A Nondestructive Detection Method Based on Target Resonance

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Abstract. Conventional eddy current testing (ECT) considers the detected target as an RL series (RLs) circuit. Starts from the problem of grounding grid break point detection, this paper proposes a detection method based on RLC series (RLCs) circuit resonance since a break point introduces a capacitor for the detection target. When the RLCs target circuit is coupled with the transmitter coil, the input impedance-frequency curve changes significantly. This paper focuses on methodological exploration, and the influences of target coil capacitance, resistance and detection distance on detection system’s impedance curve are discussed. Simulation and experimental results show the proposed method can distinguish the RLs and RLCs target circuit, and the detection distance of the RLC target is much greater than the RL target detection distance under the same condition. Besides, the feature region, where the impedance curve changes significantly when RLCs circuit is coupled to the transmitting coil, is located near the resonance point of the testing target. Moreover, the detection distance increases with the decrease of the target resistance. In addition, the closer the coil distance is and the smaller the resistance is, the more obvious the feature region will be.

1. Introduction
Eddy-current testing (ECT), a popular electromagnetic nondestructive testing (NDT) methods, has been widely used in surface inspection and tubing inspections[1-3]. So far, in order to improve the efficiency and broaden the applicable fields of ECT, great effort has been made from the aspects of sensors [4], excitation methods [5], data processing [6], inverse calculation [7], etc. ECT has many advantages, such as contactless testing, without coupling medium, high speed, high sensitivity to surface defects, etc.

So far, impedance analysis is still the most widely utilized method in ECT. In this method, the metal test piece to be regarded as a secondary coil that interacts with the detection coil. The secondary coil is equivalent to an RL series circuit [1]. When the secondary coil is coupled to the detection coil, the impedance in the primary circuit changes, thereby the change in impedance in the secondary circuit can be obtained. But for some special cases, for example the grounding grid buried about 1 meter under the surface, a breakpoint in the metal rod will introduce a capacitor for the detection target. The secondary coil is no longer an RL series circuit but an RLC series circuit. This paper starts from the grounding grid breakpoint detection and inspired by eddy current testing, a detection method for detecting RLC series circuit is proposed. This method is expected to achieve efficient, long-distance grounding grid break point detection, because so far, there is no mature and effective break point diagnosis method [8-10].
Any metal mesh structure which similar to the grounding grid, when intact, can be viewed as a single turn inductor. An intact metal mesh can be considered as an RL circuit since the distributed capacitance is so small. Therefore, its detection is quite similar to the conventional ECT. But for a metal mesh with a breakpoint, the equivalent circuit is an RLC series (RLCs) resonant loop because the breakpoint introduces a capacitor for the circuit. The transmitting coil in this paper emits a swept frequency signal, and when the target is coupled to it, the input impedance-frequency curve of the transmitting coil changes. Suppose the source frequency is the resonant frequency of this RLCs circuit, the RLCs circuit is resonant and its impedance magnitude drops to the least, which means something special will occur in the input impedance of the detection system’s input impedance. According to the analysis above, this paper proposes a NDT method based on the resonance of the detection target. As a preliminary investigation, this paper focuses on the methodological exploration.

This paper introduces the principle of the proposed method firstly and then compares the influence of the RLs target and RLCs target on the impedance curve of the detection system. After that, the effects of the resonant frequency, mutual inductance and the resistance of the target on the detection are studied. Finally, the experiment was conducted to verify the feasibility of the method.

2. The principle of the proposed method
As described in the previous section, the detecting target is considered as the secondary coil which coupled with the transmitting coil. The two states of the secondary circuit correspond to different equivalent circuits which are shown in Figure 1. The transmitting coil in this paper has a compensation capacitor $C_1$ to form an RLC series circuit.

