Acoustic emission monitoring and phased array ultrasonic testing for the steel bifurcated pipe of 800MPa grade strength in hydraulic test

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Abstract - The paper analyzes and studies the acoustic emission monitoring and phased array ultrasonic testing of steel bifurcated pipe of 800MPa grade strength in hydraulic test. The comprehensive grade of AE location source is assessed, and the structure health is evaluated, the AE characteristic parameters of an important hazardous area corresponding to the load elevated stage and load holding stages are analyzed and compared, and Kaiser effect is verified. PAUT is used to examine the area of great activity located by AE, and the position of welding defects found by PAUT is basically consistent with the AE location map, then the location error of AE is illustrated in the region of irregular shape. The AE and PAUT are of great advantage in hydraulic test of the steel bifurcated pipe.

1. the introduction
Acoustic emission technology is applied to dynamically monitor the steel bifurcated pipe of hydropower station during the hydraulic test [1-3], which can identity whether there are harmful defects and send out real-time early warnings, in order to provide technical guarantee for the safety of the hydraulic test, and evaluates the running status and the safety of the steel bifurcated pipe, then master the safety margin under overload operation condition.

In this paper, the AE monitoring was carried out during the hydraulic test of a high-strength steel bifurcated pipe of 800MPa grade, and the phased array ultrasonic testing (PAUT) was used to detect the relevant AE location source area, the result showed that the defects location detected by PAUT was consistent with the AE location map. The AE characteristic parameters of the dangerous area were analyzed, and the variation law of the number of AE events, amplitude and average frequency (AF) during the load holding stages and load elevated stages was obtained.

2. AE monitoring scheme for hydraulic test of steel bifurcated pipe of 800MPA grade high strength

2.1. Main parameters of steel bifurcated pipe
An symmetric Y type of rib reinforced steel bifurcated pipe of AETS hydropower station in Kashi City, Xinjiang Autonomous Region, China, is taken as a case study. The inscribed sphere are 8.136 m, and the bifurcation angle is 77°; The thickness of the shell plate and the crescent rib are 48mm and 96mm
respectively. The material is steel Q690CFE of 800MPa grade strength, with the yield strength of 690MPa and the designed bending tensile strength varying from 750 to 940MPa.

Fig. 1 shows the hydraulic test site of the steel bifurcated pipe. The material of the transitional cone pipe at the head M1 is the same as the bifurcated pipe body, with the plate thickness of 48mm. The tapered cone at the M1 end and three heads (M1, M2 and M3) are made of Q345 steel (yield strength of 345MPa) with the wall thickness of 50mm.

The pipe is of great size, great wall thickness, irregular shape, and high strength.

The hydraulic test of steel bifurcated pipe is divided into two parts: preloading test and formal loading test. The designed pressure of bifurcated pipe, maximum test pressure, and maximum pre-pressure are 2.8MPa, 3.5MPa and 2.1MPa respectively. The loading method of hydraulic test adopts step by step loading and slow pressurization (loading speed is about 0.26MPa/hour), so as to reduce partial residual stress caused by the processing process, to adjust and homogenize the local stress of the structure. The loading procedure of hydraulic test is shown in Fig. 2.

![Fig.1 The steel bifurcated pipe](image)

![Fig.2 Loading procedure of hydraulic test](image)

2.2. AE monitoring scheme and Settings

The main areas of AE monitoring are the key load-carrying parts, the parts of stress concentration due to large geometric constraints, and the parts with high difficulty coefficient of welding: the crescent rib, and the main cone as well as the transitional cone.

AMSY-6 (38 channels) detection system of Vallen Systeme GmbH is used to carry out the AE monitoring of the steel bifurcated pipe in hydraulic test. The type of sensor is VS150-RIC, high sensitivity resonance sensor (100–400kHz) with a center frequency of 150kHz, and with a built-in preamplifier gained 34dB. The working parameters of the AE system during the test are set up as shown in Tab.1.
According to the structure, welding process and welding quality of the bifurcated pipe, the overall arrangement diagram of AE sensor is shown in Fig. 3, a total of 36 sensors are used for monitoring, and planar location and linear based on time difference of arrival (TDOA) is used for location calculation.

