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Annular Eddy Current Array Method for Detecting Capillary Pressure Pipe Corrosion and Crack Defects: COSMOL-based Simulation, Array Probe Optimization, and Experimental Verification

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Abstract: This study proposed an annular eddy current array detection method to satisfy high-precision and high-efficiency requirements on capillary pressure pipe defects. First, using COSMOL software, the annular eddy current array detection model of capillary pressure pipe defects was developed and realized, optimizing the array probe key parameters. Next, the corrosion defects on the inner and outer walls and the crack defects on the capillary pressure pipe were detected with the optimized probe, with signal features of different types of defects compared and analized in detail. Finally, the probe prototype and the related test system were developed based on the optimized theoretical model, and crack and corrosion defects on the capillary pressure pipe were detected and identified. The experimental results proved that the proposed annular eddy current array detection method effectively detected cracks on the inner and outer walls and corrosion defects along the capillary pressure pipe. The present research results show favorable application prospects for thin-wall capillary pressure pipes in the defect detection field.

Keywords: nondestructive detection, capillary pressure pipe, eddy current array, electromagnetic testing, COSMOL software

1 Introduction

Capillary pressure pipes, combining small diameter, thin wall thickness, and ability to withstand certain pressures, have been extensively applied in aerospace, energy and chemical industry, transportation, and special equipment for transport, distribution, mixing and flow control of special media with certain pressure [1, 2]. Because of the small pipe diameter and low wall thickness, some manufacturing deficiencies easily appear during production, including cracks, perforations, and stratification. The capillary pressure should bear certain pressure in use, and the transported media generally exhibit high-temperature, high-pressure, copious cooling, and corrosive features, thereby easily causing certain damages, including fatigue cracks, etch pits, and perforation. Consequently, it is necessary to adopt appropriate nondestructive detection methods during production and use processes to take periodic and effective detection of the defects and damages of the capillary pressure pipes. Accordingly, some safety accidents induced by leakage and bursts of capillary pressure pipes can be effectively avoided.

The existing nondestructive detection methods for fatigue damages and defects of capillary pressure pipes mainly include visual inspection, leakage magnetic field inspection, ultrasonic guided-wave method, and eddy current detection method. For example, Duran et al. developed a small-size visual detector to achieve visual measurement of the defects in the pipes with a diameter of 10 mm [3]. Wu et al. adopted micro-motor to drive the rotation of the reflecting mirror to achieve the scanning of laser points of the pipe section ring, and meanwhile, used the two-dimensional (2D) position sensor to receive the spot signal for the realization of three-dimensional (3D) reconstruction of the internal pipe surface with an inner diameter of 9.5~10.5 mm and the related defect detection [4]. Yang et al. used Lamb waves to detect microcracks in thin-walled tubes [2], and the detection effect was good, but it was difficult to achieve defect quantification. Black et al. used a combination of acoustics

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and accelerometers to detect defects in small-diameter nuclear power pressure pipes and could detect holes with a diameter of 7.66% of the pipe diameter [5]. Zhou designed a new type of ultrasonic probe for defects at the ring joint of small diameter thin-walled pies, which shows high sensitivity in defect detection [6]. The ultrasonic crack tip diffraction method was used by Lindenschmidt et al. for crack detection in thin-walled nuclear power tubes, detecting crack defects of up to 0.4 mm depth [7].

Visual inspection can only detect surface defects. Leakage magnetic field inspection only applies to defect detection of ferromagnetic pipes, with low detection precision. Ultrasonic-guided wave detection shows low precision and can hardly be used for defect detection of ultra-fine pipes. By contrast with the above detection techniques, eddy current detection possesses a series of advantages, such as high precision and small probe size [8, 9], which applies to the defect detection of fine pipes. Thus, Xin et al. developed a rotating-field eddy current probe for the detection of the pipes in the steam generator, which can achieve effective detection and position of the circumferential through-hole defects and notch defects; however, the probe showed complex forms and high fabricating cost [10]. Yang et al. investigated a novel circumferential-eccentricity Bobbin eddy current probe, which could detect axial and circumferential defects of small-diameter pipes (with an inner diameter of 20 mm) simultaneously but failed in quantitative analysis of defects [11]. Yu et al. provided pulsed far-field vortex detection of small-diameter pipes and realized precise quantitative detection of the pipes with a 25 mm diameter [12].

