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Non-destructive testing Techniques based on Failure Analysis of Steam Turbine Blade

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Abstract. Turbine blades are core components in turbine. It is of great significance to diagnose the blade failures at early stage and regularly inspect them at run time. Based on the analysis of blade failures, a comprehensive application summarize of different non-destructive testing techniques in blade inspection was made in this paper. The non-destructive testing techniques include visual testing, liquid penetrant testing, magnetic particle testing, radiological testing, conventional ultrasonic testing, ultrasonic phased array testing, eddy current testing and metal magnetic memory testing. The applicability and limitation of different methods were demonstrated through comparison and analysis.

1. Introduction

Turbine blades are core components in turbine, which play important roles in energy transformation. Its operation status directly decides the efficiency and safety of turbine and even the entire power plant. The operating conditions of the turbine are very complex. The turbine bears centrifugal force, steam power, steam exciting force, corrosion and vibration, and high speed erosion in wet steam area [1]. It is more likely to cause blade damage or even breakage. Once the breakage happens, the damaged blade may damage other blades. Even it will break the dynamic balance of turbine rotor, which may lead to unstable shaft of steam turbine and cause vibration of turbine rotor. In severe case, emergency shutdown may happen. Therefore, it is very important to study the non-destructive testing techniques based on the failure analysis of steam turbine blades.

2. Failure Analysis of Steam Turbine Blade

2.1. Failure modes of Steam Turbine Blade

In these exceptional cases of steam turbine, failure modes caused by blade damage make a great percentage. The main reason for blade failure is fatigue failure caused by microcosmic stress concentration [2]. Its basic characteristics appear as follows. Under the action of alternating stress less than the limit of static stress strength, many types of inner microdefects, such as dislocation, slippage and phase transformation induced by temperature or stress, were germinated and turned into macroscopic cracking. With crack extension, fracture may occur. The fatigue crack of blade usually generate from thin-wall. It is a dangerous part of microcosmic stress concentration.

Fatigue fracture can be classified into mechanical fatigue fracture and corrosion fatigue fracture. A correlational study [3] showed that the reason for the cracking and fracture of steam turbine blade is corrosion fatigue fracture. The fatigue crack originals are the pitting holes on the blade surface.

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Cracks generate under the influence of corrosive environment and exciting forces. It is mainly shown as intergranular stress corrosion and intergranular fracture at fatigue source and fatigue propagation with corrosion characteristics at crack growth regions. Therefore, many factors will influence the generation of the blade fatigue fracture, including the loading, structural strength, temperature and corrosivity of the blade.

2.2. Stress Analysis of Steam Turbine Blade

A steam turbine blade consists of the blade root, blade top and working region. From the technological structure of view, the blades can be divided into several types. They are constant chord blade with filling-up piece, straight blade with massive blade root, variable chord blade and variable chord twisted blade. By Analyzing the stresses of different types of blades (with or without shroud and lacing wire), it is observed that blades with different structures have different stress condition, and stress conditions of different parts on the same blade are also different. We takes variable chord blade as an example, the stress condition of steam turbine blade is calculated [4].

A stress analysis of the blades with a shroud or a lacing wire was shown in table 1. It is s a reference for blade force comparison with a shroud or a lacing wire. Stress analyses of the blades without a shroud or a lacing wire was shown in table 2, while the stress analysis of the blades with a shroud was shown in table 3.

Table 1. Stress analyses of the blade without a shroud or a lacing wire

Part	**Force types**	**Force value***	**Vibration**
Root	Centrifugal tensile stress; Centrifugal bending stress; Gas flow bending stress; Dynamic stress;	Most serious	More serious vibration
Top	Dynamic stress	Slightest	Mainly A0 vibration
Working region	Centrifugal tensile stress; Centrifugal bending stress; Gas flow bending stress; Dynamic stress;	Common	
*note: As a reference for blade force comparison with a shroud or a lacing wire.			

