Eddy Current Testing in Service of the Boiler Heating Surface Tube Elbow in Thermal Power Plants

Yunlong Liu¹ ²*, Ameng Xie¹ ², Dingjie Shen¹ ² and Xiangwei Yang¹ ²

¹ Hunan Xiangdian Test Research Institute Co.Ltd., Changsha, Hunan, 410004, China
² State Grid Hunan Electric Power Company Research Institute, Changsha, Hunan, 410004, China
*Corresponding author’s e-mail: 13874809964@163.com

Abstract. According to the characteristics of closed ends, tight tube screen and narrow testing spaces of the eddy current testing in service of the boiler heating surface tube elbow in thermal power plants, an external placed saddle eddy current testing probes which could be used to test the small diameter austenitic stainless steel tube elbow was designed. Then the comparative sample tube was processed in accordance with the eddy current testing technical standards. Through the sample testing and the applications in thermal power plants, the results show that the designed saddle-shaped eddy current detecting probe device has high detection sensitivity and reliability for linear defects above 0.2 mm and hole defects above Φ1.4 mm. It can realize the non-destructive testing in service of the austenitic stainless steel tube elbow, which has more serious oxidation, corrosion and more focused stress.

1. Introduction
The boiler heating surface tube is an important production equipment of the thermal power plant. In order to ensure the safe and stable operation of power production, it is necessary to carry out planned inspection and maintenance. Since the detection of the austenitic stainless steel elbow for the heating surface tube of the power plant boiler is mostly in service, and the steel pipe material and the site environment are limited, the ordinary surface non-destructive testing method is not applicable [1-3]. At the same time, due to the closed ends of the steel pipe, the tight installation between the pipe panels and the narrow detection space, the traditional eddy current testing methods (outer-wearing and internal-wearing) cannot complete the testing operation as required.

At present, in view of some shortcomings of traditional eddy current testing methods [4, 5], researchers at home and abroad have improved the eddy current testing technology, and also proposed more and newer detection technologies, such as D G Park and C S Angani of Korea Institute of Atomic Energy, S Hosseini of Newcastle University [6-8], Z Chen of Xi'an Jiaotong University, and Z Xu of Huazhong University of Science and Technology [9, 10]. However, for the eddy current testing technology of weak magnetic austenitic stainless steel, no systematic testing methods and experimental research have been carried out by scholars.

In this paper, a saddle-shaped eddy current testing probe has been developed for the problem of the elbow portion, which is more susceptible to oxidative corrosion and difficult to achieve in-service non-destructive testing. According to the requirements of the eddy current testing technology standard, the comparative sample tube was fabricated by using the spare heating surface tube of the thermal
power plant. Through the sample detection and field application, the results show that the developed saddle-shaped eddy current detecting probe device has high detection sensitivity and reliability.

2. **Principle of eddy current testing**

The enclosed turbine runner chamber automatic detection system contains the computer simulation comparison and control systems, the integrated module for data acquisition and processing, the track crawler, the steering and transmission device, the positioning and distance measuring device, the image acquisition and illumination device and the DC power supply.

The principle block diagram of the automatic detection system is shown in figure 1. The track crawler with track system could carry the real-time image acquisition device to complete the crawling work on the inner surface of the enclosed chamber. Then the image acquisition device is used to complete the real-time collection of the scene image of the enclosed chamber, and the positioning and distance measuring device is used to achieve the positioning of the crawler.

When a direct current is passed through the wire, the current density across the cross section is uniform. However, if an alternating current passes through the wire, the changing magnetic field around the wire will also induce current in the wire, which will result in non-uniform current distribution along the wire cross section. The current density is smaller and smaller from the surface to the centre, and decays by a negative exponential law, especially when the frequency is high, the current flows almost in a thin layer near the surface of the wire. This current is mainly concentrated near the surface of the wire, which is called the skin effect.