However, the existing eddy current detection methods still show certain shortcomings, so they can hardly achieve accurate and rapid defect detection for capillary pressure pipes, especially those with a diameter below 5 mm. This study proposed annular eddy current array detection for capillary pressure pipes to achieve high-precision and high-efficiency nondestructive detection of both damages and defects of capillary pressure pipes. First, using COSMOL software, the eddy current array detection model of the capillary pressure pipe was established to analyze the design method of the annular eddy current array probe. Next, the signal characteristics of different defects of the capillary pressure pipe were examined with simulation. Finally, the eddy current array probe prototype and the related experimental system were prepared to inspect the defects of the capillary pressure pipes. According to the present experimental data, the proposed annular eddy current array detection method for capillary pressure pipes can effectively detect many types of defects of capillary pressure pipes with high detection efficiency and precision.

2 Theoretic Research

2.1 Detection Principle

The eddy current defect defection technique (depicted in Fig. 1) refers to an exciting eddy current field on the near-surface of the conductive metal in the alternative electromagnetic field B1 excited by the inductance coil. In case of no defect, the vortex field is uniformly distributed near the surface of the conductive metal. After the appearance of defects, the originally uniform-distribution eddy field is subjected to the defects. Since the eddy current field of the near-surface of the metallic conductor can generate the secondary magnetic field B2 in the nearby space, the spatial distribution of the generated secondary magnetic field B2 can change when the originally uniform eddy field is disturbed by defects. Accordingly, the spatial distribution of the resultant magnetic field (i.e., the superimposition of B1 and B2) changes. By obtaining the change information of the resultant magnetic field with the detection lines and taking feature analysis, the eddy current detection of the defects of the metallic conductor can be achieved.

The common eddy current detection coils show two typical structures: self-excitation/self-receiving and one excitation/one receiving [13]. Aiming to enhance defect detection precision, this study adopted the one-excitation/multi-receiving array coil structure based on one excitation/receiving structure. As shown in Fig. 2, the capillary pressure pipe was sleeved by the circular excitation coils. This study placed traditional and exciting coils in parallel to enhance detection precision. It changed the detection coils with the same specifications into many detection coils at smaller sizes with axial distribution along the capillary pressure pipe. The detection coils were laid side by side on one side of the exciting oil. When the alternating current at a certain frequency was loaded, an annular eddy field was formed on the pipe wall below the coil. In case of no defects, the detection coils output the same signals since the eddy current field with circumferential distribution along the capillary pipe shows the same characteristics. When the defects appeared below a detection coil, the output signal changed and the signal output from the other detection coils without defects below remained unchanged. By contrast with

the traditional one excitation/one receiving design structure, the proposed array coil structure can significantly reduce the size of the detection coil and, meanwhile, enhance defect detection precision.

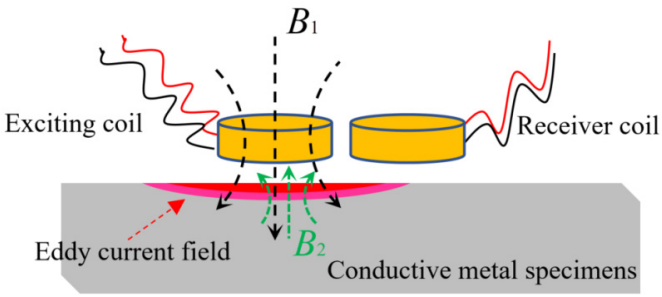

Fig. 1. The principle of eddy current detection

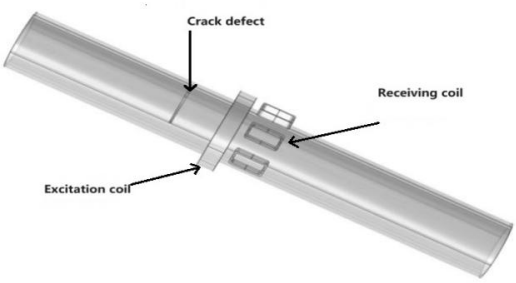

Fig. 2. Principle of defect detection for capillary pressure pipes based on eddy current array

2.2 Probe Simulation

Generally, the diameter of a capillary pressure pipe is smaller than 10 mm, and the wall thickness is below 1 mm. This study focused on a steel capillary pressure pipe with a diameter of 4.0 mm and a wall thickness of 0.2 mm. It analyzed the defect detection method based on an eddy current array. The related parameter settings are described below. For the exciting coil, the number of windings was 1, the initial inner diameter and external diameter were 4.5 mm and 6.5 mm, and the width was 1.0 mm; for the detection coil, the number of windings was 100, and the size was 2.0 mm × 1.0 mm × 1.0 mm. The initial spacing between the exciting and detection coils was 0.5 mm, and the wall thickness of the capillary pressure pipe was 0.2 mm. According to the formula of eddy current penetration depth, the following expression can be derived as follows:

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

where δ is the eddy current penetration depth, μ is the magnetic permeability of the material, f is the excitation frequency, and σ is the material conductivity.

