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Multidirectional Alternating Current Potential Drop Technique for Detecting Random Cracks

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ABSTRACT The alternating current potential drop technique has been widely used to measure subsurface cracks in metal structures. However, the application of the technique to random cracks has, to date, been limited. By using a multidirectional alternating current potential drop technique, the angle between crack and exciting electrode wire changes from 0° − 90° to 67.5° − 90°, which considerably expanded the ranges of detection. Simulation and experiment results showed that this technique can accurately measure the depth of random cracks.

INDEX TERMS Alternating current potential drop technique, multidirectional current, random cracks, depth measurement.

I. INTRODUCTION

The alternating current potential drop (ACPD) technique makes use of an increase in electrical resistance of a metallic conductor caused by crack initiation and growth [1]. It can achieve high sensitivity with low injected current [2]–[4]. The technique is based on 'skin effect' [5]–[8], which is closely related to the current frequency. As the frequency decreases, the current distribution in the material shifts from the surface of the conductor to the entire conductor. The skin depth δ can be represented by the following relation:

$$\delta = \frac{1}{\sqrt{\pi \mu_r \mu_0 \sigma f}} \tag{1}$$

where μ_r is the relative magnetic permeability, μ_0 the magnetic permeability of free space, σ the electrical conductivity, and f the frequency of excitation current.

Figure 1(a) shows the initial state of a metal pipe without defects. After a period of service, defects form in the inner walls of the pipe, whereas the outer walls are always well protected. Figure 1(b) shows a crack defect with depth d in the inner wall.

$I(f)$ is the excitation current with frequency f. It can be represented by:

$$I(f) = Ie^{j2\pi ft} \tag{2}$$

Where I is the current amplitude, $j = \sqrt{-1}$, and t is time.

The electric field equation is as follows:

$$\nabla^2 E(r) + k^2 E(r) = 0 \tag{3}$$

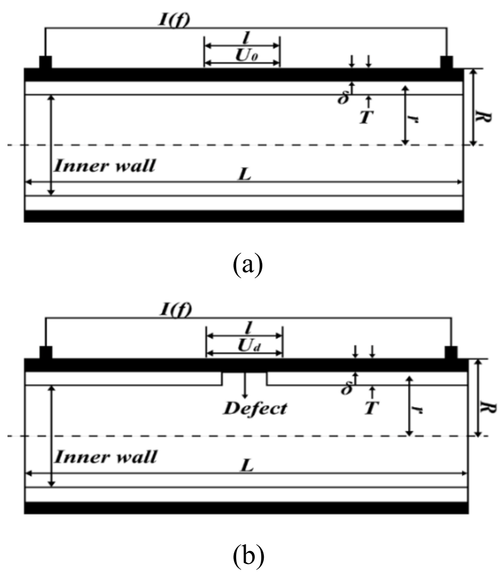

FIGURE 1. Schematic diagram of (a) initial state without defects and (b) presence of a crack defect.

with

$$k = (1 - j)\sqrt{\pi \mu_r \mu_0 \sigma f} \tag{4}$$

The current density $J(r)$ can be determined by the intensity of the electric field at the same position r:

$$J(r) = \sigma E(r) \tag{5}$$

Where r is the radial position measured from the center of the conductor, and $E(r)$ is the intensity of the electric field at r.

The solution of $J(r)$ in the conductor is as follows [9]:

$$J(r) = \frac{Ik}{2\pi R} \cdot \frac{J_0(kr)}{J_1(kR)} \tag{6}$$

where J_0 and J_1 are Bessel functions of the first kind, with order zero and one, respectively, R *is* the outer radius of specimen, and l *is* the distance between each pair of electrodes, so the theoretical potential drop across this distance can be described as:

$$U(r) = l \cdot \frac{I \cdot k}{2\pi R\sigma} \cdot \frac{J_0(kr)}{J_1(kR)} \tag{7}$$