The distance of the eddy current into the conductor is called the penetration depth. The penetration depth was defined as the skin depth, when the eddy current density attenuated to $1/e$ of its surface value, characterizing the degree of skin eddy in the conductor, expressed by $\delta$, in meters (m). The expression could be formatted as:

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

where $\mu$ is the permeability of the material (H/m); $\sigma$ is the conductivity of the material (S/m); $f$ is the frequency of the alternating current (Hz).

It can be seen from the formula that the higher the frequency, the better the conductivity and the magnetic permeability, the more significant the skin effect.

3. **Eddy current testing system**

The components of the detection system are shown in figure 2, including the signal generator, probe, data acquisition system, data processing and analysis system, and results recording and display module.

![Figure 1. Principle of eddy current testing.](image1.png)  ![Figure 2. Diagram of eddy current testing system.](image2.png)

The probe may contain two coils for excitation and reception, or contains only one coil, which is used both for excitation and reception, called self-inductive coil. The excitation coil is pulsed by a signal generator (if necessary, the power amplifier can be used to amplify the excitation signal), and
the data acquisition system records the induced voltage on the reception coil (namely detection coil) during the detection process to obtain the signal. The data processing and analysis system performs noise reduction and classification on the detected signals. The recording and display module stores and displays the test results.

According to the obtained location by using the positioning auxiliary device, the position of the real-time detection image in a virtual 3-D model was calibrated. Through comparing of the real-time detection images and the computer simulation images, the defects or foreign matter fall into could be accurately positioning, in order to clean up and eliminate system error conveniently without opening the cover of the hydropower turbine runner chamber.

4. Eddy current testing probe
The boiler heating surface tube is a small diameter tube with an outer diameter of 30~80 mm. In order to obtain better magnetic coupling characteristics, the front end of the eddy current testing probe is designed as a saddle shape. The internal coils contain one excitation coil and four detection coils as shown in figure 3, in which the four detection coils are divided into two groups, and were placed on both sides of the excitation coil. The two detection coils in each group adopt differential connection to double-channel detection and display on the surface of the work piece. Both the detection coil and the excitation coil are wound by enamelled wire, and both use silicon steel sheet as the electromagnet core, which can effectively improve the magnetic field strength of the excitation magnetic field and enhance the signal strength.

5. Testing and application
5.1. Equipment
The eddy current detection system are composed of a PC control platform, a signal generator, the eddy current detection probe, signal transmission lines, and various functional circuit integration boxes, as shown in figure 4. The working process of the eddy current detecting probe is as shown in figure 5. During the detection, the probe is closely attached to the inner elbow of the heating surface tube, and is smoothly slid from the A position to the B position to complete the eddy current detection of the elbow in the heating surface tube. Similarly, the detection of the outer and the side are surface of the tube can be completed. The signal collected during the detection is displayed real time on the
notebook working interface. The amplitude and phase angle of the current impedance waveform can be obtained by calculating the waveform curve, to determine the defect size.

In order to study the structural performance of the eddy current probe conveniently, the support skeleton of the probe was fabricated by aluminium alloy processing. The coil core was made of 0.3 mm thick silicon steel sheets. The sample and finished product of the eddy current probe are shown in figure 6 and figure 7, respectively. The relevant parameters of the coil core silicon steel sheet are shown in table 1.

| Parameters       | Value   |
|------------------|---------|
| Grade            | 30G130  |
| Thickness        | 0.3 mm  |
| Relative permeability | 8000    |
| Rolling type     | Cold    |
| Orientation      | Oriented|
5.2. Production of sample tube

According to the standard requirements [11, 12], the pipe spare parts are used to process the test sample tube. The steel pipe is made of austenitic stainless steel pipe TP347H, with the specification Ф57×4 mm. Three kinds of artificial defects were processed, which contains circumferential groove, axial groove and radial via hole. The distance between each artificial defect was 35 mm, as shown in figure 8. The photo of the test sample tube is shown in figure 9. The size and position parameters are shown in table 2.