In this study, the excitation frequency was set as 10kHz. Table 1 lists the material parameters of the capillary pressure pipe.

Table 1. Material parameters of the capillary pressure pipe

Property	Value	Property	Value
Poisson's ratio	0.29	Heat capacity at constant pressure	440 [J/(kg*K)]
Relative dielectric constant	1.0	Heat conductivity coefficient	76.2 [W/(m*K)]
Conductivity	1.12×10^{7} [S/m]	Density	7870 [kg/m^3]
Relative magnetic conductivity	4000	Thermal expansivity	12.2×10^{-6} [1/K]

The inner diameter of the exciting coil is a key parameter that affects the detection signal. This study first investigated the effect of the exciting coil's inner diameter on the defects' detection signal. The transverse defect, with a width of 0.1 mm, a length of 2.0 mm, and a depth of 0.1 mm, was set on the surface of the outer wall. The excitation signal frequency was 10kHz, and the excitation current was 50 mA. For the detection coils, the inner diameter ranged from 4.5 mm to 5.4 mm at an interval of 0.3 mm. The probe scanned the cracked defect, and the variation of the peak-to-peal value of simulated detection signal with the inner diameter of the exciting coil was obtained, as shown in Fig. 3.

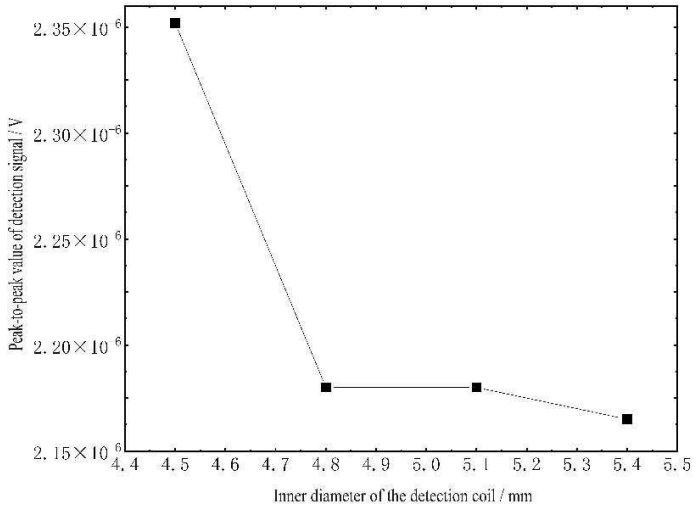

Fig. 3. Variation of the peak-to-peak value of the simulated detection signal with the inner diameter of the exciting coil

Apparently, at an inner diameter of 4.5~4.8 mm, the peak-to-peak value of the detection signal decreased rapidly with the increasing inner diameter; as the inner diameter of the exciting coil exceeded 4.8 mm, the peak-to-peak value also decreased with the increase of the inner diameter, but the rate of descent dropped. It can also be observed from Fig. 3 that the probe shows higher detection sensitivity at a smaller inner diameter of the excitation coil. However, a certain gap must exist between the detection probe and the surface of the capillary pressure pipe during the actual detection process. Otherwise, the probe can hardly slide smoothly. Therefore, the inner diameter of the exciting coil was set as 4.5 mm in this study. Next, the effects of the spacing between the exciting coil and the detection coil on the detection signal were examined. The inner diameter of the exciting coil was set as 4.5 mm, and the spacing between the exciting coil and the detection coil increased from 0.5 to 1.7 mm at an interval of 0.3 mm. Under the same detection condition, the variation of the peak-to-peak value of the simulated detection signal with the spacing was measured, as shown in Fig. 4.