![Figure 1](image)

\textbf{Figure 1.} Equivalent circuits of the detection system. (a) the secondary coil is an RLs circuit; (b) the secondary coil is an RLCs circuit.

| Table 1. List of parameters |
|-----------------------------|
| $f_1$ | resonant frequency of the transmitting coil |
| $f_2$ | resonant frequency of RLCs target coil |
| $Z_1$ | impedance of the transmitting coil |
| $Z_{in_{rl}}$ | impedance of the detection system (RLs target) |
| $Z_{in_{rlc}}$ | impedance of the detection system (RLCs target) |
| $f_{rl}$ | resonant frequency of the detection system (RLs target) |
| $f_{rlc}$ | resonant frequency of the detection system (RLCs target) |

\begin{align*}
Z_1 &= R_1 + j(\omega L_1 - \frac{1}{\omega C_1}) = R_1 + jX_1 \\
Z_{in_{rl}} &= \left( R_1 + \frac{\omega^2 M^2 R_2}{R_2^2 + (\omega L_2)^2} \right) + j \left( \frac{\omega^2 M^2 (\omega L_2 - \frac{1}{\omega C_2})}{R_2^2 + (\omega L_2 - \frac{1}{\omega C_2})^2} \right) = R_{rl} + jX_{rl} \\
Z_{in_{rlc}} &= \left( R_1 + \frac{\omega^2 M^2 R_2}{R_2^2 + (\omega L_2 - \frac{1}{\omega C_2})^2} \right) + j \left( \frac{\omega^2 M^2 (\omega L_2 - \frac{1}{\omega C_2})}{R_2^2 + (\omega L_2 - \frac{1}{\omega C_2})^2} \right) = R_{rlc} + jX_{rlc} \\
\end{align*}

The parameters in this section are shown in Table 1.
This paper uses $Z_t$ as the reference. When the detecting target is coupled with the transmitting coil, the input impedance of the system will change, which is shown in Figure 2.

According to equation (1) and (2), $R_t > R$, $X_t < X1$ and $f_t > f_1$. But because $R_2$ and $L_2$ of the coil in this paper are small, the impedance curves of $Z_{rlc}$ are not significantly different from that of $Z_t$.

For the case shown in Figure 1(b), according to equation (1) and (3), $R_{rlc} > R$ and there is a maximum value when $f = \sqrt{\frac{(L_2 C_1 - R_1 C_1^2)}{2}}$ which is slightly greater than $f_2$. Besides, when $f < f_2$, $X_{rlc} > X1$; when $f = f_2$, $X_{rlc} = X1$; when $f > f_2$, $X_{rlc} < X1$. Therefore, near the resonance frequency of the secondary coil, an oscillation phenomenon occurs in the imaginary part of the impedance. Equation (3) shows that the larger $M$ is and the smaller $R$ is, the more obvious the oscillation phenomenon is. Besides, the resonant frequency of the system $f_{rlc}$ is slightly smaller than $f_1$ and there is a minimum value, called $f_3$, on the phase-frequency curve when $f > f_2$. As shown in Figure 2, when the secondary coil is in resonance, the impedance curve will change significantly. As a result, it is prone to find the target when the target corresponds to an RLCs circuit, which is the focus of this paper.

![Figure 2](image)

**Figure 2.** Comparison of impedance curves of different detection targets. (a) real part-frequency curve; (b) imaginary part-frequency curve; (c) phase-frequency curve; (d) magnitude-frequency curve

In the later sections, the phase frequency curve is selected to explore the characteristics of the detection method since the phase value is limited in the range of $-90^\circ$ to $90^\circ$ and it is easier to find the change region in the curve. In this paper, the change region, shown in Figure 2(c), is defined as the feature region which reflects the resonant frequency information of the target coil. But because it is too complex to calculate $f_3$ and the minimum point of the curve, this paper just carries on the qualitative analysis in later sections.

