Research on Magnetic Induction Detection of Steel Bars Corrosion

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Abstract. Reinforced concrete structures are widely used in modern buildings. However, the structural damage caused by the steel bars corrosion seriously affects the building remaining life. The reinforcement corrosion in concrete is slow, so the long-term detection of reinforcement corrosion is very important. The development of reinforcement corrosion detection equipment in China is slow, which cannot meet the application requirements of domestic concrete structures, this paper proposes a non-contact magnetic induction detection method for reinforcement corrosion. Through theoretical analysis and experimental design, a simple model is built and simulated. Simulation results of single and multiple steel bars corrosion to verify the feasibility of the method. This paper provides theoretical support and technical solutions for the operation state detection of non-contact reinforced concrete, and makes contribution to the non-contact magnetic induction detection technology.

1. Introduction

Reinforced concrete structure is an essential component of modern architecture. No matter in infrastructure or science industry, reinforced concrete structure is the top priority. However, due to the difference of application environment and people's low awareness of reinforced concrete protection, structural failure or even collapse accident will occur, which brings great threat to people's safety and causes economic losses. Professor Mehta from Berkeley University summed up several important factors in the concrete structures destruction in the world at the second International Conference on concrete durability. He pointed out that the primary factor affecting the durability of concrete structures was the steel bars corrosion [1]. Therefore, the detection and research of reinforcement corrosion has become an important problem in today's society [2].

At present, there are many detection and research methods for steel bars at home and abroad. According to the damage to the structure, there are destructive detection and non-destructive detection. According to the detection principle, there are analytical method, physical method and electrochemical method [3]. The analysis method is to comprehensively analyse various factors of the tested object environment, such as temperature, humidity and pH value, which will affect the corrosion rate of steel bars, and predict the steel bar corrosion by modelling. Compared with the destructive detection, the advantage is low cost and no waste, but the disadvantage is too many factors affecting the steel bars corrosion, which cannot be considered comprehensively. Besides, lacking of theoretical support and...
the low reliability are also affect the results. There are many physical detection methods, but the existing detection methods can only be used for qualitative analysis, mainly used in the laboratory testing stage, which existence large errors in the actual measurement. As for the electrochemical detection process, there must be signal injection. On the one hand, it will damage the reinforced concrete in a certain extent, on the other hand, the signal cannot be injected into the corroded reinforcement under some working conditions.

In view of the above problems, this paper proposes a non-contact magnetic induction detection method for corroded steel bars. Firstly, this paper explains the non-contact magnetic induction method, and introduces some principles of the non-contact magnetic induction method. Secondly, the basic principle of contactless magnetic induction experiment is described. Then, according to the internal reinforced concrete structure, a simple magnetic induction model is built by using the finite element simulation software COMSOL. Considering the actual effect of magnetic induction, the single corrosion and multiple corrosion simulation are carried out under the single-layer reinforced structure by injecting pulse excitation current. Comparing the magnetic field intensity distribution simulation on the coil and the reinforcement surface, combining the simulation results and the actual experiment of the reinforcement, under the appropriate excitation frequency, the reinforcement corrosion state can be effectively distinguished. It provides the theoretical support and technical solution for the operation state detection, and provides the foundation for the non-contact magnetic induction detection technology.

2. Non-contact magnetic induction measurement method and basic principle

In order to realize the high-speed and high-efficiency automatic detection of the steel bars corrosion degree without damaging the reinforced concrete. In this paper, a non-contact magnetic induction detection method is proposed. Its measurement method and basic principle are as follows.

2.1. Non-contact magnetic induction measurement method

The non-contact magnetic induction measurement method is shown in figure 1., the universal non-contact reinforcement corrosion detection device can move freely on the concrete surface, generate eddy current effect on the reinforcement material in the concrete through the excitation coil, then detect the eddy current signal through the detection coil. Finally, it can judge the reinforcement material corrosion degree through experimental comparison and analysis [4, 5].