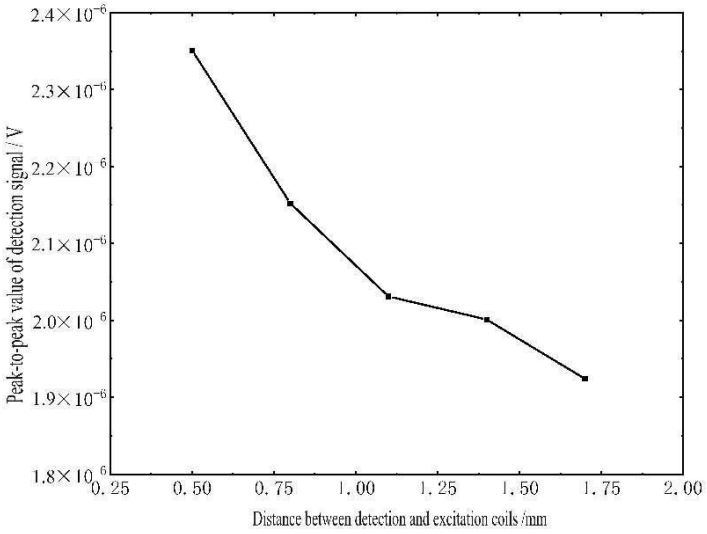

Fig. 4. Variation of the peak-to-peak value of the simulated detection signal with the spacing between the exciting and detection coils

It can be observed that the peak-to-peak value of the detection signal dropped linearly with the increasing spacing between the exciting coil and the detection coil within a range of 0.5~1.7 mm. Further, the detection sensitivity of the probe dropped with the increase of the spacing. This study set the spacing between the exciting and detection coils as 0.5 mm.

3 Numerical Simulation of Defect Detection Process

Capillary pressure pipes generally show different types of defects, including corrosion, cracks, and deformation. On the other hand, the defect types include inner defects, outer defects, and penetration defects. Both defect depth and direction also significantly affect the detection signal. This study focused on commonly-existed crack and corrosion defects to examine the signal characteristics of different types of defects. It investigated the effects of some key factors of different types of defects (including depth, size, and direction) on the detection signal with COMSOL software. In the present simulation, the frequency of the exciting coil in the eddy current array probe was set as 10 kHz, and the excitation current was set as 50 mA.

3.1 Detection of the Crack Defects

Because of the small wall thickness, penetration cracks are commonly found in the capillary pressure pipe. In this study, five longitudinal penetration crack defects with the same width of 0.1 mm and different lengths (0.5, 1.0, 1.5, 2.0, and 2.5 mm) were set along the capillary pressure pipe along the axial direction. Next, the probe scanned these five longitudinal crack defects in turn. The corresponding vortex current detection signals were obtained, as shown in Fig. 5. Overall, the detection signals of the longitudinal penetration crack defects with different lengths showed identical waveforms. Still, the detection signal's peak value increased with the longitudinal crack's length. The observation from Fig. 5 confirmed the designed eddy current array probe's feasibility in detecting longitudinal penetration crack defects, with a detection precision of up to 0.5 mm.

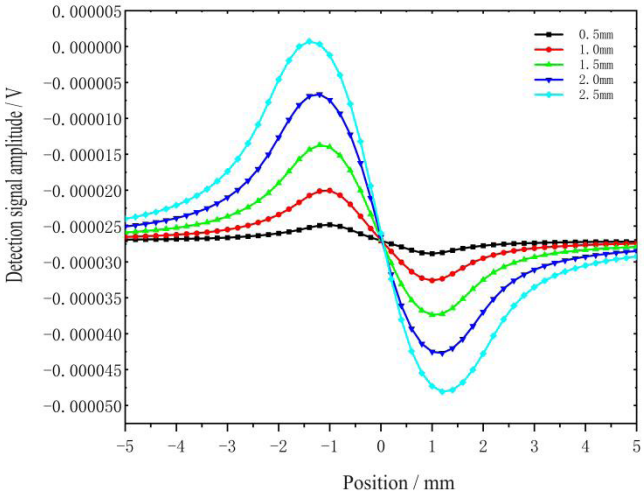

Fig. 5. Waveform of simulated detection signals for longitudinal penetrating crack defects with different lengths

Next, five different transverse crack defects with an identical width of 0.1 mm and different lengths (0.5, 1.0, 1.5, 2.0, and 2.5 mm) were set along the axial direction of the capillary pressure pipe. Under the same detection condition, the simulated detection signal of the transverse defects with different lengths was obtained, as shown in Fig. 6. For the crack with a length of 0.5 m; the detection signal showed almost no change; as the crack lengths reached 1.0 mm, the detection signal changed significantly. As the length of the transverse crack increased, the detection signal was constantly enhanced. It can be concluded from Fig. 6 that the designed probe can effectively detect the transverse penetration crack with a no smaller than 1.0mm length.

