Structural condition monitoring system of steam/water piping in thermal power plant and its application

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Abstract. In view of the steam/water piping outside the boiler of thermal power unit, considering its spatial structure characteristics of long distance, large drop and the working conditions under high temperature, high pressure and flexible operation. On the base of the static and dynamic analysis of the structure, the key nodes and parameters of monitoring were selected, the method of sensor installation and debugging was put forward, which was easy to maintain and reliable. A distributed monitoring data acquisition and digital processing analysis system was developed. The monitoring results showed that the monitoring system ran stably and reliably, and the test data of each node could accurately reflect the structural state of the piping. The monitoring system has a strong engineering application value.

1. Introduction
As the Chinese government mandates comprehensive promotion of the flexibility transformation of the thermal power unit and the implementation of the peak load regulation capacity improvement project, the thermal power unit emphasizes more on the deep peak load regulation capacity, fast climbing capacity and fast start and stop capacity. Higher requirements are put forward for the structural deformation of steam/water piping under high temperature, high pressure and deep peak regulation. piping accidents in recent years show that the short time of steam/water piping blasting outside the furnace is harmful to the equipment. The unit shutdown caused by the blasting will directly impact the power grid, which poses a great threat to the safe operation of thermal power plants [1-3].

The traditional manual periodic inspection method is used for the safety of the steam/water piping structure with short effective time, high labor cost and low efficiency, which cannot solve the technical problems such as transient parameter collection, database establishment and real-time warning. The on-line monitoring of the main steam/water piping system in the thermal power unit can timely know the vibration, stress and other changes under the actual operating conditions, providing effective technical support for the safe operation of the piping, structural fault diagnosis, quality inspection and acceptance, and safety status evaluation.

Different from ordinary engineering piping, the steam/water piping system outside the furnace of thermal power units has a long piping and a large drop, the operation characteristics under high temperature, high pressure and flexible operation working conditions [4]. We through technology in piping field investigation and numerical simulation analysis, based on the actual structure of the selected representative monitoring nodes, developed a set of key node sampling by distributed the whole structure of on-line monitoring system, break through the limitation of traditional human data collection, implements the piping under complicated conditions outside the furnace run time structure of on-line monitoring.
2. Analysis of the structure of steam/water piping

2.1. Structural characteristics of piping

The steam/water piping outside the furnace are mainly composed of piping, fittings, valves, insulation materials and support-hanger system. The overall method of flexible design is adopted to limit the thermal displacement, primary stress and secondary stress of the piping through reasonable allocation of support-hanger and piping trend [5]. In view of the large drop space structure of steam/water piping, the rigid hangers are used as the boundary point of axial displacement to control the expansion direction and displacement of piping reasonably. In addition, the safety valve can produce a large transient impact on the piping during the steam exhaust process, and the nearby support-hanger frame is a key component to bear the impact [6]. Therefore, for the transportation piping, the actual working state of the support-hanger is dynamic, and the stress and deformation of the support-hanger become one of the most important factors for the safe operation of the steam/water piping.

At the same time, the instability of medium flow in the piping, the relief valve discharge, and water hammer transient impact could cause piping vibration, so the pipe need keep enough stiffness and stability to prevent the piping vibration. For larger flexible pipe, low-order vibration is most easily excited [7-8].

In the current paper, by spatial elastic pipe structure modeling, finite element analysis method was carried out on the system of steam-water pipes, static, dynamic loads analysis, find the maximal static a stress point, the maximal maximum static secondary stress points, the pipe heat displacement and maximum response first mode, at the same time, combining with the piping cut-off axial displacement, impact load distribution characteristics of saddle point, provide theoretical basis for targeted choose monitoring nodes.

![Figure 1. Schematic diagram of pipe and support-hanger [9].](image)
2.2. Static and dynamic analysis of piping structure

In the current paper, the main steam/water piping of a thermal power unit was selected as the study case. The design pressure of the pipe was 17.44MPa and the design temperature was 540°C. Three types of pipes were adopted. Along the medium flow direction, the pipe segment from the boiler's end through the header outlet to the horizontal elbow of the top of the furnace was 12Cr1MoV (OD610×95mm), the pipe segment from the top elbow to the steam engine was A335P91 (ID368.3×40mm), and the pipe segment connecting the three lines to the main valve was A335P91 (ID273.05×30mm). The piping was consisted of 1 tee, 15 elbows, 6 dampers and 20 supports and hangers (see Figure 1 for the schematic diagram of the piping and Figure 1 for the types of supports and hangers).

Using CAESAR II software, based on elastic mechanics finite element numerical analysis method, the beam element model of main steam/water piping was established, the support-hanger were arranged according to the actual steam-water node position, the tee, valves and other original rigid as a concentrated mass added in the corresponding node. Then, the endpoint displacement, piping structure parameters and piping operating conditions were input for calculation and analysis under static load conditions. The calculation results and analysis of the main characteristic positions were listed in Table 1 and Table 2.