![Figure 1. Non-contact magnetic induction measurement method.](image)

When the metal conductor cuts the magnetic line in the magnetic field or places in a changing magnetic field, according to Faraday's electromagnetic induction theorem, the metal conductor will feel a current similar to the water vortex, which is called eddy current because of its vortex shape. Compared with the traditional eddy current detection technology, the pulse eddy current detection technology loads the pulse current signal with a certain duty cycle and frequency on the excitation coil. When the excitation current signal is turned off instantaneously, the excitation coil induces a pulse magnetic field which decays rapidly with time, which called a primary field. The fast changing primary field induces a vortex like pulse current inside the conductor specimen. The pulse eddy
current signal attenuates with time propagation in the conductor and induces a new changing magnetic field, which is called the secondary field, as shown in figure 2. According to the principle of electromagnetic induction, when the conductor material is detected by the detector probe, the detector coil output is the transient voltage induced by the decay of the magnetic field around the coil with time [6].

![Figure 2. Basic principle of pulsed eddy current testing.](image)

The pulsed eddy current testing technology use the eddy current effect physical phenomenon. When the tested steel bar is corroded and its thickness and outer surface structure are changed, the induced eddy current in the steel bars and the magnetic field distribution are bound to be affected by the corrosion and change accordingly. By analysing these changes, we can master the corrosion situation in the steel bar. Therefore, the information such as the conductivity, magnetic conductivity or thickness of the corroded steel bars will have a direct impact on the induction signal. Through the data collection, processing and analysis of the induction voltage signal, the corresponding corroded steel bars corrosion information can be mastered.

2.2. Basic principle of non-contact magnetic induction testing for corroded steel bars

![Figure 3. Basic principle of magnetic induction testing for non-contact corrosion reinforcement.](image)

In this paper, the basic principle of non-contact corrosion reinforcement magnetic induction detection is shown in figure 3. The pulse excitation signals with different fundamental frequency, duty cycle and amplitude are generated by the excitation source. Then input the excitation signal into the excitation coil $L_1$, the excitation coil will generate a magnetic field in space, and the reinforcement in reinforced concrete will generate eddy current effect under the space magnetic field [7]. Assuming that the medium in the field is linear isotropic, the eddy current electric field $E$ can be expressed as follows:

$$E = -j\omega A - \nabla \phi$$  (1)
Where, $\omega$ is the angular frequency, $A$ is the magnetic vector potential, and $\varphi$ is the scalar potential. The area where eddy current exists is passive, and the eddy current density meets the following formula:

$$ \nabla \cdot J = 0 $$  (2)

The formula (2) is substituted into the differential form $J = \sigma E$ of Ohm's theorem, then the result is substituted into the formula and use the vector operation. Finally, the Coulomb specification $\nabla \cdot A = 0$ is used:

$$ \nabla \cdot (\sigma \nabla \varphi) = -\omega A \cdot \nabla \sigma $$  (3)

According to the condition that the normal component of current density is continuous on the interface between concrete and reinforcement, the boundary condition and the interface connection condition between concrete and reinforcement can be obtained:

$$ \frac{\partial \varphi}{\partial n} = -\omega \vec{A} \cdot \nabla \sigma $$  (4)

$$ \sigma_2 \frac{\partial \varphi_2}{\partial n} - \sigma_1 \frac{\partial \varphi_1}{\partial n} = -\omega (\sigma_2 A_{2n} - \sigma_1 A_{1n}) $$  (5)

Where, $\vec{A}$ is the component of the magnetic vector position in the normal direction outside the boundary of the medium. The above three formulas constitute the partial differential equation and the definite solution condition of the vortex flow field in the field. The distribution of eddy current field can be obtained by (6):

$$ J = \sigma E = \sigma (-j \omega \vec{A} - \nabla \varphi) $$  (6)

The magnetic induction intensity in the measurement coil consists of two parts: the magnetic induction intensity $B_p$ generated by the current in the excitation coil; the magnetic induction intensity $B_s$ generated by the eddy current in the reinforcement. That is $\vec{B} = \vec{B}_p + \vec{B}_s$. $\vec{B}_p$ basically unchanged, so the magnetic induction intensity change in the measuring coil is the change of $\vec{B}_s$. That is $\Delta \vec{B} = \Delta \vec{B}_s$.