![Assignment of the AE Sensors](image)

Tab.1  Parameter setting of the AE system

| Threshold /dB | Sample Frequency /MHz | Sampling point | Filter/ kHz | Dur.DisT./ μs | RearmT. /μs |
|--------------|-----------------------|----------------|-------------|---------------|-------------|
| load elevated stage: 46 | 10 | 16384 | 25~850 | 400 | 3200 |
| load holding stage: 40 |                |                |             |                |             |

3. AE data analysis

3.1. AE location analysis

Since the maximum pre-pressure reached 2.1MPa, during the formal loading test, AE met Kaiser effect before the pressure over 2.1MPa, and no meaningful AE located events occurred.
This part analyzed the relevant data of four load holding stages (2.1, 2.8, 3.1, 3.5MPa) and four load elevated stages (1.4-2.1, 2.1-2.8, 2.8-3.1, 3.1-3.5MPa) during the formal loading test. AE data were continuously collected during the load elevated stages, and the acquisition time of AE data in the four load holding stages was 10min respectively.

Fig. 5 and Fig. 6 shown the AE location of the main cone and its adjacent region A1, the cluster adopted a circular box with a diameter of 700mm in Fig.5.

3.2.  Phased array ultrasonic testing for AE location source area

A large number of AE events occurred in the five regions of Zone1~Zone5 during the load elevated stages as shown in Fig. 6 and the load holding stage as shown in Fig. 5, and in accordance with the standard SL 751-2017 "Technical code for inspection of AE testing of hydraulic steel structures" [4], the activity level of the five zones is super active, and the strength level is high strength because the amplitude (the average of the five most large amplitude in the located source area) reached more than 80 dB, then the comprehensive grade evaluation of the five zones is in level IV, it is necessary to adopt other nondestructive testing methods for re-inspection of the relevant regions.

After the hydraulic test, PAUT[5] techniques were used to detect the area of Zone1~Zone5. A large number of welding defects were found in Zone1, Zone3 and Zone4, which were located on the circumferential weld H2 (as shown in the solid red line in Fig. 5), and no welding defects were found in the other 2 zones.

In order to improve the strength of the last closure joint H2 (welded outside with V-groove of 60°), the manufacturer has taken reinforcement technique: welding 16 pieces of 30 × 200 × 400 (mm) stiffener plate across the circumferential weld H2 every 20° along the circumferential direction. The AE location events in zone2 area is mainly caused by the tensile deformation, friction between the two ends of the stiffener across the circumferential weld H2 and the base metal on both sides. Zone5 is located near the
top of crescent rib, which is a triangular area composed of the main cone, two branch cones and the rib end welding, the local geometric constraint is very large and so is the welding residual stress, so the AE events maybe be caused by the release of residual stress.

In this test, Omni Scan SX ultrasonic phased array equipment was used for weld re-inspection.

For PAUT detection, 32 elements linear array probe of 5L32A31 was selected, the elements pitch of p =0.6mm, central frequency of 5MHz. The wedge type is A12N55S of 55° wedge angle; compound S-Scan, the aperture size of 16 elements, and 32 elements were used in the focal law, the spreading angle range was from 40° to70°, the angle step was 0.5°, the focusing depth was 30mm, the scanning resolution was 1mm, the scan offset was 30mm, 80mm.

The types and depth of the welding defects found in Zone1, Zone3 and Zone4 are basically the same. In this paper, defects in Zone3 were taken as an example.

The types of defects in region Zone3 are mainly side wall incomplete fusion and cracks, two sections were scanned, with the length of 500mm and 400mm respectively. The defects were intermittent, with a length of 900mm, and the depth was mainly concentrated in 34-38mm. The PAUT diagram is shown in Fig. 7, which indicate the defects in welds intuitively and accurately

![PAUT diagrams of defects in region Zone3](image)

The position of welding defects detected by PAUT is basically consistent with the AE location map, and there is a certain deviation in the axial direction (Y direction in the AE location map). The main reason is that the shell plates on both sides of the weld H3 shown in figure 2 with a turning angle of 12.62° and the shell plates on both sides of the weld H4 also with a turning angle of 10.47°, which has a great impact on the wave transmission paths, acoustic attenuation, waveform characteristics and wave velocity. (The sound wave caused by defects in the weld H2 can be received by the sensors of No. 1# ~ 4 # without transmitting through the thick-wall weld, but it can't be received by the sensors of No. 6# ~ 13# until without transmitting through the thick-wall weld H3 and H4; what's worse, because of the irregular shape, when using 2D TDOA location method, several conical surfaces with unequal cone top angles are approximately expanded into a 2D planes for location, resulting in graphic distortion and measurement error of sensor coordinators to some degrees [6].

