Study on defect type in eddy-current testing based on phase spectrum analysis

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Abstract: This article proposes the use of phase angle gradient as a feature to detect and classify different types of defects. Based on the principle of eddy-current testing (ECT), the ECT platform was designed and manufactured. Based on phase-sensitive demodulation principle, the phase angle and gradient of the detected signal are analysed. The results show that the phase angle and phase angle gradient of different types of defect detection signals show different trends; the phase angle gradient of the integrated position direction and frequency direction can effectively identify the defect types.

1 Introduction

Eddy-current testing (ECT) is a category of non-destructive testing (NDT). ECT has been widely used in the field of defect detection [1], positioning [2], and property estimation of metal materials [3]. Compared with traditional NDT methods such as ultrasonic testing and radiographic testing, ECT has the advantages of low cost, no radiation, and no contact [4]. However, due to the large number of eddy-current detection interference factors, the traditional ECT method is vulnerable to the change of lift-off, and it is difficult to qualitatively and quantitatively measure defects. In response to this problem, many scholars have put forward their own solutions. Yin W.L. et al. [5] used analytical methods to prove that when the distance between the excitation coil and the detection coil is much larger than the diameter of the two coils, the phase angle of the electromagnetic eddy-current signal hardly changes with the lift-off. This conclusion makes phase angle measurement a valid method for solving lift-off noise problems.

The detection, classification, and quantitative evaluation of defects are an important part of ECT technology [6]. Defect classification classifies detected defects into correct defect types, such as surface defects or internal defects. In the time domain analysis, the eddy-current transient response signal peak time, time rise point, eddy-current response differential signal peak time, and zero-crossing time have been used as features to classify and identify defects. In terms of frequency domain analysis, the literature [7, 8] proposed that the spectral separation points classify and identify defects, but this feature is not easily extracted in the actual detection process.

Here, the phase angle gradient is used as a feature to classify and identify defects. The experimental results show that the defect types can be effectively identified while effectively suppressing lift-off noise.

2 Theoretical background

ECT is a conventional NDT method based on the principle of electromagnetic induction. Place the AC excitation coil over the metal plate under test, the alternating magnetic field generated in and around the excitation coil induces a swirling-induced current in the metal plate, which is called eddy current. The detection coil is used to obtain the total magnetic field information. Defects in the metal plate affect the size, phase, and flow pattern of the eddy current, which in turn causes the signal taken by the detection coil to change. By analysing the changes in the detection signal can be obtained metal plate defects and other information.

3 Experimental setup

The experimental device and its schematic diagram are shown in Fig. 1. The hardware system includes a function generator, a linear DC power supply, a V/I circuit, a sensor, a signal amplification circuit, a DAQ, a computer. The computer-controlled function generator provides a sinusoidal excitation signal to the sensor via the V/I circuit. Move the sensor along the scanning-path on the coordinate paper. The signal collected by the sensor is amplified by a signal amplifying circuit, transmitted to a computer through a DAQ for data processing and display. The V/I circuit and signal amplifier are powered by a linear DC power supply. Excitation signal is sinusoidal current signal, RMS is 500 mA, scan frequency is 1–10 kHz.

The phase angle of the electromagnetic eddy-current signal hardly rises with the lift-off when the distance between the excitation coil and the measurement coil is much larger than the diameter of the two coils. However, if the distance between the coils is too large, problems such as a decrease in the positioning accuracy of the defects and a reduction in the induced voltage will occur. Therefore, based on evaluation indicators such as defect location accuracy, induced voltage strength, and lift-off noise interference level, we set and tested the parameters such as distance between coils and scanning path. Based on the experimental results, a double air-cored coil sensor was fabricated. The excitation coil and the measurement coil have the same size, the distance between coils and scanning path are shown in Fig. 2.

Fig. 3 shows the illustration of the sample. For the specimens, A, B two aluminium plates of the same size and material have been used whose dimensions are 200 mm × 200 mm × 2 mm. A laser engraver was used to produce a defect of 10 mm × 0.1 mm × 0.1 mm at the centre of the surface of the aluminium plate B. As the
is the ideal demodulated signal

\[ n = 0 : N - 1; R \text{ and } I \text{ are the real and imaginary parts of the demodulated signal, respectively.} \]

\[ V_r(n) = K\sin(2\pi f_s n T + \varphi) = K\sin(2\pi f s n T + \varphi) \]
\[ = K\sin(2\pi f s n T + \varphi) \]

\[ r(n) = \sin(2\pi f_s n T) = \sin(2\pi f s n T) = \sin(2\pi f s n T) \]
\[ = \cos(2\pi f_s n T) = \cos(2\pi f s n T) \]

\[ R = \sum_{n=0}^{N-1} V_r(n) = \sum_{n=0}^{N-1} K\sin(2\pi f s n T + \varphi)\sin(2\pi f s n T) \]
\[ = 1/2N\cos\varphi \]

\[ I = \sum_{n=0}^{N-1} V_i(n) = \sum_{n=0}^{N-1} K\sin(2\pi f s n T + \varphi)\cos(2\pi f s n T) \]
\[ = 1/2N\sin\varphi \]

\[ \varphi = \arctan \frac{I}{R} \]

The phase angle solution block diagram (Fig. 4) can be obtained by the mathematical realisation of the above orthogonal sequence demodulation. According to practical experience, only the Nyquist sampling frequency is used to sample the demodulated signal, and the demodulated data have a large error. So this paper uses \( 8f_s \) to sample \( V_r \).