The transmitting coil and target coil in this paper are both one-turn copper circular coils with the same model parameters, which are shown in Figure 3. The electrical parameters can be calculated from the following equations.
\[ L = \frac{\mu_0 r}{2} \int_0^{2\pi} \left( -r_p \sin \phi_p + (r + a) \right) d\phi_p d\phi_p \]  
\[ M = \frac{\mu_0 r}{2} \int_0^{2\pi} \left( -\sin \phi_p r_p + (r + a) \right) d\phi_p d\phi_p \]  
\[ R_0 = \sqrt{\frac{\mu_0 \omega (r + a)}{2\sigma} - \frac{2a}{2a}} \]  

where \( a \) is the wire radius and \( R_0 \) is the resistance of the copper coil.

![Figure 3. Two coaxial coils](image)

Figure 3. Two coaxial coils

Therefore, the impedance of the detection system can be calculated accurately.

3. Simulation analysis through HFSS

The simulation is performed on the HFSS and the simulation model is shown in Figure 4. The model parameters are shown in table 2. The compensation capacitor \( C_1 \) of the transmitting coil is 30nF.

![Figure 4. The simulation model built in HFSS](image)

Figure 4. The simulation model built in HFSS

| Table 2. The parameters of the two coils |
|-----------------------------------------|
| **Coil radius (mm)** | **Wire radius (mm)** | **turn** |
|----------------------|----------------------|---------|
| 102.5                | 1.25                 | 1       |

3.1. The secondary coil with different resonant frequencies

Here 5 different compensation capacitors are chosen to investigate the change rule of the phase-frequency curve. From the simulation, the resonant frequencies with 5 different compensation capacitors are obtained, which are shown in table 3. The distance between the two coils is 6cm.
With different $C_2$, the impedance phase-frequency curves of the system are demonstrated in Figure 5. The simulation indicates that the curve change occurs when the secondary coil is resonant. The feature region appears near the resonant frequency $f_2$, and $f_1$ is slightly greater than $f_2$.

$$
\begin{array}{c|cccccc}
C_2 (\text{nF}) & 4.04 & 5.10 & 6.18 & 7.00 & 8.00 \\
\hline
f_2 (\text{MHz}) & 3.2825 & 2.9465 & 2.6720 & 2.4935 & 2.3330 \\
f_1 (\text{MHz}) & 3.3695 & 3.0245 & 2.7260 & 2.5460 & 2.3540 \\
\end{array}
$$

### Table 3. Comparison between $f_2$ and $f_3$ with different $C_2$ in simulation

3.2. **The influence of $R_2$ and the coils distance $d$**

This part aims to find how the detection distance changes when the target coil has different resistances. Resistance $R_2$ includes coil self-resistance $R_0$, contact resistance $R_{\text{con}}$, and additional resistance $R_{\text{add}}$. Among them, $R_{\text{con}}$ cannot be ignored because in the later experiment, the connection of the circuit will inevitably introduce contact resistance. $R_{\text{con}}$ is about 0.150Ω which measured by WK6520B impedance analyzer. The additional resistance $R_{\text{add}}$ can be artificially changed to obtain different $R_2$. In this simulation, $R_{\text{add}}$ is 0.1Ω, 1Ω and 2Ω respectively. The simulation results are shown in Figure 6. Here, a rule is made that when the phase angle changes by about 5°, the feature region is considered to be observable.
Figure 6. The change of the detection distance with different $R_2$. (a) $R_{add}=0.1\ \Omega$; (b) $R_{add}=1\ \Omega$; (c) $R_{add}=2\ \Omega$

Figure 7. The phase-frequency curves with different detection distances when $C_2=0$ and $R_{add}=2\ \Omega$
It is obvious that a smaller $R_2$ means a greater detection distance. Besides, with the increase of distance $d$, the feature region becomes less noticeable or even disappears. If $R_2$ is too large, it will be hard to find the feature region even the two coils are close to each other.

If the secondary circuit has no compensation capacitor and the additional resistance $R_{add}=2\Omega$. The phase-frequency curve in different distances are shown in Figure 7. Only when $d=2$, the curve with a RLs target can be distinguished easily.