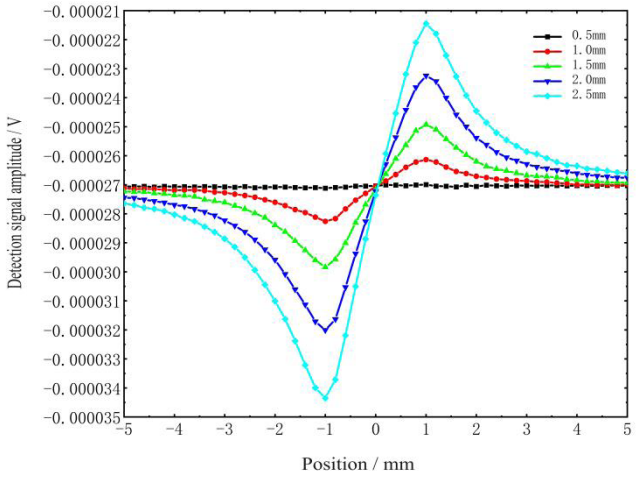

Fig. 6. Waveform of simulated detection signals for transverse penetrating crack defects with different lengths

Non-penetration cracks can seriously affect the performance of capillary pressure pipes. This study set both inner- and outer-wall cracks along the capillary pressure pipe to investigate the signal characteristics of non-pen-

etration cracks in the capillary pressure pipe. The cracks were 50% in corrosion depth, with a length of 1.0 mm and a width of 0.1 mm. Next, under the same conditions, the probe scanned two non-penetration cracks in turn, and the eddy current detection signal of both inner and outer cracks with a corrosion depth of 50% was obtained.

As shown in Fig. 7, signals of these two types of cracks showed opposite directions, and the signal strength of the inner cracks exceeded that of the outer cracks. The capillary pressure pipe was thin, and the eddy current density differed slightly in the whole wall. The eddy currents at the outer wall defect were concentrated on the bottom of the defect; accordingly, the eddy current field was far away from the detection coil, leading to a decline in signal strength. On the contrary, the eddy currents at the inner-wall defect were close to the detection coil, and therefore, the signal strength of the inner-wall defect was greater than the value of the inner defect at the same depth. It can be observed from Fig. 7 that the designed eddy array probe can not only effectively detect the non-penetration crack at both the inner and outer wall of the capillary pressure pipe with a depth of 50% but also adequately judge the position of the non-penetration crack.

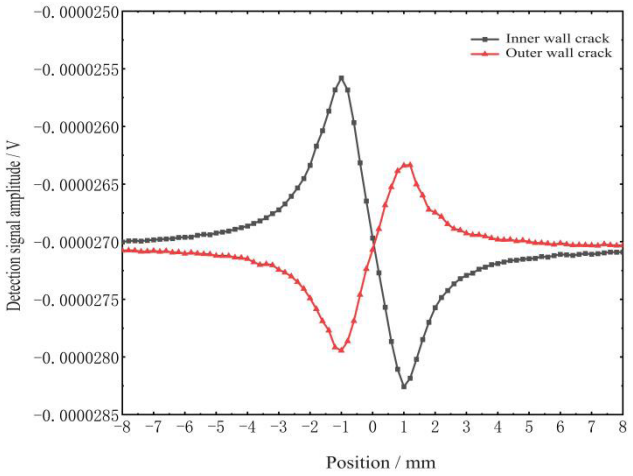

Fig. 7. Waveform of simulated detection signals for transverse cracks on inner and outer walls with a corrosion depth of 50% of wall thickness

3.2 Detection of Corrosion Defects

Corrosion defects are also commonly found in capillary pressure pipes. This study also investigated the signal characteristics of different types of corrosion defects. First, the signal features of through-hole corrosion defects were examined. In this study, five through-hole corrosion defects with different diameters (0.5, 1.0, 1.5, 2.0, and 2.5 mm) were set in success along the capillary pressure pipe, the excitation frequency of the eddy current array probe was set as 10 kHz, and the excitation current was set as 50 mA. Next, the probe scanned the through-hole corrosion defects with different diameters in turn, and the simulated detection signals of these defects were obtained, as shown in Fig. 8. It can be observed that the peak value of the detection signal increased with the diameter of the through-hole corrosion defect in the range of 0.5~2.5 mm. Moreover, the probe can detect through-hole corrosion defects with a minimum hole diameter of up to 0.5mm.

