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Estimation of efficiency of vibration damage detection in stepped shaft of steam turbine

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ABSTRACT

The vibration based damage detection has practically no alternative as applied to the rotating shafts of steam turbines during operation. However, taking into account the heavy operating conditions of turbines and the complex shape of the turbines shaft, the choice of most effective method of vibration diagnostics is not an easy problem. To solve this problem, there was developed a relatively simple procedure of comparative evaluation of the effectiveness of vibration diagnostics of damage. The procedure is based on the determination of the change of shaft's compliance caused by a crack with the use of linear fracture mechanics. It was demonstrated as applied to the stepped rotors and shafting of steam turbine. The comparative analysis of efficiency of vibration diagnostics was performed based on the change of natural bending, longitudinal or torsional frequency of vibration to detect transverse or longitudinal crack in rotors and shafting of steam turbine K-200-130.

1. Introduction

The vibration based damage detection has practically no alternative as applied to the rotating shafts of steam turbines during operation [1]. The presence of natural sources of bending and torsional vibrations and the availability of advanced procedures and sensors for the measurement of vibrations are the evident advantages of vibration diagnostics of turbines. At the same time the theory of vibration diagnostics has been developing as applied to the structural elements of simple geometry. Therefore such a theory can hardly be applied to the real structure like steam turbine shafting without essential losses for the accuracy of damage severity prediction.

Steam turbine is a complex mechanical system, structural elements of which are subjected to intense thermomechanical loading, which causes damage of turbines structural elements. This damage accumulates for a long period of time and sooner or later may lead to catastrophic destruction of turbine [2,3]. One of possible way to prevent such an undesirable scenario is the application of vibration diagnostics of damage. Vibration diagnostics can be used as well for the on-line estimation of fatigue damage, which is the consequence of intense vibrations [4].

A lot of vibration based methods of damage detection were developed till present time. The most widely used among them are the ones that detect the change of natural frequencies, mode shapes, or modal damping, and non-linear effects [1,5,6]. That is why practical engineers often face the problem to make decision on choosing the most appropriate ones among the variety of damage detection methods as applied for definite structure. Unfortunately, this problem cannot be solved easily because the efficiency of vibration damage detection is very dependent on the type of structure, way of its deformation and on the type of damage. The assessment of possibility of vibration diagnostics to detect damage of sub-critical size is a complex and time-consuming process. Currently it is carried out either theoretically using quite sophisticated models or experimentally [1]. These both ways, however, are not appropriate for engineering applications.

The results of analytical investigations and laboratory tests on small-scale models of shafts demonstrated high efficiency of vibration based damage detection [7–10]. The investigations on large-scale laboratory models also confirmed the possibility to detect cracks in rotating shafts using vibration diagnostics [11,12], although their sensitivity in some cases was found to be insufficient. Practice of vibration diagnostics of real steam turbines is quite controversial. On the one hand, vibration diagnostics helped to prevent a breakdown of turbine [13,14]. On the other hand, a deep crack in the turbine shafting did not reveal itself by any change of vibration's parameters [15].

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The reasons for such a different judgements on the effectiveness of vibration damage detection can be attributed to the influence of the structure's compliance on the sensitivity of diagnostics. In particular, the study [16] on bending vibrations of cracked shaft showed that the influence of crack on the shaft's natural frequencies is significantly dropped with the increase of its flexibility. Furthermore, during operation of steam turbines the modulus of elasticity and damping characteristics of materials of turbines structural elements vary because of temperature change, which causes significant influence on the vibration characteristics of turbine. Thus, the proper damage detection itself becomes problematic or even impossible [17].

The appropriate modelling of the influence of crack on the stiffness (compliance) of mechanical systems is of paramount importance in the problem of vibration damage detection. The most widely used way to determine the compliance of cracked section is based on the fracture mechanics approach using the Castigliano's theorem and the relations between the strain energy release rate and the Stress Intensity Factor (SIF) [18]. This approach makes it possible to develop simple models of cracked structures, which can accurately predict the change of natural frequencies and mode shapes. Besides such models can reveal the non-linearity of vibration of structures with the so called closing crack (crack which periodically opens and closes during vibrations).