![Figure 8. Sample artificial defect distribution.](image)

![Figure 9. Ф57×4 mm austenitic stainless steel test sample tube.](image)

| No. | Defect type         | Defect size (mm)                          |
|-----|---------------------|------------------------------------------|
| 1   | Axial groove        | 0.5 (depth)× 0.2 (width)× 25 (length)    |
| 2   | Circumferential groove | 0.2(depth)× 0.2(width)× 25(arc-length) |
| 3   |                     | 0.4(depth)× 0.2(width)× 25(arc-length)   |
| 4   |                     | 0.6(depth)× 0.2(width)× 25(arc-length)   |
| 5   |                     | 0.8(depth)× 0.2(width)× 25(arc-length)   |
| 6   |                     | 1.0(depth)× 0.2(width)× 25(arc-length)   |
| 7   |                     | 1.5(depth)× 0.2(width)× 25(arc-length)   |
| 8   |                     | 2.0(depth)× 0.2(width)× 25(arc-length)   |
| 9   |                     | 2.5(depth)× 0.2(width)× 25(arc-length)   |
| 10  | Radial via hole A(Ф2.2) |                                           |
| 11  | B(Ф1.4)             |                                           |
| 12  | Axial groove        | 1.0(depth)× 0.2(width)× 25(length)        |

5.3. Artificial defect detection test

Considering the characteristics of the austenitic stainless steel material such as conductivity and permeability, and adjusting the phase of the interference and clutter signals to the horizontal position, the impedance diagrams of various defects were analysed and compared. It shows that they all have a consistent display rule. Therefore, the austenitic stainless steel tube of the specification Ф57×4 mm
and the material TP347H is used to be analysed as an example of the impedance diagram of defect. The impedance waveforms of each defect are shown in figure 10 to figure 12.

![Figure 10](image)

Figure 10. Axial groove impedance topography: (a) defect No.1; (b) defect No.12.

![Figure 11](image)

Figure 11. Circumferential groove impedance topography: (a) defect No.2; (b) defect No.4; (c) defect No.6; (d) defect No.8.

![Figure 12](image)

Figure 12. Radial via hole impedance topography: (a) defect No.10; (b) defect No.11.

It can be seen from above figures:
- The eddy current signals of artificial defects on the test sample tube are clear and obvious, and basically no interference signal can be seen. After gaining 40 dB, the amplitude of the impedance signal of 0.2 mm depth circumferential groove defect and 0.5 mm depth axial groove defect both reach...
more than 70% of the full amplitude value; for 0.4 mm depth circumferential groove defect, 1.0 mm depth axial groove defect and 1.4 mm radial via hole defect, the amplitude of the impedance signals all reach more than 100% of the full amplitude value.

- It shows that the eddy current detection probe has a high signal-to-noise ratio for the detection of the test sample tube, and has high detection sensitivity for 0.4 mm depth circumferential groove defect, 1.0 mm depth axial groove defect and 1.4 mm radial via hole defect. It is particularly noteworthy that the eddy current detection probe can identify defects of 0.2 mm depth circumferential groove and 0.5 mm depth axial groove. At the same time, it can meet the Class B inspection requirements of the standard GB/T 7735-2004.

- As shown in Figure 10 and Figure 11, as the depth of axial groove and circumferential groove increases, the amplitude of the impedance signal of each artificial defect gradually increases. It shows that the deeper the axial groove and circumferential groove defects of the test sample tube, the higher the eddy current detection sensitivity.

- As shown in Figure 10(b) and Figure 11(c), the amplitude of the impedance signal of circumferential groove defect is larger than the axial groove defect under the same or similar defect size. It shows that the eddy current detection probe has higher sensitivity for the circumferential groove defects of the test sample tube than the axial ones.

5.4. Field inspection application

- Testing environment: During the shutdown of Unit 2 of a power plant in Hunan Province, the eddy current detection probe was used to test the austenitic stainless steel pipe elbow of the high temperature reheater. The high temperature reheater tube is located at the upper part of the flame angle. There are 64 screens from the left to the right of the furnace, and 11 tubes per screen, in which the parameters of the elbow from the 4th tube to the 11th is TP347H (Φ57×4 mm).