Next, the signal features of the non-through corrosion defects at the capillary pressure pipe's inner and outer walls were simulated. The corrosion holes at both inner and outer walls were 1.0 mm in diameter, with a corrosion depth of 50%. Next, the corrosion hole defects at the capillary pressure pipe's inner and outer walls were investigated under the same conditions as the waveforms shown in Fig. 9. The designed probe can effectively detect the non-through corrosion defects at both inner and outer walls. The waveforms of the detection signals of the defects at both inner and outer walls showed consistent variation tendencies. Furthermore, the detection signal of the defect at the inner wall exceeded the value of the defect at the outer wall.

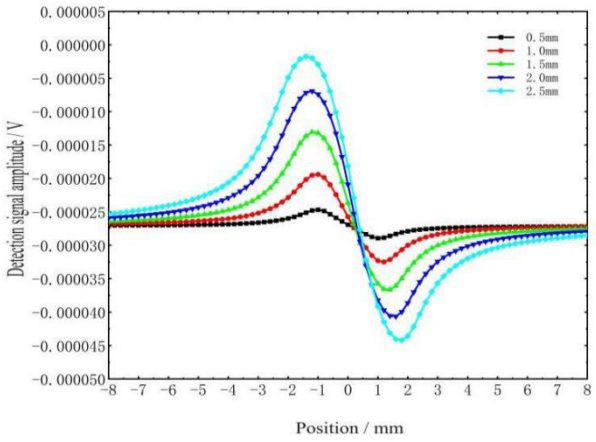

Fig. 8. Waveforms of the simulated detection signals of the through-hole corrosion defects with different diameters

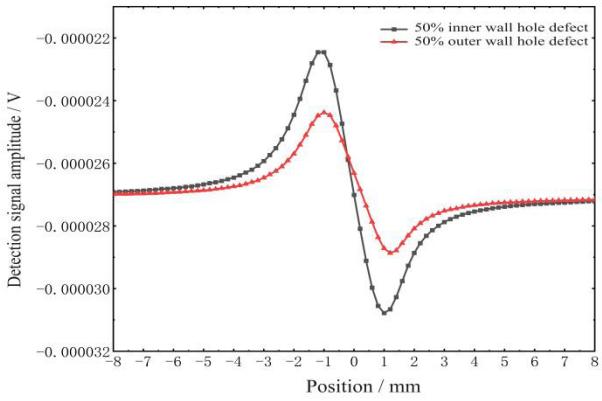

Fig. 9. Waveforms of the simulated detection signals of the corrosion defects at both inner and outer walls with a corrosion depth of 50%

Finally, the effect of the depth of the corrosion holes at the outer wall on the strength of the detection signal was simulated. 5 corrosion holes were set. The diameter was 1.0 mm, but the depths varied as 20, 40, 60, 80, and 100% of wall thickness. The probe scanned these five corrosion holes at the outer wall with different depths in turn, and the simulated detection signals were obtained, as shown in Fig. 10.

The designed probe effectively detected the corrosion hole with a diameter of 1.0 mm and the smallest corrosion depth (20% of wall thickness). Moreover, the defect signal increased gradually with the corrosion depth. As the corrosion depth reached 80% of wall thickness, the strength of the detection signal dropped obviously with the increase of the corrosion depth. It can also be observed in Fig. 9 that the designed probe can achieve the detection of the corrosion hole with a diameter of 1.0 mm and the smallest depth (20% of wall thickness).

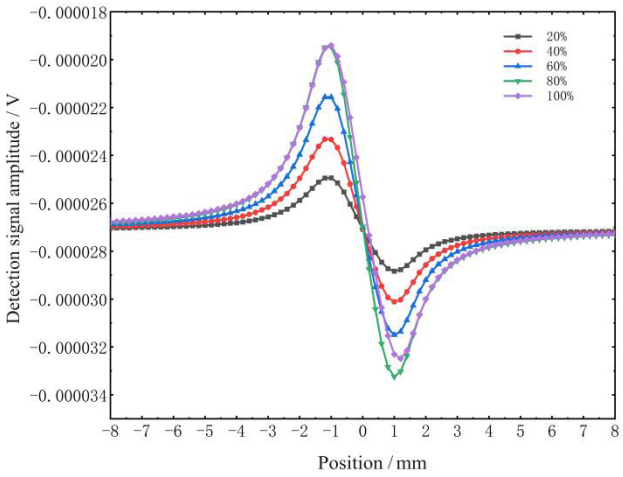

Fig. 10. Waveforms of the simulated detection signals of corrosion holes with different depths