Table 1. Stress analysis results of main nodes.

| Indicators             | Location     | Maximum stress | Permitted | Evaluation |
|------------------------|--------------|----------------|-----------|------------|
| Maximum primary stress | Hanger 917   | 70.3MPa        | 111.1MPa  | qualified  |
| Maximum secondary stress| Bend near hanger 909 | 80.7MPa       | 266.6MPa  | qualified  |

Table 2. Displacement analysis results of main nodes.

| Indicators             | Location     | Maximum displacement | Permitted       | Evaluation       |
|------------------------|--------------|----------------------|-----------------|------------------|
| Maximum thermal displacement | Bend near hanger 909 | 191.6mm           | Meet design requirements | qualified       |
| Axial displacement segmentation point | Hanger 906 | 0mm                  | Meet design requirements | qualified       |

The results of calculation and analysis showed that both the static primary and secondary stresses of the piping were within the allowable stress range, and the thermal displacement of the piping was in line with the provisions of China DL/T 5366-2016 "technical code for stress calculation of power plant steam/water piping"[10]. The maximum primary stress was located at No. 917 hanger, the maximum secondary stress point was also the maximum thermal displacement point, located at the elbow near No. 909 hanger, and the axial displacement segmentation point was located at No. 906 hanger.

On the basis of static load calculation and analysis, the model of piping system was refined and then modal analysis was carried out. Modal analysis decomposes a complex piping system into multiple vibration response modes, each of which had a specific natural frequency and mode of vibration. Table 3 showed the values of the first five natural frequencies of the piping system.

Table 3. The former 5 natural frequencies of the main steam pipe.

| Order number | First frequency | Second frequency | Third frequency | Fourth frequency | Fifth frequency |
|--------------|-----------------|------------------|-----------------|------------------|----------------|
|              | 0.17            | 0.48             | 0.57            | 0.63             | 0.96           |

The calculation results showed that the first-order natural frequency of the piping was 0.17Hz, and the first-order mode of vibration was shown in Figure 2. The maximum response point was located at the elbow near the No. 909 hanger. The former five natural frequencies were all within 1Hz, and the frequencies were relatively low, which easily induced low-order resonance.
3. **On-line monitoring technology of piping**

3.1. **Monitor nodes selection**

Based on the operating condition, the characteristics of acting load and the numerical simulation results of the piping, the monitoring nodes layout on the piping were determined. At the same time, considering that the relief valve would produce a large recoil force when discharging steam, the support-hanger near it were particularly important to protect the piping [11]. Therefore, monitoring points were also set at the No.902 and No.903 hanger bearing capacity near the three safety valves. The overall monitoring scheme was shown in Table 4.

| Location         | Reason                          | Monitoring parameters          | Direction |
|------------------|---------------------------------|--------------------------------|-----------|
| Hanger No. 902   | Relief valve outlet             | Derrick stress, Pipe vibration displacement | Y         |
| Hanger No. 903   | Solenoid release valve exhaust | Derrick stress, Pipe vibration displacement | Y         |
| Hanger No. 906   | Axial displacement segmentation point | Derrick stress | Y         |
|                  | Maximum secondary stress point |                                 |           |
| Hanger No. 909   | Maximum thermal displacement point | Pipe vibration displacement | X/Y/Z     |
|                  | Maximum response point of first mode |                                 |           |
| Hanger No. 917   | Maximum stress point           | Derrick stress, Pipe vibration displacement | Y         |

3.2. **Sensor installation and commissioning**

The installation and protection treatment of the sensors for the on-site online monitoring were determined according to the specific characteristics of the monitoring structure, the load condition and
the operating environment conditions. It should meet the requirements of high reliability, easy disassembly and long service life, and facilitate daily maintenance management, calibration and replacement [12].

The boom stress monitoring of the hanger adopted the bow-type strain gauge with a range of 100mm. Reliable and accurate installation method and safe and durable protection measures were the key elements to ensure the sensor to work effectively for a long time and obtain the correct monitoring data.

The U-shaped clamp was used as the fixed base at both ends of the sensor at the selected position, and the reference plate was positioned and fixed by adjusting the clamp bolt, so that the center of the mounting hole of the two bases was on the same plane axis, then the reference plate was removed and the bow strain gauge was fixed on the base by bolt. The function of the reference plate was to avoid additional assembly stress to the sensor due to installation. After the sensor was calibrated, all installation bolts should be fitted with silicone rubber with good electrical insulation, sealing and aging resistance, and then the metal protective cover should be installed. The signal connection line adopted fully shielded stranded cable, and all cables were wrapped with plastic hose for protection. Figure 3 showed the installation situation on site.

Figure 3. Photos of strain gauge field installation.

Piezoelectric acceleration sensor was used for vibration test. First, we connected the prefabricated sensor base to the square plate, welded it at the measuring point according to the set direction, and calibrated and positioned it with the aid of goniometer and other auxiliary gauges. Then the base of the sensor was installed on the square plate by four connecting bolts, and the position of the outgoing port was adjusted reasonably according to the location of the specific measuring point. After the sensor calibration was qualified, apply sealant and install metal protective cover. All cables were protected by plastic hose. Figure 4 shows the installation of on-site vibration sensors.

