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Vibration analysis for failure detection in low pressure steam turbine blades in nuclear power plant

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ABSTRACT

This paper presents an investigation of the failure of a low-pressure steam turbine blade in a pressurized water reactor (PWR) nuclear power plant. The dynamical behaviour of the blade is analyzed theoretically and experimentally. A three-dimensional finite element model is used to predict the blade resonances in the operational speed range. Natural frequencies and mode shapes of the blade at static condition are obtained, then natural frequencies of the blade at different rotational speeds are calculated with consideration of centrifugal force and steam flow forces. A Campbell diagram is plotted to predict the likely operational conditions that may cause resonant vibration of the blade. Vibration tests are conducted to determine the vibration characteristic of the blade. It is found that the 2nd natural frequency of the blade is very close to the 9th rotor speed harmonic. The experimental natural frequencies are in good agreement with the finite element predicted values. Fretting wear is observed at the concave root surfaces of the blade trailing edge caused by resonant vibration. The fracture surface of the cracked blade shows typical fatigue patterns. The fretting wear characteristics in the crack initiation regions are observed.

Stress distribution of the blade at the 9th harmonic frequency is analyzed using an elastic-plastic finite element model. Fretting fatigue experiments indicate that the fatigue life of the blade is greatly reduced due to fretting wear. The results of the investigation show that the failure of the blade is attributed to a combination of high cycle fatigue (HCF) and fretting wear.

1. Introduction

Turbine blades are the critical components in power plants which convert steam flowing into rotary shaft [1]. However, Failures of turbine blades are widely observed in power plants that will shut off the power supply [2]. The failure mechanisms of blades may include corrosion due to working fluids, low cycle fatigue caused by transient operations, high cycle fatigue induced by forced vibrations, etc. [3–5]. Vibration induced fatigue is one of the predominant causes for blade failures in steam turbines [6]. Blades vibrations are generally excited by the fluid flow, and they may become severe when resonances occur. The turbine blades subjected to several sources of excitation are highly susceptible to undergo forced vibrations, which may occur at or near natural frequencies of the blades [7]. The forced vibrations may enlarge the stresses resulting in degradations of the blades, which is referred as high cycle fatigue (HCF) [8]. Furthermore, a large number of high-stress cycles are accumulated in the blades during startup of turbines.

During the past decades years, vibration analysis for failure detection in turbine blades have been conducted by many scholars [9–11]. Research on the blades vibration focused on natural frequencies and mode shapes, which were analyzed by modal analysis,

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and the causes of cracked blades were also investigated. Static and dynamic finite element analysis were used to determine the vibration characteristics of blades, modal and harmonic analysis were conducted to analyze the dynamical behaviour of blades, and Campbell diagrams were used to reveal the critical conditions for resonances when the exciting frequencies are near the natural frequencies of blades. It was concluded that the dynamic stress coupled with the maximum static stress due to the centrifugal force may induce the blade fatigue damage.

Since resonance vibration of blades is inevitable, and can affect the fatigue life of blades, vibration analysis of blades is very important in operational turbines. A three-dimensional finite element model was adopted to investigate the resonances of blades, and tip timing technique was used to assess the vibration characteristics of blades by Madhavan et al. [12]. A contact stress measurement method was used to analyze the responses of rotating blades by Robinson and Washburn [13], however, it has a few disadvantages such as harsh operational conditions and failure of gauges at severe environments. A non-contact stress measurement method was adopted to investigate the dynamical behaviour of blades by Zielinski and Ziller [14], it can overcome the disadvantages of direct measurement method and monitor the vibration of blades effectively. Recently, a method was used to investigate the dynamics of blades by means of monitoring casings vibrations [15–18]. A Lagrangian and Eulerian meshing approach based on signal analysis of the casing vibration was adopted to study the dynamical behaviour of a single blade by Rao and Dutta [16–18]. In their research, the vibration response of the casing excited by blade passing frequencies was analyzed to diagnose the status of the blade. A simple model was used to investigate the dynamics of blades with snubbing effect by Pennacchi et al. [19], the effect of the snubbing on the blade vibration reduction was studied experimentally, it was found that snubbing was effective when the blade was excited in resonance or close to resonance.

In the present paper, the failure of the damaged blade is investigated theoretically and experimentally. A finite element analysis (FEA) and vibration tests are performed to analyze the dynamical behaviour of the blade. The turbine operational conditions that could lead to resonant vibration of the blade are predicted. The stress distribution of the blade working in resonance condition is calculated using the finite element method (FEM). Fretting fatigue experiments are conducted to analyze the effect of fretting on the blade fatigue life.

2. Background

A nuclear power plant was shut down due to high vibration of a steam turbine, and several fourth stage blades were seriously damaged. The turbine accumulated around 60,000 operation hours to failure. The fourth stage blades with four-tooth fir-tree fixing roots are free-standing types, one of the fractured blades is shown in Fig. 1. The blade under investigation is a 3000 rpm fourth stage blade of the 650 MW low-pressure steam turbine, it is made of 0Cr17Ni4Cu4Nb stainless steel, which is a Chinese GB standard material with chemical composition of C 23.42, Cr 12.76, Ni 2.73, Cu 2.19, Si 0.68, Mn 1.49, Fe 56.73. A crack is observed between the blade root platform and the first tooth with the use of dye penetration, as shown in Fig. 2. The crack propagates at an angle from concave side to convex side of the blade root. The crack sizes on the concave side and on the convex side are, respectively, 22 mm and 8 mm.

3. Modeling and analysis

Dynamic analysis of the blade is performed using a finite element method. The three-dimensional model of the blade is established, and the high quality meshes are generated. The natural frequencies and the mode shapes of the blade at static condition are predicted. The natural frequencies of the blade at different rotational speeds are also calculated with consideration of centrifugal

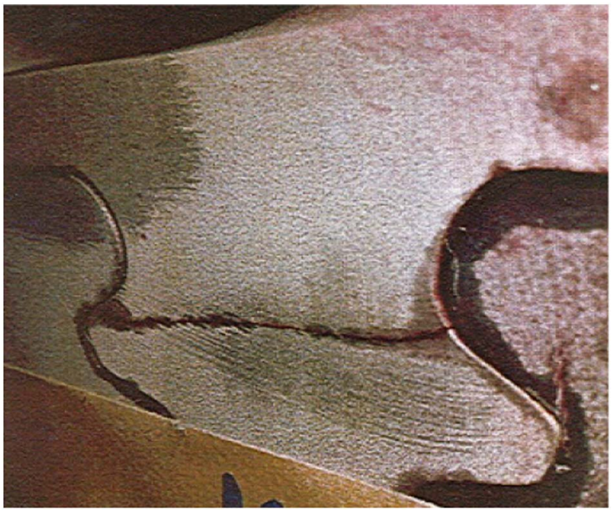

Fig. 1. View of the blade root with crack.