4 Experimental Verification

This study developed an 8-channel eddy current probe prototype and the related test system for the capillary pressure pipe to validate the established model's accuracy. The test system mainly consists of a signal source module, power amplification module, signal processing module, data acquisition module, and the related test software. The signal source module provides the excitation signal for the exciting coil. The power amplification module magnifies the excitation signal and then loaded to the exciting coil. The multi-channel signal is then processed with a signal processing module. Finally, using a signal processing module, the processed signal is uploaded to the principal computer and processed by the principal computer for display. Fig. 11 shows the test system.

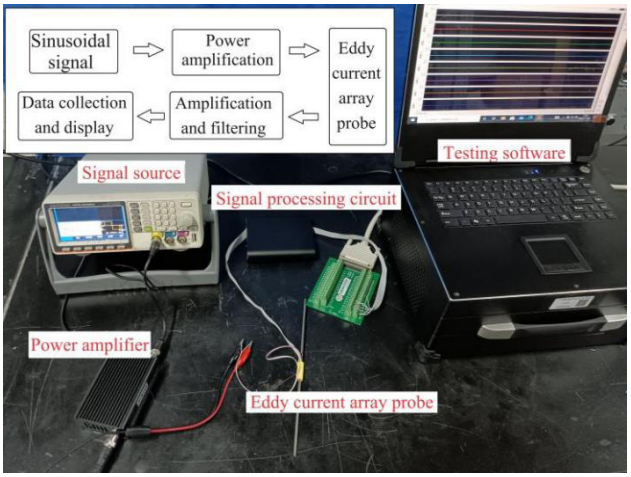

Fig. 11. Configuration of the developed test system

Next, two steel capillary pressure pipes with corrosion and crack defects were selected from the manufactured defective samples. As shown in Fig. 12, the crack defect was the penetration transverse defect, with a length of approximately 5.0 mm, and the corrosion defect was the non-penetration defect, with a corrosion depth of approximately 40% and a hole diameter of 1.2 mm. The excitation frequency was set at 10 kHz.

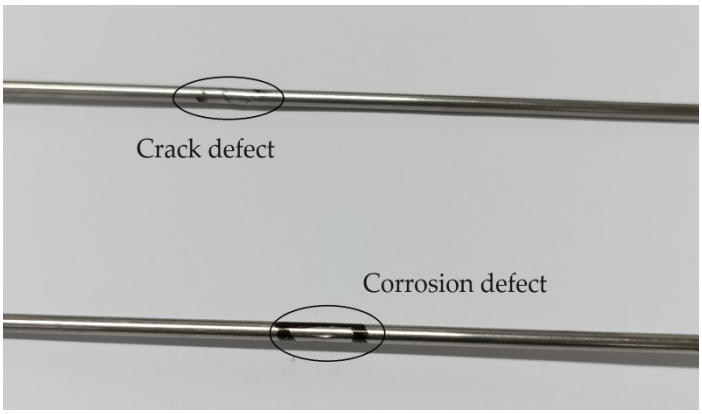

Fig. 12. Capillary pressure pipes with corrosion and crack defects

4.1 Penetration Crack Defect Detection Test

First, the penetration crack defect on the capillary pressure pipe was examined with the designed test system, as the 8-channel test signal shown in Fig. 13. Overall, four channels in the crack defect detection output signals. The signal from the middle two channels exceeded that from the outer channels in terms of strength. This is because the detection coils in the middle two channels were located at the center of the crack defects, showing great signal strength. The other two detection coils on the two sides were located at the edge of the crack defect, corresponding to low detection signal strength. It can also be observed from Fig. 13 that the designed defect detection method for the capillary pressure pipe can effectively recognize the crack defect along the capillary pressure pipe.