- Preparation before testing: Before the eddy current test, the outer surface of the tube elbow is cleaned and macroscopically inspected to eliminate the effects of macroscopic defects such as scale or pit on detection.

- On-site testing and conclusion: When the eddy current testing equipment was developed to detect the inner and outer arc surfaces of the high temperature reheater elbow, the interference signal was effectively controlled, the detection sensitivity was high, and the operation was convenient. Through eddy current testing, it is found that the second number of the furnace was found before the fourth screen. There is a defect signal was found on the outer arc surface of the second tube elbow in the 4th screen, as shown in figure 13. The rest did not find an abnormal signal. The abnormal part of the eddy current detection signal was cut and sampled, and after surface grinding and penetration detection, a dense crack-like defect was found, as shown in figure 14, which was consistent with the eddy current test result.

6. Summary

In this paper, the heating surface tube of the in-service boiler of thermal power plant was taken as the research object. A saddle-shaped eddy current testing probe has been developed for the problem of the elbow portion, which is more susceptible to oxidative corrosion and difficult to achieve in-service
non-destructive testing. According to the requirements of the eddy current testing technology standard, the comparative sample tube was fabricated by using the spare heating surface tube of the thermal power plant. Through sample testing and field application, the following conclusions are obtained:

- The developed saddle-shaped eddy current detection probe device has high detection sensitivity and reliability for linear defects above 0.2mm;
- The developed saddle-shaped eddy current detection probe device has high detection sensitivity and reliability for hole defects above \( \Phi 1.4 \) mm;
- The developed saddle-shaped eddy current detection probe device has the characteristics of small size, convenient operation and strong anti-interference ability, which can realize the non-destructive detection of the heating surface pipe of the boiler in service in the thermal power plant.

Acknowledgments

This research was financially supported by the Hunan Xiangdian Test Research Institute (NO. XDKY-2019-04).

References

[1] Liu, G. (2006) Nondestructive Testing Technology. National Defense Industry Press, Beijing.
[2] Xu, K., Zhou, J. (2004) Eddy Current Testing. Mechanical Industry Press, Beijing.
[3] Wang, X., Li, Q., Zhao, J. (2014) Application of Far Field Eddy Current Technology in Power Plant Boiler Inspection. China Special Equipment Safety, 6: 32-35.
[4] Yang, L., Guo, X., Gao, S. (2014) Method of the Eddy Current Testing to Pipeline Inner Surface Defects. Instrument Technique and Sensor, 10: 78-81.
[5] Jiang, H. (2013) Research on Multi-frequency Eddy Current Testing Based on Frequency Modulated Excitation. Nanjing University of Aeronautics and Astronautics, Nanjing.
[6] Park, D.G. (2009) Evaluation of Pulsed Eddy Current Response and Detection of the Thickness Variation in the Stainless Steel. IEEE TRANSACTIONS ON MAGNETICS, 10: 3893-3896.
[7] Angani, C.S. (2010) The Pulsed Eddy Current Differential Probe to Detect a Thickness Variation in an Insulated Stainless Steel. Nondestructive Evaluation, 29: 248–252.
[8] Hosseini, S., Lakis, A. (2012) Application of time–frequency analysis for automatic hidden corrosion detection in a multilayer aluminum structure using pulsed eddy current. NDT&E International, 47: 70–79.
[9] Chen Z. (2012) Reconstruction of Stress Corrosion Cracks Based on Pulsed Eddy Current Signals. Electromagnetic Field Problems and Applications, 39: 203–211.
[10] Xu Z., Wu X., Huang C. (2011) Pulsed Eddy Current Response to A Ferromagnetic Specimen with Finite Thickness. Journal of Huazhong University of Science and Technology (Natural Science Edition), 6: 91-95.
[11] GB/T 7735-2016. Automated Eddy Current Testing of Seamless and Welded (Expect Submerged Arc- Welded) Steel Tubes for Detection of Imperfections.
[12] GB/T 14480-2015. Non-destructive testing instruments-Equipment for eddy current examination-Part 1: Instrument characteristics and verification.