3.3. Statistical analysis of AE parameter’s parameter in key location source region

Relevant AE data in Zone3 during the formal loading test is counted as shown in Tab. 2 and Tab. 3. The distribution diagrams of AE parameters are shown in Fig.8-Fig.11.

\[ A_{mean}, AF \] represent the average of the five most large amplitude in the located source area and average frequency respectively.

\[
\text{Number of AE events} = \frac{\text{Located Events per MPa}}{\text{Pressure increment of the pressure of elevated stage(30%)}}
\] (1)
Number of AE events
Located Events per M in = \frac{\text{Number of AE events}}{\text{Duration of the pressure of elevated stage (min)}} \quad (2)

AF = \frac{\text{counts}}{\text{duration}} \quad (3)

The first hit of each AE event results in a discrete data point (ringing count, duration), and the slope of the fitting line of the discrete data points (ringing count, duration) related to all events in the same AE location source area is taken as the AF of AE events. Fig. 9 shows the scatter diagrams and fitting lines of scatters about region Zone3 of each elevated stage.

Fig.8 Counts vs duration during each load elevated stage

Tab.2 AE parameters during each load elevated stage

| Load elevated stage | Located Event | Located Events per MPa | Located Events per Min | A_{mean}/dB | AF/kHz |
|---------------------|--------------|------------------------|------------------------|-------------|--------|
| 1.4-2.1MPa          | 7            | 10                     | 0.049                  | 55.2        | 53.6   |
| 2.1-2.8MPa          | 91           | 130                    | 0.607                  | 70.8        | 73.0   |
| 2.8-3.1MPa          | 121          | 403                    | 1.613                  | 75.9        | 90.6   |
| 3.1-3.5MPa          | 200          | 500                    | 1.905                  | 79.1        | 100.1  |

Tab.3 AE parameters during each load holding stage

| Load holding stage | Located Events | A_{mean}/dB | AF/kHz |
|--------------------|----------------|-------------|--------|
| 2.1MPa             | /              | /           | /      |
| 2.8MPa             | 18             | 57.7        | 86.8   |
| 3.1MPa             | 8              | 61.3        | 76.6   |
| 3.5MPa             | 17             | 55.8        | 80.5   |
According to Fig. 9, in the region Zone3, the number of AE events, the number of AE events per MPa and per min all increase successively with the increase of load during the four load elevated stages, which means, the region is more and more active. In the four load elevated stages, with the increase of load, the $A_{\text{mean}}$ increases successively, that is, the intensity of the AE events increase successively. The AF increases in turn.

According to Fig. 10, no significant AE events occurred in the region Zone3 due to the fact that the maximum preloading pressure reached 2.1MPa and Kaiser effect was satisfied in the formal loading test below 2.1MPa. By comparing Tab. 2 and Tab. 3, the number of AE events in the load holding stage is significantly reduced compared with that in the load holding stage, so is the AE amplitude. In each load holding stage, region Zone3 tends to be stable.

Fig. 10 shows that the $A_{\text{mean}}$ of AE events in region Zone3 does not change much in the last three load holding stages, nor does the AF.

4. the conclusion

Taking the AE monitoring and phased array ultrasonic testing (PAUT) for steel bifurcated pipe of 800MPa grade strength of hydropower station in hydraulic test as an example, the AE characteristics of a typical AE location source area are studied, and some achievements and prospects are obtained as follows:

a. The comprehensive grade of AE location source is assessed, and the structure health is evaluated.

b. PAUT is used to detect the welding defects intuitively and accurately, and the position of defects defected by PAUT is basically consistent with the AE location map.

c. The AE characteristic parameters of a key risk zone corresponding to the load elevated stages and load holding stages are analyzed and compared, and Kaiser effect is verified.

d. The location error of AE events in the region of irregular shape is illustrated, and it is necessary to improve the accuracy of AE location based on TDOA for irregular structures, and to further study the relationship between defect properties and AE mechanism.

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