Bessel functions can be approximated by an exponential function. In this case, the absolute value of the voltage can be written as [10]:

$$|U(r)| = \frac{I}{\sqrt{2}\pi R\delta} e^{\frac{r-R}{\delta}} \tag{8}$$

Equation (8) shows that the voltage changes at different radial distances. In this work, the contact depth d_0 between the potential electrodes and the outer wall of the pipe was approximately 0.5mm, so the voltage obtained on the two electrodes was:

$$U = \frac{I}{\sqrt{2}\pi R\delta} e^{-\frac{d_0}{\delta}} \tag{9}$$

The wall thickness of the pipe is given by T. The initial voltage is U_0, and the voltage measured with a defect is U_d. An approximation can be made using (9). If the defect of the inner wall is extremely shallow ($d \approx 0$), then, as the frequency decreases, U_d/U_0 approaches 1. If the defect of the inner wall is attributed to general corrosion [11], [12], then, as the frequency decreases, U_d remains constant once $\delta = T - d$, and $U_d/U_0 \approx m/U_0$ (where m is constant). However, if the defect is a crack, the current around the defect layer will infiltrate downward as the frequency decreases, i.e., $U_d < m$, then $U_d/U_0 < m/U_0$.

Therefore, a general solution to calculate a crack defect can be approximated by a linear superimposition of two extreme cases: that without defects and that where the defect is due to general corrosion:

$$\frac{U_d}{U_0} = a_1 \cdot 1 + a_2 \cdot de^{a_3 d} \tag{10}$$

where a_1, a_2 and a_3 are constants.

II. MULTIDIRECTIONAL ACPD TECHNOLOGY DEVELOPMENT

We studied the relationship between the directions of the exciting electrode wire and the crack. The COMSOL finite element simulation software (COMSOL Inc., Stockholm, Sweden) was used to perform a numerical analysis to illustrate the relationship. Figure 1 shows the metal pipe simulation model with properties as listed in Table 1.

TABLE 1. Parameters of model.

I/A	σ/ms	μ_r	*l/mm*	*R~r~L*/mm	*T/mm*	*d/mm*
2	43	1	20	160~140 ~400	10	2~0.5~6

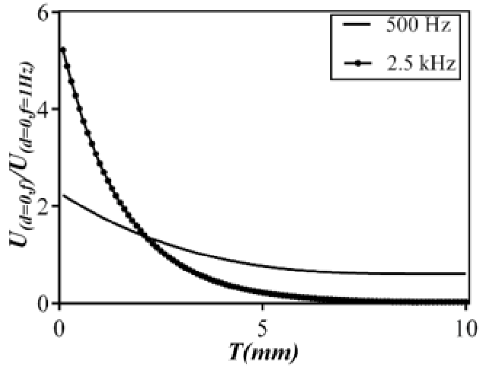

FIGURE 2. Calculated distribution of alternating current potential drop.

The calculated distribution of potential drop was obtained by substituting parameters from Table 1 and current frequency f into (4) and (7).

Before calculating the potential drop, we should confirm the value of f. In Figure 2, the skin current could not completely penetrate the pipe wall at 2.5 kHz, so the voltage U_d could not reflect information pertaining to a shallow defect in this case. When the frequency decreased to 500 Hz, the penetration current was able to reach the defect layer at each depth. Considering that δ should be smaller than the wall thickness ($T = 10$ mm), the lower limit of frequency was calculated as 59 Hz according to (1). Therefore, the current frequency could be selected between 59 and 500 Hz. In this work, we chose 100 Hz as the frequency of the excitation current.

In Figure 3(a), U_0 could be obtained without defects. Figures 3(b)-(e) represented four position defects with the same length, width, and depth. φ is the angle between the crack and exciting electrode wire.

In Figure 5, when φ was smaller than 45°, the value of U_d/U_0 could not assess the crack depth using (10). However, when φ was greater than 45°, and the closer it was to 90°, the more closely the relationship between the value of U_d/U_0 and crack depth followed the exponential distribution of (10). In addition, the value of U_d/U_0 at 90° was larger than at any other angle.