The aim of the study is to develop a relatively simple procedure to perform the comparative analysis of efficiency of any vibration based diagnostics of damage which can be used by practical engineers to ensure the safety of turbine in operation. This procedure is demonstrated as applied to the stepped turbine shafts. As a vibration method of damage detection is considered the change of natural frequencies of turbines rotors and shafting at bending, longitudinal and torsional vibration caused by the transverse or longitudinal crack.

In essence, the procedure of efficiency estimation is based on the experimentally verified in many researches theory of vibration diagnostics. The core of this theory is the determination of the change of structure's compliance caused by the appearance of damage [1]. So if the change of compliance is determined accurately (and numerous experiments proved that [5,7,9 etc.]), then most probable that the procedure can be successfully applicable to different types of structures with other types of cracks.

The only restriction for the application of procedure is possible lack of appropriate mathematical apparatus of fracture mechanics. Namely for this reason the slant crack was not considered in the work, since at the moment the corresponding SIF functions for such a crack has not been calculated yet.

2. Efficiency estimation of vibration based damage detection

Practically all vibration based methods of damage detection determine the relationship between the vibration characteristic and the parameters of damage via the change of compliance of cracked section. Linear fracture mechanics makes it possible to derive relatively simple equations for the determination of compliance of cracked section in different structures under various types of deformation. In such a way, in present study the theory of linear fracture mechanics was applied to the shaft type structure.

2.1. Compliance of a shaft with an edge transverse crack at bending

The compliance of cross-section with a crack can be determined based on linear fracture mechanics approach. For the linear-elastic body the changes of strain energy due to edge transverse crack of mode I with a straight front can be expressed in terms of the SIF K_I [19]

$$\Delta U = \frac{b\left(1-\nu^2\right)}{E}\int_0^a K_I^2 d\alpha, \tag{1}$$

where a is the crack depth; b is the width of crack front (Fig. 1a); E and ν are the Young's modulus and Poisson's ratio of the material, respectively.

At the same time, the change of strain energy of the cross-section with a crack can be expressed in terms of the change of compliance of this section δ_0

$$\Delta U = 0.5\cdot\delta_0 M^2, \tag{2}$$

where M is the bending moment in the section with a crack.

For the edge crack with straight front at bending of shaft the SIF is determined by the equation [19]

$$K_I = F_I\frac{M}{W}\sqrt{\pi a}, \tag{3}$$

where $F_I = 1.1105 - 2.6475\gamma + 5.6875\gamma^2$; $\gamma = a/D < 0.6$; W is the axial section modulus. In this case, the width of the crack front can be expressed in terms of its depth and diameter of the cross-section

$$b = 2\sqrt{a(D-a))}. \tag{4}$$

From (1)–(4) it is possible to determine the expression for the change of compliance

$$\delta_o(\gamma, L_c) = \frac{4096\cdot\gamma^2\left(1-\nu^2\right)\sqrt{a(D-a)}}{\pi\cdot E\cdot D^4} \times\left(0.616 - 1.961\gamma + 4.914\gamma^2 - 6.031\gamma^3 + 5.396\gamma^4\right)\cdot|\overline{M}_i(L_c)|, \tag{5}$$

where L_c is the crack location; $\overline{M}_i(L_c)$ is the normalized bending moment for the i-th mode shape of the shaft vibration in the cross-section with a crack.

2.2. Compliance of a shaft with an edge transverse crack at tension

In the case of tensile deformation of the shaft with an edge transverse semi-elliptical crack of mode I (Fig. 1b) the changes of strain energy can be expressed in terms of the SIF K_I [19]

$$\Delta U = \frac{2}{E}\left(1-\nu^2\right)\int_0^c\int_0^a K_I^2 dx d\alpha, \tag{6}$$

where c *is* the half-width of the crack front. The SIF is defined by the equation

$$K_I = F_I\frac{P}{F}\sqrt{\pi a}, \tag{7}$$

where P is the tensile force; F is the cross sectional area. In the case $a/b_x = 0.6$ SIF is practically constant along the crack front and can be expressed by the equation [20]

$$F_I = 0.797 + 0.58147\gamma + 0.424948\gamma^2 + 7.862319\gamma^3; \gamma = a/D < 0.6. \tag{8}$$

At tensile loading P the change of strain energy of the cross-section with a crack may be determined in terms of the change of compliance of this section δ_0

$$\Delta U = 0.5\cdot\delta_0 P^2. \tag{9}$$