Table 2. Stress analyses of the blade with a shroud

Part	**Force types**	**Force value**	**Vibration**
Root	Centrifugal tensile stress; Centrifugal bending stress; Gas flow bending stress; Dynamic stress;	Tensile stress increases Dynamic stress decreases	Vibration is lighter Mainly A0 vibration
Top	Tensile stress; Pressure stress; Torque;	Dynamic stress of some blades increase considerably	
Working region	Centrifugal tensile stress; Centrifugal bending stress; Gas flow bending stress; Dynamic stress; Torque;	Gas flow bending stress increases Dynamic stress decreases	

Table 3. Stress analyses of the blade with a lacing wire

Part	Force types	Force value	Vibration
Root	Centrifugal tensile stress; Centrifugal bending stress; Gas flow bending stress; Dynamic stress;	Integral stress decreases	Vibration is lighter Mainly A0 vibration
Top	Bending stress	The minimum stress	
Working region	Centrifugal tensile stress; Centrifugal bending stress; Gas flow bending stress; Dynamic stress; Torque;	Gas flow bending stress and dynamic stress decrease	
Lacing hole	Tensile stress; Pressure stress; Torque;	Mainly dynamic stress, easily causing stress concentration	

The study [3] indicated that under the operation situation of the steam turbine, the rotating blades bear the maximum static stress and alternating stress. In addition, the blades face forced vibration under the excitation force, which will increase the risk of blade fracture. According to the analysis of the blade actual operation situation, its fracture mode is not simply belonging to fatigue fracture, the environmental medium and the surface salt also exacerbate the crack producing and spreading.

3. Non-destructive testing methods of steam turbine blades

There are various reasons for the failure of steam turbine blades, such as the damage caused by the unqualified specific characteristics. During the actual operation process, it is common that the nonconforming frequency of the blade could generate resonance and result in resonance damages. Defective design, poor materials and immaturity processing technic will also cause the blades failure. In addition, operational issues of the steam turbine are the essential reason for the blade failure, such as the operation deviation from the rated power, overload operation, low temperature, poor steam quality, too high or too low vacuum degree, water-entry impact and frequent starts and stops. It can be seen from the above reasons the steam turbine blades may suffer from damages at each stage of the design, manufacturing and operation. Therefore, it is very important to periodically inspection the blades during the refueling outages, find the failure blades with defects or deformity timely and repair or replace them, to avoid a serious accident and heavy losses of economy.

3.1. Surface Examination

Visual testing is used to test the physical dimension, structural integrity and shape defect of the blade. It is also capable of finding out the defects and other details on the blade surface. There are many advantages of visual examination. The principle is sample. It is easy to operate and should not be affected by the material, the structure, the shape nor the size. The inspection result is simple, rapid, reliable and sensitive with repeatability. However, due to limited to human vision and the equipment resolution, the slightest defects on the blade surface may be ignored during the inspection process.

Liquid permeation method is used to test the surface-breaking defects on the blade surface. The permeated solution has strong permeability. Because of the wetting action and capillary action, when brushed on the tested area, the permeated solution will infiltrate into the surface-breaking defects on the blade surface. Then the permeated solution is wiped away and the developer with strong sorption ability is uniformly sprayed. Under the capillary action, the permeated solution remaining in the defect is adsorbed to the blade surface and shows the location and shape of the defects. The inspection principle of liquid permeation method is easy. The inspection sensitive is comparatively high. However, the inspection range of the liquid permeation method is definitely limited. The technique can only test surface-breaking defects and have a high demand on the surface roughness and clearness.

Magnetic particle testing is another surface examination method. The blade inspection process of magnetic particle testing technology is as follows. When the ferromagnetic blade is magnetized, due to discontinuity, local distortion of magnetic field lines on the surface and near surface occurs, lead to the generation of leakage flux. By adsorbing the magnetic particles on the blade surface, visible magnetic particle indication occurs and shows the position, shape and size of the defects. A related study inspected the steam turbine rotor blades by using the method of fluorescent magnetic particle testing with proper inspection techniques [1]. The factors of affecting the sensitivity are researched, including the number of turns of the magnetized coils, magnetic suspension concentration and magnetizing time. Results indicate that the fine defects at the blade tip, the blade root and the blade surface can be detected reliably by using the method of fluorescent magnetic particle testing. It has high testing sensitivity and reliability, which is suitable for defect inspection of irregular parts of blade.