According to Biot-Savart Law:

$$ B_s = -j \frac{\mu_0}{4\pi} \int \frac{\vec{J} \times \vec{R}}{R} dV = -j \frac{\mu_0}{4\pi} \int \left[ \sigma (\omega A + \nabla \varphi) \times \frac{\vec{R}}{R} \right] dV $$  (7)

In the above formula, $\vec{R}$ is the vector from the source point to any field point in the reinforcement. In order to determine the corresponding relationship between the magnetic induction intensity change $\Delta \vec{B}_s$ and the conductivity change $\Delta \sigma$, it is assumed that $\vec{B}_{s0}$ and $\vec{B}_{s0}$ are the magnetic induction intensities when the conductivity is $\sigma_0$ and $\varphi_0 + \Delta \varphi$, $\sigma_0 + \Delta \sigma$ instead of the $\varphi$ and $\sigma$ in the above formula, the following formula is obtained:

$$ \vec{B}_s = -j \frac{\mu_0}{4\pi} \int \left[ \sigma_0 (\omega A + \nabla \varphi_0 + \Delta \varphi) \times \frac{\vec{R}}{R} \right] dV $$  (8)

Substituting the above formula into $\Delta \vec{B}_s = \vec{B}_s - \vec{B}_{s0}$, ignoring the last term of the above formula, and substituting $\frac{\partial (\nabla \varphi)}{\partial \sigma} \Delta \sigma$ with $\nabla (\Delta \varphi)$, we can get the following corresponding relationship with the change of $\Delta \vec{B}_s$ and conductivity $\Delta \sigma$:

$$ \Delta \vec{B}_s = -j \frac{\mu_0}{4\pi} \int \left[ \omega \vec{A} + \nabla \varphi_0 + \sigma_0 \frac{\partial (\nabla \varphi)}{\partial \sigma} \right] \Delta \sigma \times \frac{\vec{R}}{R^2} dV $$  (9)

The above formula explains the relationship between the reinforcement conductivity change and the magnetic field change in the measuring coil. In the actual measurement, the system records the
induction electromotive force in the detection coil, so only the relationship between the induction electromotive force change and the conductivity change needs to be clarified. Through the detection of electromotive force change, the data is transmitted to the upper computer, and the upper computer background software realizes data recording and analysis, which can complete the judgment of the steel bars corrosion degree.

3. Simulation and verification of contactless magnetic induction

3.1. Simulation model building

Figure 4 is the model diagram of single-layer grid reinforcement. In the figure, the ring is the excitation coil. Under the ring, there are 10 reinforcements arranged in a crisscross single layer. The diameter of a single reinforcement is 16mm and the length is 100cm. The distance between each two reinforcements is 1.5cm. The distance between the coil and the centre of the reinforcement is 12cm. The rectangle outside the reinforcement is concrete, and the largest cylinder outside is the boundary.

3.2. Simulation of single steel bar corrosion under pulse excitation

At this time, it is simulated that one reinforcement in a single layer is corroded and the other reinforcement is in good condition. The number of coil turns is 1000, and the excitation is the pulse excitation signal with peak value of 1A. At this time, the radius of the steel bar is 10-16mm, and a parametric scan is made every 2mm. The change of the magnetic flux density with time at the point directly below the coil centre is shown in figure 5.

![Grid reinforcement model](image)

Figure 4. Grid reinforcement model.

![Change of flux density mode with time for different thickness of steel bars](image)

Figure 5. Change of flux density mode with time for different thickness of steel bars.
It can be seen from figure 5 that the corresponding magnetic flux density of different diameter steel bars increases first and then decreases with the pulse signal. The thicker the steel bars are, the maximum magnetic flux density increases with the increase of the steel bars radius. When the coil is directly above the steel bars, the steel bars corrosion degree can be determined by measuring its magnetic flux density mode. The coil power factor is shown in figure 6.

![Figure 6. Change of coil power with time.](image)

3.3. Simulation of coil position change relative to reinforcement under pulse excitation (single reinforcement corrosion)

As shown in figure 7, the positions of the coil positive center relative to the reinforcement are 10cm and 5cm (x=-10, -5) to the left, 10cm and 5cm (x=10,5) to the right and above (x=0) of one reinforcement respectively.

![Figure 7. Position of coil relative to reinforcement.](image)

(a)x=-10  (b)x=-5  (c)x=0  (d)x=5  (e)x=10
Through simulation, the relationship between the coil position relative to the reinforcement and its corresponding flux density is analysed, and the results are in table 1.

| Position of coil relative to reinforcement (cm) | Peak flux density (mT) |
|-----------------------------------------------|------------------------|
| -10                                           | 36.35063491274944      |
| -5                                            | 36.313986890932        |
| 0                                             | 36.44302044251746      |
| +5                                            | 36.29281354084986      |
| +10                                           | 36.3778573627404       |

It can be seen from the figure that for the single corrosion steel bar, when the coil is directly above the steel bar (x = 0), its relative magnetic flux density is the largest, about 36.4mT, so when the coil moves slowly, the magnetic flux density mode reaches the maximum value, it can be judged that the steel bar is directly below the coil.