When the distance between the excitation coil and the detection coil is large, the phase angle of the electromagnetic eddy-current signal is hardly affected by the lift-off. Calculate the positional and frequency phase angle gradients of the experimental results. Based on the scan results, we obtain a phase function \( \phi(x, y) \) for position \( x \) and frequency \( f \), and the phase angle gradient along the position and frequency directions can be expressed as

\[ g_x = \frac{\partial \phi}{\partial x} \]
\[ g_y = \frac{\partial \phi}{\partial y} \]

The acquired phase angle gradient is used to create 2D colour-filled contour plot. Fig. 5 shows gradient angle diagrams of the no defect, subsurface defect, and the internal defect testing signals in the position direction (left) and the frequency direction (right) when the lift-off is 0 mm.

4.2 Defect analysis

The green area in the phase angle gradient diagram shows that there is no change in the phase angle corresponding to it, the phase angle of the red region increases, and the phase angle of the blue region decreases.

Comparing Figs. 5a and b, by observing the colour change on both sides of the defect position (position is 0CM), it can be seen that surface defect can be clearly detected in some excitation frequency ranges, and other frequency ranges can hardly detect defect. We refer to the frequency of excitation that can detect defect as the sensitive frequency range. Surface defect has a sensitive frequency range of 1–2 kHz.

As can be seen from Figs. 5c and d, the sensitive frequency range of the subsurface defect is 1–5 kHz, and the sensitive frequency range of the internal defect is 1–4 kHz.
As the internal defects of the test piece are not easy to process, there is noise in the internal defect detection result chart.

### 4.3 Defect classification

Observe the phase angle gradient plot of the position direction in Fig. 5. In the sensitive frequency range, the subsurface defect and the internal defect exhibit the same colour change on both sides of the defect position, and the colour change of the surface defect on both sides of the defect position is opposite to the surface defect and the internal defect. Combined with the experimental scanning path, it can be known that the phase angle becomes larger at the subsurface defect and internal defect, and becomes smaller at the surface defect.

Observe the phase angle gradient diagram in the frequency direction of Fig. 5. The surface defect and the subsurface defect exhibit the same tendency of the protrusion at the defect position, and the internal defect exhibits a change in the shape of the opposite trend at the defect.

### 5 Conclusion

Here, orthogonal sequence demodulation is used to extract the phase angle gradient. The experimental results show that the experimental system can effectively detect different types of defects, but due to the internal defects are not easy to process, the internal defect detection effect is not ideal.

The different types of defects show different trends in the phase angle gradient diagrams of the position and frequency directions, and the defects can be classified effectively by combining the change trends of the two directions.

The experiment found that different types of defects have different sensitive frequency ranges. When the change in the phase angle in the frequency direction is gentle, the corresponding frequency cannot detect the defect, and when the change in the phase angle is severe, the corresponding frequency can detect the defect. The sensitive frequency range may be related to the slope of the phase angle with respect to the frequency change.

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### 7 References

[1] Helifa, B., Oulhadj, A., Benbelghit, A., et al.: ‘Detection and measurement of surface cracks in ferromagnetic materials using eddy current testing’, *NDT E Int.*, 2006, 39, (5), pp. 384–390

[2] Zhang, R., Shan, L., Liu, Z., et al.: ‘Pulse eddy current nondestructive testing method based on the spatial distribution entropy’, *Chin. J. Sci. Instrum.*, 2015, 36, (4), pp. 804–811

[3] Tian, G.Y., Sophian, A., Taylor, D., et al.: ‘Wavelet-based PCA defect classification and quantification for pulsed eddy current NDT’, *IEEE Proc., Sci. Meas. Technol.*, 2005, 152, (4), pp. 141–148

[4] Ghoni, R., Dollah, M., Sulaiman, A., et al.: ‘Defect characterization based on eddy current technique: technical review’, *Adv. Mech. Eng.*, 2014, 2014, (1), p. 11

[5] Yin, W., Binns, R., Dickinson, S.J., et al.: ‘Analysis of the liftoff effect of phase spectra for eddy current sensors’, *IEEE Trans. Instrum. Meas.*, 2007, 56, (6), pp. 2775–2781

[6] Gao, J., Pan, M., Luo, F., et al.: ‘Spectrum analysis and defect classification of pulsed eddy current testing’, *Proc. CSEE*, 2011, 31, (28), pp. 154–160

[7] Yang, B.: ‘Quantification and classification of cracks in aircraft multi-layered structure’, *Chin. J. Mech. Eng.*, 2006, 42, (2), pp. 63–67

[8] Yang, B., Luo, F., Han, D.: ‘Pulsed eddy current technique used for non-destructive inspection of ageing aircraft’, *Insight*, 2006, 48, (7), pp. 411–414