3.2. Radiological testing

X-ray radiographic testing is one of the important methods for turbine blade defect inspection at early stage. When x-rays penetrate through the examined objects, the absorbing ability of the defective part is different from that of non-defective parts. In general, the intensity of the X-ray transmitting through the defective part is higher than that of the non-defective parts. The differences in film blackness can show the defects in the examined components. The results can be directly observed on the films and the films are suitable for long-term preservation. Because the turbine blade is thin and has variable thickness with technology of high quality requirements, the flaw detection sensitivity and film definition are important factors during the X-ray radiographic testing. The early study on the turbine blade inspection by using the X-ray radiographic testing method was around the flaw detection sensitivity [5-6].By choosing the proper hardness of X-rays, focal length, trans-illumination mode, film type and using the intensifying screen and double film technique, the defect in the turbine blades are successfully inspected with quite high sensitivity.

3.3. Ultrasonic testing

Ultrasonic testing is a common nondestructive testing method to inspect the volume defects. Ultrasonic waves can travel through the material. Ultrasonic testing has advantages, such as short time, flexible operation and low cost. Meanwhile, it has very high requirement for the shape, the surface condition of the blades and the experience of technical personnel. Therefore, ultrasonic testing is feasible for blade surface and blade root section, but not appropriate in effectually inspecting the blade roots. At present, ultrasonic phased array testing is used for the full coverage inspection of the turbine blade roots.

The common types of blade root include the T type, the mushroom shaped type, the fork shaped type and the fir type. According to the stress analysis, during the running process the stress mainly concentrated in the joint part of the blade root and the rotor wheel groove. The stress generally reaches the maximum on the surface of the first or second root, easy to cause the root cracks. Additionally, the roots have complex structure and small spacing. It is hard to inspect the roots by using the traditional ultrasonic testing technique. Therefore, it is widely to study the inspection techniques of different types of roots based on the ultrasonic phased array testing technique. Zhang Yicheng et al inspected the fir type rotor blade roots by using the PAUT technique [7]. Researchers first determine the key ultrasound scan area according to the stress analysis. By the means of simulation, two types of ultrasonic phased array testing probes, transverse wave and longitudinal wave probes, are optimized and designed. The turbine blade with passing hollow is the simulated test block. Several scanning patterns are set up. The inspection results indicate that the designed ultrasonic phased array testing technology is highly accurate and effective. It can be used to effectively inspect the turbine blade root. Zhang Wuneng et al designed a special phased array ultrasonic transducer [8].By using a matched wedge block, the mushroom shaped roots were well scanned. With the accurate beam index, the inspection system enhances the inspection efficiency and can achieve the crack defects in a quicker, more intuitive and more effective way. Huang Qiaosheng et al inspected the mushroom shaped blade roots by using the method of ultrasonic phased array testing technique [9], aimed at studying the judgment method of defect signals. Wang Jun studied the quantitative method of PAUT results of the mushroom shaped blade roots [10], giving that -6dB quantitative method is most suitable for measuring the defect length of the mushroom shaped blade roots. He Cheng et al inspected the T type rotor blade roots by using the PAUT technique [11]. In consideration of that the T type blade roots are buried in the impeller rim, it is of great significance to study the online inspection of T type roots. To realize a full coverage PAUT of cracked areas of T type roots, the researchers developed special small-size linear array phased array probe. By using its CAD advanced artifact diagram import module, the T type roots were loaded on to S-scanning mode images. The inspection results are comprehensive, clear and easy to judge.

3.4. Eddy current testing

Eddy current testing technique is an efficient surface and near-surface defect inspection method. When the eddy current probe moves on the blade surface, if there are defects on the blade surface or its conductivity, permeability and shape change, the coil impedance of the eddy current probe will change correspondingly. The features of eddy current signals can show the defects on the blade surface.