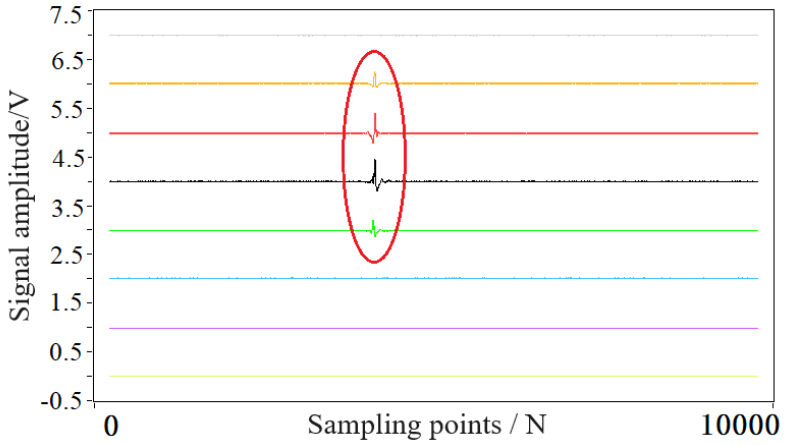

Fig. 13. Detection signal of the penetration crack defect

4.2 Test on the Surface Non-through Corrosion Defect

Next, under the same test conditions, the non-through corrosion defect on the surface of the capillary pressure pipe was measured, as the detection signal shown in Fig. 14. It can be observed from Fig. 14 that two channels in the eddy current array probe for corrosion defect detection output signals/one channel output strong signal while the other channel output relatively weak signal. Since the corrosion defect was small, the detection coil in one channel was located right above the defect, and the other was at the defect's edge. By comparing Fig. 14 and Fig. 13, it can be found that the detection signal of surface non-through corrosion defect was weaker and broader than the penetration crack defect. This can be attributed to the fact that the non-through corrosion defect on the surface was shallower and wider than the crack defect, showing a weaker and broader detection signal. It can also be observed from Fig. 14 that the designed capillary pressure pipe test method can effectively detect non-through corrosion defects on the surface of the capillary pressure pipe.

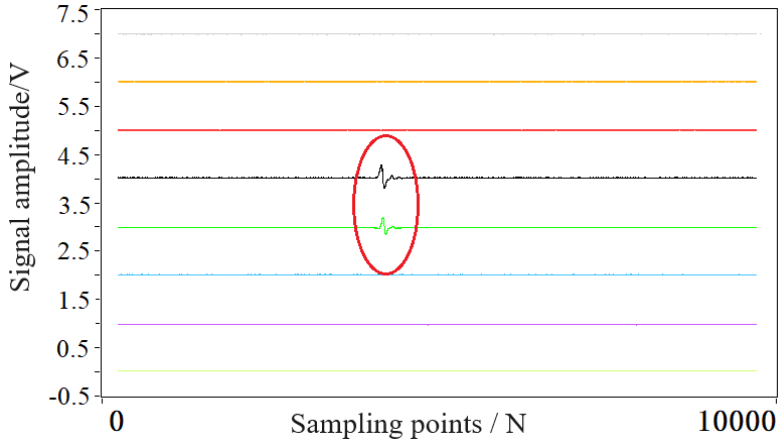

Fig. 14. Detection signal of the non-through corrosion defect on the capillary pressure pipe surface

5 Conclusions

Because of the small pipe diameter and thin wall thickness, cracks and corrosion defects are easily produced in the capillary pressure pipe during the whole process covering manufacturing, transportation, and use. Small defects are difficult to detect. This study proposed an eddy current array detection method for capillary pressure pipes to satisfy the design process's high-precision and high-efficiency defect requirements. First, using COSMOL software, the annular eddy current array detection model for the defects on the capillary pressure pipe was established, and the effects of some key parameters, including the diameter of the excitation coil and the spacing between the excitation coil and the detection coil, on the detection results were analyzed. Next, corrosion and crack defects on both inner and outer walls were simulated with the optimized probe, and the features of the detection signals of different defects were compared. According to the present simulation results, using the designed eddy current array probe, the detection precision of the longitudinal crack was 0.5 mm, the detection precision of the transverse crack was 1.0 mm; for the corrosion defect, the detection precision of diameter and depth were 0.5 mm and 20% of hole wall thickness, respectively. The probe could also indicate the defect location on the capillary pressure pipe. Finally, using the established theoretical model, the probe prototype and the related test system were developed to evaluate the detection performance of crack and corrosion defects on the capillary pressure pipe. The experimental results demonstrated that the proposed annular eddy current array detection method can effectively detect crack and corrosion defects on the capillary pressure pipe. However, due to limitations of test conditions, this study detected only penetration transverse defects and surface non-penetration corrosion defects without exploring signal features of other defect types. These will be the research focus of our follow-up study.

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