The variation of U_d could be assessed by Ohm' law. We could regard the area measured between the potential electrodes as a volume resistance R_{es}.

$$U_d = R_{es} I \tag{11}$$

R_{es} was conversed with the cross-section of the volume resistance:

$$R_{es} = \frac{\rho l}{S} \propto \frac{1}{S} \tag{12}$$

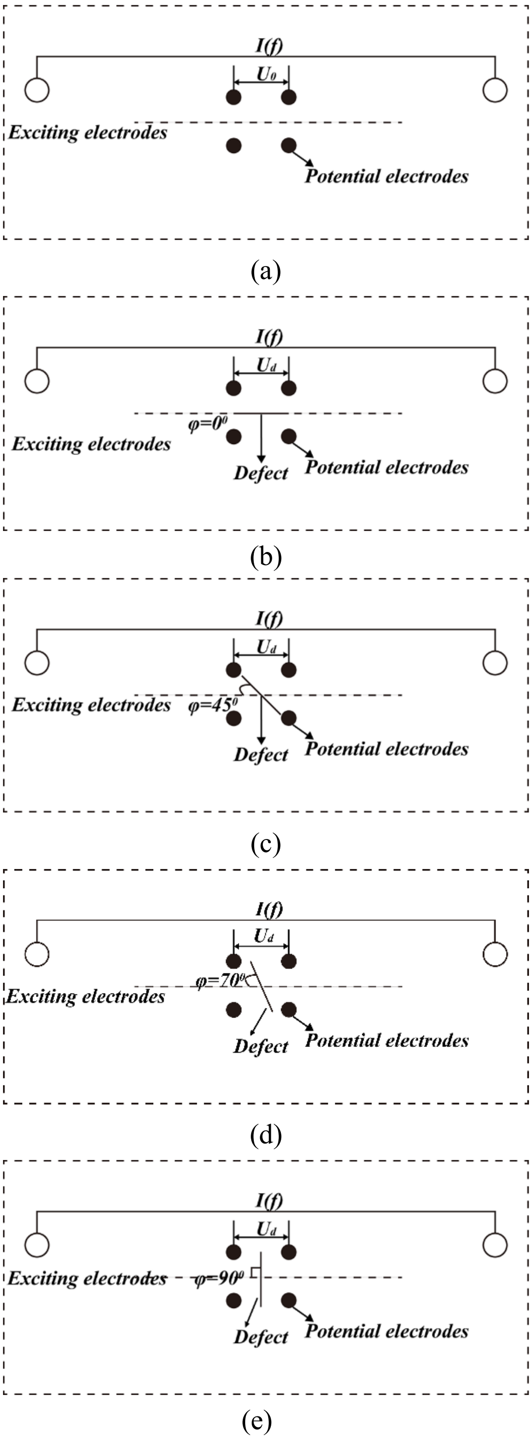

FIGURE 3. Diagrams of (a) initial state without defects and with crack defects at (b) 0°, (c) 45°, (d) 70°, and (e) 90° relative to the position of the electrode wire.

Where ρ is the resistivity of conductor, and S is the cross-section perpendicular to the direction of the current.

Figures 4(a)-(b) represented the current distribution of two cases involved in Figure 3, where φ were 0° and 90 °. Compared Figure 4(a) with 4(b), the current flew through a larger cross-section when φ was 0° :

$$S_1 > S_4 \tag{13}$$

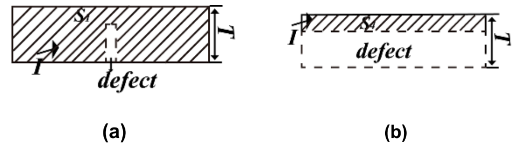

FIGURE 4. current distribution in the cross sectional area of two cases ($\varphi = 0^0, 90^0$).

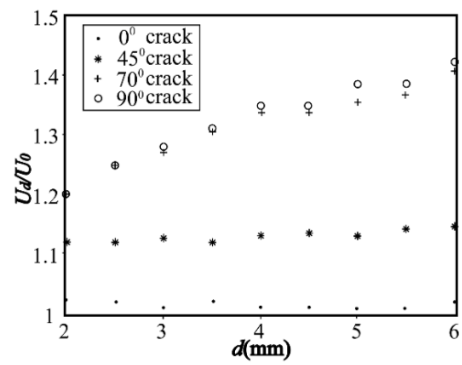

FIGURE 5. Voltage ratio curve ($\varphi = 0^0, 45^0, 70^0, 90^0$).