At present eddy current testing technique is a positive try, which will become an additional inspection of the turbine blade.Shao Zebo et al inspected the blade simulated crack with the methods of eddy current testing technique [12]. By quantitatively studying the corresponding relation between the defect sizes and response signals, the experimental parameters used for practical application are confirmed. However, the inspection sensitivity of conventional point-type probe is related to the defect direction. Therefore, for the special blade parts, such as the blade groove, some defects may be skipped over when the defect direction is consistent with the eddy current direction. Based on the structural features of the blade grooves, flexibility and copying array probes are made [13] and used to inspect the blade body and blade grooves of low-pressure rotor last stage blade. It has features of easy operation, no-pollution and high sensitivity and reliability.

3.5. Magnetic memory testing

Based on the leakage magnetic field detection of the components, metal magnetic memory testing technique is used to determine the stress concentration and damage degree of components. It can detect locations where macroscopic defects are not present. Early diagnosis is helpful to evaluate the safety of equipment accurately. Magnetic memory testing is the only nondestructive detection method that can accurately identify the stress and deformation concentration areas and other dangerous areas. In this, it is often used to diagnose microscopic defects and early failure and damage, preventing sudden fatigue damage.

For turbine blades, the main reason of blade fracture is fatigue failure caused by microstress concentration. The conventional methods are mainly used in detecting the macroscopic cracks of turbine blades. Therefore, magnetic memory technique is an effective method to find stress concentration zone, which can provide early diagnosis for blade damages. Dai Guang et al inspected the various stages of rotor blades with a stress concentration magnetic detector [2]. Based on the leakage magnetic field and scattering magnetic field gradient of the detected component, the position and severity of blade stress concentration are analyzed. Results show that the most dangerous stress concentration areas of blade is the blade root, the joint between the blade and the girdle and the vicinity of the rib hole. This provides a reference for the early diagnosis and maintenance strategy of turbine blades. Another inspection found cracks in the stress concentration line of the blade [14], it is verified that the metal magnetic memory detection method is very reliable for the initial diagnosis of stress concentration in turbine blades. Researches on the application of metal magnetic memory testing technique include metal equipment strength and reliability diagnosis, quality inspection and sorting of mechanical parts and pressure vessel strength and life diagnosis. Development of intelligent metal magnetic memory diagnostic equipment and signal processing software will also contribute to the improvement of metal magnetic memory testing technique.

3.6. Comparison and analysis of NDT methods

Comparison and analysis of different NDT methods are shown in table 4.

Table 4. Stress analyses of the blade with a lacing wire

NDT Methods	Defect Type	Examination area	Sensitivity	Efficiency and Reliability
VT	Surface Defect	Blade Body	Lower	Higher
PT	Surface-Breaking Defect	Blade Body, Lacing Hole	Lower	Lower
MT	Surface Slight Defect	Blade Edge	Higher	Lower
RT	Volume Defect	Blade Weld	Higher	Low Efficiency & High Reliability
ET	Near Surface Defect	Blade Edge, Lacing Hole	Higher	Higher
UT	Volume Defects	Blade Body	Lower	Lower
PAUT		Blade Root	Higher	Lower
MMM	Micro And Macro Defects	Blade Edge	Very High	Higher

4. Summary

Nondestructive testing technologies play important role in turbine blade inspection. Different NDT methods have their own advantages and limitations during the blade detection process. The main characteristics are summarized as follows.

(1) Traditional nondestructive testing methods play an important role in the inspection of surface and near-surface defects.

(2) The application of phased-array ultrasonic technology solves the problem of high leakage rate and low inspection efficiency in conventional ultrasonic inspection of blades.

(3) The metal magnetic memory technology can be used to diagnose the micro-defects, the early failure and damage. It has a broad prospect in early fault diagnosis of the blades.

(4) The development direction of nondestructive testing technology for blade inspection is that: the intellectualization of the inspection equipment, high efficiency of the inspection process, the digitalization of test results and realizing the early fault diagnosis and prediction.

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