The measurement points of the steam/water piping outside the furnace of the thermal power unit have high temperature resistance technical requirements. Installing mica sheet between the sensor and the base plate can play a good role in heat insulation and insulation. Considering that the vibration frequency of the steam/water piping outside the furnace is low, its impact can be ignored [13].

4. Integration of on-line monitoring system for piping structure

4.1. Monitoring system integration

The monitoring system guaranteed the reliability of the system and the authenticity of the data through the contact acquisition of integrated shielded analog signals, the wireless data transmission technology of WIFI signals, and the dynamic curve visualization technology based on the characteristic parameters of the monitoring points.

The monitoring system was designed with the following characteristics: 1) the test node was taken as the unit, and the modular distributed design was adopted to facilitate management and maintenance; 2) the data acquisition unit was set at the test node site to minimize the transmission distance of the weak analog signal output by the sensor. It was transmitted by digital signal through A/D conversion
of the acquisition unit; 3) in view of the complex working environment conditions on site, the signal transmission system of the acquisition unit of each test node of the system was independent of each other, which enhanced the anti-interference capability of the test system, and the local faults of the acquisition sub-station would not affect other parts of the system, ensuring the security of data. Figure 5 is an integration diagram of the designed monitoring system.

In order to make the monitoring system can solve complicated field measuring point spread, transmission lines, running environment conditions such as testing the technical difficulties, we had carried on the system anti-interference design, mainly take the following several kinds of treatment technology: 1) sensor output way was introduced and the system signal and completely isolated points, overcome the uncertainty of measuring point position influence on test system; 2) reasonable grounding and shielding can prevent other interference signals from entering the signal transmission circuit under test, so the system had strong anti-interference capability; 3) the use of isolated power supply ensured that the system would not be affected by the power grid voltage fluctuation and surge caused by the start-up and shutdown of any high-power equipment around the site and the changing working conditions, thus avoiding the occurrence of false alarm.

Figure 5. An integration diagram of the monitoring system.

4.2. Monitoring data collection and analysis
Arched strain sensors convert strain signals into electrical signals, the acceleration sensor convert vibration signal into electrical signal, measuring bridge after weak electrical signals by the amplifier amplification by cut-off frequency filter to get the analog signal, the using the A/D conversion, the processed results through serial communication module are transmitted to computer for further processing. We can use manual input to adjust the parameters. The power supply module converts 220V AC current through rectification, filtering and voltage stabilization into DC power supply of different voltage levels required by each module to supply power to each module.
We developed a set of data acquisition and storage for high-parameter steam/water piping structure condition monitoring of thermal power plants, which realizes remote wireless monitoring of the piping, intelligent control and fault early warning and other functions. The method of establishing a database index based on a multi-tree operation can improve the efficiency of the instantaneous query of the distributed collection of the structural parameters of the piping structure [14], and retrieve the monitoring of each period through the method of storing and retrieving the files of the entire measurement point and period. The data builds a statistical data table, draws real-time dynamic curves, and realizes terminal visualization of characteristic parameters. At the same time, it constructs a piping structure database classified by measurement point location, measurement time, characteristic parameters, and implementation direction.

The finite element modeled piping system used static load analysis to obtain key node stress limits and piping structure modal analysis to obtain vibration limits. Input data acquisition system was used as a comparison threshold, and 80% of the threshold was set as a warning value. The threshold value was used as the alarm value, and the actual data was compared with the early warning value and the alarm value by software to realize the real-time data instant discrimination and early warning. Figure 6 is the time history curve of the monitoring signals collected by the monitoring system.

![Figure 6. Time history curve of monitoring signal at each measuring point.](image)

The database composed of real-time measured data can conveniently retrieve the piping parameter values during the startup, shutdown, load change, safety valve exhaust, damage of hangers, cracks in welds, abnormal deformation of the piping and sinking. The system's safe operation, structural fault diagnosis and accident cause analysis, quality inspection and acceptance, and safety condition assessment provided data information [15].

After installing the structural condition monitoring system, the test steam/water piping has been running for about 10,000 hours. The sensors deployed at the site are in good working condition and the signal transmission is stable and reliable. The monitoring values and changes of each node are within the threshold, and the monitored piping runs smoothly. No vibration or overload damage occurred to the pipe support-hanger system.

5. Conclusions

Based on the analysis of the structure of high-parameter steam/water piping in power plant, a real-time monitoring system for the structure status of steam/water piping is build and applied in the current paper, and the following conclusions are drawn:

(1) Based on steam/water piping structure features and operation condition, through on-site technical research and numerical simulation is based on the actual structure of the static and dynamic analysis, select the typical monitoring nodes, and on the basis of building distributed key node
sampling of the state of the real-time online monitoring system to monitor the piping structure method is practical and feasible.

(2) The high-parameter monitoring system of soda water piping structure breaks through the limitation of traditional manual data collection, effectively solves the synchronous monitoring and data collection of burst conditions, and lays a foundation for fault diagnosis, safety status assessment of piping structure and the flexible operation of thermal power unit, which can be popularized and applied in related projects.

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