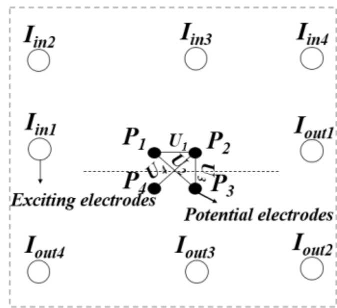

FIGURE 6. Measured metal with multidirectional current (U_1 represents U_{1d} or U_{10}, U_2 represents U_{2d} or U_{20}, U_3 represents U_{3d} or U_{30}, U_4 represents U_{4d} or U_{40}).

Where S_1 is the cross-section of 0° crack, and S_4 is of 90° crack.

Substituting (13) into (12), We could observe that the value of R_{es} at 0° was smaller than 90°. Thus the former voltage was smaller than the latter. A method defined as the multidirectional alternating current potential drop (MACPD) technique was therefore extracted to measure random crack depths. The angle between the crack and exciting electrode wire changed from 0° –90° to 67.5° –90° by adding three sets of excitation currents, as shown in Figure 6.

The depth could be accurately determined by substituting the largest values of U_d/U_0 from the four voltages as follows into (10):

$$\left(\frac{U_{1d}}{U_{10}}, \frac{U_{2d}}{U_{20}}, \frac{U_{3d}}{U_{30}}, \frac{U_{4d}}{U_{40}}\right)$$

III. EXPERIMENTAL VERIFICATION

To verify the accuracy of the proposed method, experiments were conducted using an SR850 digital lock-in amplifier (Stanford Research Systems, CA, USA) and a power ampli-

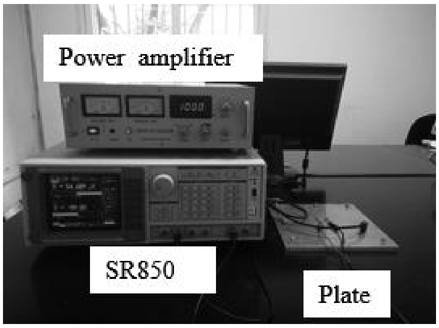

FIGURE 7. Experimental equipment.

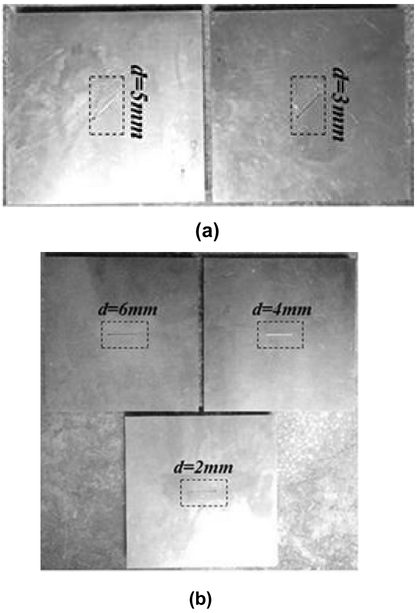

FIGURE 8. Metal plate specimens with crack defects at (a) 45° and (b) 0°.

fier, as shown in Figure 7. The power amplifier provided a maximum sinusoidal current (***I***) of 2 A with a frequency at 100 Hz from a source signal from the SR850 amplifier. Figure 6 shows the probe configuration. Five 220 mm × 220 mm × 10 mm metal plates were used as test specimens, as shown in Figure 8. The μ_r, μ_0, and σ values of these specimens are summarized in Table 1. Plate 1-2 measured cracks at 45° at depths of 3 mm and 5 mm. Plate 3-5 had 0° cracks at depths of 2 mm, 4 mm, and 6 mm.

