnetic field in the center of the coil change as shown in Figures 8 and 9:

![Figure 8. Coil current variation diagram.](image)  ![Figure 9. Variation diagram of magnetic field in the positive center of coil.](image)

It can be seen that under the excitation of 20V voltage-type pulse signal, the rise and fall edges of coil current and magnetic field caused by this 1000-turn square coil inductance are about 0.1s. Controlling the pulse width to 0.2-0.3s with a duty cycle of 50% can make the coil current (the magnetic field of the coil) almost steady after reaching its maximum value within the pulse width time and return to its initial state basically before the next rising edge.

In order to meet the requirement of exciting magnetic field (10000-30000μT), under different voltage amplitude pulse signals, coil turns and enameled wires, the peak magnetic field at the center of the coil and the current flowing through the coil are studied by using COMSOL simulation software. The common 1.0mm, 1.1mm and 1.2mm enameled wires in the market is selected. And the data are shown in tables 3, 4 and 5.

Table 3. Wire diameter of enameled wire is 1.0mm: Peak magnetic flux density (μT) & peak coil current (A) at different excitation voltages and coil turn

| Voltage (V) | 20   | 40   | 60   | 80   | 100  | DC resistance (Ω) | Inductance (mH) | Time constant τ |
|------------|------|------|------|------|------|------------------|-----------------|-----------------|
| 700        | 3457 & 1.23 | 6906 & 2.45 | 10370 & 3.68 | 13818 & 4.9 | 17273 & 6.13 | 16.3 | 223 | 13.68 * 10^-3 |
| 800        | 3456 & 1.07 | 6912 & 2.15 | 10368 & 3.22 | 13833 & 4.29 | 17267 & 5.36 | 18.6 | 291.8 | 15.69 * 10^-3 |
| 900        | 3455 & 0.95 | 6916 & 1.91 | 10365 & 2.86 | 13820 & 3.81 | 17301 & 4.77 | 21 | 369 | 17.57 * 10^-3 |
Table 4. Wire diameter of enameled wire is 1.1mm: Peak magnetic flux density (μT) & peak coil current (A) at different excitation voltages and coil turns.

| Voltage (v) | 20  | 40  | 60  | 80  | 100 | Coil DC resistance (Ω) | Coil inductance (mH) | Time constant τ |
|-------------|-----|-----|-----|-----|-----|------------------------|----------------------|------------------|
| 700         | 4106&1.49 | 8213&2.99 | 12327&4.48 | 16436&5.98 | 20520&7.46 | 13.4 | 222 | 16.57*10^-3 |
| 800         | 4112&1.31 | 8223&2.62 | 12318&3.92 | 16433&5.23 | 20545&6.54 | 15.3 | 290 | 18.95*10^-3 |
| 900         | 4104&1.16 | 8213&2.32 | 12319&3.49 | 16412&4.64 | 20521&5.81 | 17.2 | 367.6 | 21.37*10^-3 |
| 1000        | 4101&1.04 | 8202&2.09 | 12303&3.13 | 16404&4.18 | 20505&5.22 | 19.1 | 453.8 | 23.76*10^-3 |

Table 5. Wire diameter of enameled wire is 1.2mm: Peak magnetic flux density (μT) & peak coil current (A) at different excitation voltages and coil turns.

| Voltage (v) | 20  | 40  | 60  | 80  | 100 | Coil DC resistance (Ω) | Coil inductance (mH) | Time constant τ |
|-------------|-----|-----|-----|-----|-----|------------------------|----------------------|------------------|
| 700         | 4885&1.78 | 9771&3.55 | 14665&5.33 | 19556&7.11 | 24424&8.88 | 11.2 | 222 | 19.82*10^-3 |
| 800         | 4883&1.55 | 9770&3.11 | 14656&4.66 | 19529&6.22 | 24412&7.77 | 12.85 | 290.5 | 22.61*10^-3 |
| 900         | 4876&1.38 | 9752&2.76 | 14628&4.14 | 19512&5.52 | 24374&6.90 | 14.5 | 367 | 25.31*10^-3 |
| 1000        | 4863&1.24 | 9740&2.48 | 14600&3.72 | 19474&4.96 | 24343&6.20 | 16.07 | 453.9 | 28.25*10^-3 |

It is found that when the pulse excitation amplitude is 60-100V and the coil turns are 700-1000, the magnetic field requirement can be satisfied by winding the coil with enameled wire with a diameter of 1.0-1.2mm (the side length of the square coil is 25cm). However, when the coil is 1000 turns and the wire diameter is 1.2mm, the time constant τ reaches a maximum of 28.25 * 10^-3, which means that the rising and falling time of the coil current (the magnetic field of the coil) reaches a maximum of about 0.2s (as shown in the figure below), so the excitation signal pulse width is required to be controlled at least 0.3s.

Figure 10. Changes of coil current of coils with 1000 turns and 1.2 mm enameled wire diameter under 20V pulse voltage excitation.

4. Conclusion

It can be found by simulation that when the amplitude of the exciting pulse voltage source is 60-100V, the pulse width is greater than 0.3s, the duty cycle is 50%, and the coil turns are 700-1000, the square
coil with the edge length of 25 cm made of 1.0-1.2mm enameled wire can meet the requirements of the exciting magnetic field. By comparison, it is also found that the larger diameter enameled wire not only produces a larger magnetic field, but also has a smaller power loss.

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