Through the simulation analysis of the single steel bar corrosion degree, it is found that the coil magnetic flux density is different at different positions above the steel bar and when the steel bar in different diameter. Through the effective analysis of the waveform, the coil position relative to the steel bar and the change of the steel bar thickness can be determined. That is to say, the steel bar corrosion degree can be determined by the magnetic flux density measurement.

3.4. Simulation of multiple steel bars corrosion under pulse excitation

In the process of actual reinforcement corrosion, one piece of reinforcement will be corroded when it is corroded. Assuming there are four reinforcement corroded at the same time, and they are all under the coil. As shown in figure 8, four longer reinforcements are corroded.

![Figure 8. Uniform Corrosion of reinforcement.](image)

At this time, the diameter of the steel bar is 10-20 mm, and a parametric scan is made every 2 mm. The change of the magnetic flux density in the centre of the coil with time is shown in figure 9.
Figure 9. The flux density mode change with time for different diameter of uniform corrosion steel bars. 
As shown in figure 9, the results of steel bars uniform corrosion are similar to the signals detected by a single. The detection signals corresponding to different diameter of steel bars are different. The corrosion degree of steel bars can be determined by detecting the magnetic flux density.

3.5. Simulation of the position change of the coil relative to the reinforcement under pulse excitation (multiple reinforcement corrosion) 
As shown in figure 10, the positions of the coil positive centre relative to the reinforcement are 10cm and 5cm (x = -10, -5) to the left, 10cm and 5cm (x = 10, 5) to the right, and above (x = 0).

Figure 10. Position of coil relative to reinforcement. 
(a)x=-10 (b)x=-5 (c)x=0 (d)x=5 (e)x=10

Through simulation to analyse the relationship between the position of the coil relative reinforcement and its corresponding magnetic flux density, the results are shown in table 2.
Table 2. Peak flux density in different position.

| Position of coil relative to reinforcement (cm) | Peak flux density (mT) |
|-----------------------------------------------|------------------------|
| -10                                           | 35.99007598205135      |
| -5                                            | 35.95712238590436      |
| 0                                             | 36.1018454916774       |
| +5                                            | 36.034059815755526     |
| +10                                           | 36.05307547262015      |

It can be seen from Table 2 that in the case of multiple steel bars corrosion, when the coil is directly above the steel bar (x = 0), its relative magnetic flux density is the largest, about 36.1mT, so when the magnetic flux density mode reaches the maximum value, it can be judged that the steel bar is directly below the coil at this time.

The single-layer and multi mesh reinforced structure will produce a lot of eddy current effects under the magnetic field. The superposition of multi magnetic fields will cause the signal waveform under the coil to be unstable. However, through the analysis of the relative magnetic flux density peak value, the reinforcement position and the corresponding corrosion degree can be determined.

4. Conclusion

Reinforced concrete material is a very important part of modern buildings, such as bridges, tunnels, various buildings and so on. In order to ensure the safety of the building, find out the possible problems in time, and make corresponding remedial measures to protect the national economy and people's life. The concrete structure quality detection technology has become a very important research topic in today's society. In this paper, the research status of concrete structure detection technology at home and abroad is introduced. By comparing the steel corrosion detection technology at present, the advantages of non-contact magnetic induction detection of corroded steel bars are obtained. Then, the non-contact magnetic induction method is introduced, including the pulse eddy current effect, excitation coil and detection coil electromagnetic parameter analysis theory. The basic principle and experimental scheme of non-contact magnetic induction detection method are studied. On the basis of a large number of principle analysis, a simple corrosion model of reinforced concrete is built for the reinforced concrete corrosion detection, and the simulation is carried out through the finite element simulation software COMSOL. It is concluded that the coil magnetic flux density is different at different positions above the steel bar and when the steel bar is of different diameter. The position of the coil relative to the steel bar and the change of the steel bar diameter can be judged by the waveform effective analysis, that is to say, the steel bar corrosion degree can be determined by the magnetic flux density measurement.

5. References

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