4. Experiment results

After the simulation of HFSS, this part focuses on the related experiments, which aims to verify the feasibility of the proposed detection method. The experiment in this paper is shown in Figure 8. It includes the R&S vector net analyzer, the transmitting coil and the target coil. The coil parameters are the same with that in the previous simulation section.

![Figure 8. Experiment device](image)

### 4.1. The relationship between the feature region and the resonant frequency $f_3$ of the target coil

Before the test, the resonant frequencies $f_3$ of the target coil with different compensation capacitors were measured by the impedance analyzer. $f_2$ and $f_3$ are shown in table 4.

| $C_2$ (nF) | 4.04 | 5.10 | 6.18 | 7.00 | 8.00 |
|-----------|------|------|------|------|------|
| $f_2$ (MHz) | 3.1694 | 2.8491 | 2.5772 | 2.4018 | 2.2535 |
| $f_3$ (MHz) | 3.1850 | 2.8630 | 2.6120 | 2.4070 | 2.2610 |

The experimental results in table 4 are in good agreement with the simulation results. The feature region appears near the resonant frequency $f_3$, and $f_2 > f_3$. The results show the feature region is the reflection of the resonance of the secondary coil.

### 4.2. The influence of $R_2$ and the coils distance $d$

In order to change $R_2$, the compensation resistance $R_{add}$ is added. Consistent with the simulation, $R_{add}$ has 3 values, 0.1 $\Omega$, 1$\Omega$ and 2$\Omega$ respectively. Here, a rule is made that when the phase angle changes by about 5°, the feature region is considered to be observable.

The experiment results shown in Figure 9 reveal the change rule of the detection distance with the increase of $R_2$. When $R_{add}=0.1$ $\Omega$, the maxima detection distance is about 14cm; and when $R_{add}=2$ $\Omega$, the maxima detection distance is about 6cm. The experiment indicates that a high quality factor coil is easier to be detected.

When it comes to the RL target coil, the impedance phase curve of the detection system shown in Figure 10 changes slightly even when the distance is 2cm. As a result, RLCs and RL targets can be distinguished easily. What’s more, the experiment results indicate the testing distance of the RLCs target is much greater than that of RLs target.
Figure 9. The change of the detection distance with different $R_2$. (a) $R_{add}=0.1 \ \Omega$; (b) $R_{add}=1 \ \Omega$; (c) $R_{add}=2 \ \Omega$. 
10. \[ f = \frac{1}{2\pi\sqrt{LC}} \]

\[ V = \frac{IE}{E_{in}} \]

From these equations, the phase-frequency response of the system can be determined.

\[ \arg\left(\frac{V}{I}\right) = \tan^{-1}\left(\frac{\omega}{\sqrt{LC}}\right) \]

\[ \omega = 2\pi f \]

**Figure 10.** The phase-frequency curves with different detection distances when \( C_2 = 0 \) and \( R_{add} = 2 \Omega \)

5. Conclusion

Starts from the diagnosis of grounding grid breakpoints and inspired by the eddy current testing method, this paper proposes a non-destructive testing method based on target resonance. The following conclusions are drawn:

This method makes it easy to distinguish RL and RLC target circuits. When a detection target equivalents to an RLC circuit, the input impedance of the system changes significantly. In addition, the detection distance of the RLC target is much larger than that of RL target.

For an RLC target, this paper defines the feature region that reflects the information of target body. Simulation and experiments show that the feature region is located near the target resonance frequency. The frequency of the minimum value in the feature region is slightly larger than the target resonance frequency.

For a target with a fixed resonant frequency, resistor \( R_2 \) and distance \( d \) are the two major factors that affect the detection. Studies have shown that the smaller \( R_2 \) is and the smaller \( d \) is, the more obvious the feature region will be. In addition, with the decrease of \( R_2 \), the detection distance increases; however, if \( R_2 \) is too large, it is difficult to detect the target even if the transmitting coil is close to it. This is one aspect that needs improvement in subsequent research.

6. References

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