Before machining the defects, alternating current of 2 A with a frequency of 100 Hz was successively injected into the plate through I_{in1}, I_{in2}, I_{in3}, and I_{in4}. The SR850 amplifier was used to measure the initial voltages U_{10}, U_{20}, U_{30}, and U_{40} between probes (P_1–P_2), (P_1–P_3), (P_2–P_3), and (P_3–P_4), respectively. The values of U_{1d}, U_{2d}, U_{3d}, and U_{4d} were obtained in the same way.

After the voltage measurements were completed, eight voltages for each plate were obtained. Substituting the largest values of U_d/U_0 into (10), we could acquire the results. The constants in (10) were given by simulation data. COMSOL

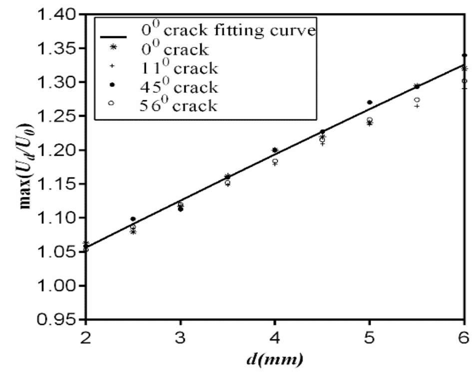

FIGURE 9. Max(U_d/U_0)-*d* curve($\varphi = 0^0$).

TABLE 2. Simulation results.

φ (0)	Real depth (mm)	Measuring depth (mm)	error (%)
11	2.00	1.93	-0.7
	3.00	2.86	-1.4
	4.00	3.79	-2.1
	5.00	4.65	-3.5
	6.00	5.51	-4.9
45	2.00	2.03	0.3
	3.00	2.81	-1.9
	4.00	4.15	1.5
	5.00	5.15	1.5
	6.00	6.17	1.7
56	2.00	1.96	-0.4
	3.00	2.91	-0.9
	4.00	3.79	-2.1
	5.00	4.77	-2.3
	6.00	5.64	-3.6

Multiphysics 4.5 was used for theoretical calculations. Material parameters and dimensions of the simulation model were the same as test specimens. The simulation cracks measured at 0°, 11°, 45°, and 56° at depths of 2 mm, 2.5 mm, 3 mm, 3.5 mm, 4 mm, 4.5 mm, 5 mm, 5.5 mm and 6 mm. Figure 9 and (14) showed the fitting results. Table 2 showed the partial results of simulation. The measuring depth could be obtained by substituting the largest values of U_d/U_0 into (14). The error was calculated by [14], [15]:

error (%) = 100 % × (measuring depth – Real depth)/*T*

$$\frac{U_d}{U_0} = 0.9137 + 0.07261de^{-0.009146d} \tag{14}$$

Table 3 showed the voltage ratios of different depths and angles based on 5 test specimens. The results were listed in Table 4.

TABLE 3. The voltage ratio of different depths and directions.

φ^0	d/mm	$\frac{U_1(d)}{U_{10}}$	$\frac{U_2(d)}{U_{20}}$	$\frac{U_3(d)}{U_{30}}$	$\frac{U_4(d)}{U_{40}}$
0	2.00	0.950	0.956	1.091	0.988
	4.00	0.967	1.086	1.191	1.048
	6.00	0.952	1.236	1.350	1.237
45	3.00	0.992	0.952	1.003	1.142
	5.00	1.044	0.987	1.055	1.269

TABLE 4. Experimental results.

φ^0	Real depth (*mm*)	Measuring depth （mm）	error (%)
0	2.00	2.49	4.9
	4.00	3.96	-0.4
	6.00	6.37	3.7
45	3.00	3.24	2.4
	5.00	5.15	1.5

The results clearly demonstrated that the proposed method could accurately measure the depth of random crack defects.

IV. CONCLUSION

MACPD could be used to assess random defects on a subsurface. We used the largest values of U_d/U_0 to determine the crack depth because numerical analysis showed that the angle between the crack and exciting electrode wire changed from 0° –90° to 67.5° –90° by using this technique. The experimental results were in good agreement with fitted equations based on simulation.

To enable the more widespread use of MACPD technology, the applicability of (14) to identifying cracks with varying depth and the occurrence of complex defects (cracks) should also be considered.

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