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Crack detection for a Jeffcott rotor with a transverse crack: An experimental investigation

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A B S T R A C T

In this paper, an experimental investigation is carried out to verify the theoretical results of the dynamic behavior and the EMD based crack detection method for the cracked rotor proposed in our former research. The breathing crack in the rotor is simulated by a real fatigue crack. The whirl orbits during passage through the 1/2, 1/3 and 1/4 subcritical speeds are investigated. The dynamic responses in these subcritical speed zones are decomposed into several subcomponents by the EMD method, and the variation of the high-frequency component are studied. As a comparison, the fast Fourier transform method is used to derive the amplitude variation of the high order frequencies from the frequency spectra of the experimental vibration signal. The experimental results are well concordant with the theoretical analysis, which indicates that the EMD based crack detection method is practicable.

1. Introduction

In large rotating machinery, such as turbine, generator and aero-engine, the rotor is one of the most important parts. Fatigue cracks have great potential to cause catastrophic failures in rotors which can lead to huge economic loss, or even serious human injury. Crack detection has attracted the attention of researchers all over the world based on the idea that changes of a rotor's dynamic behavior could be used for general fault detection since 1970s [1]. During the past 40 years, a great deal of papers have been published on the theoretical and experimental study of dynamic analysis of the cracked rotor [2–4]. It has been shown that accurate modeling of breathing crack in a damaged rotor system is a critical step in well understanding the dynamic effects of the crack and in identifying its vibration features. There are several crack models proposed by former researchers to calculate the stiffness of the cracked rotor [5–14]. In 2011, Al-Shudeifat and Butcher [15] developed new breathing functions for the cracked rotor by using Fourier series based on their former research [16] which used the integration method to calculate the true stiffness. These functions were in a close and independent mathematical form and were proved to be more accurate than the Mayes' model. However, in Ref. [15], the function of cross-coupling stiffness was not provided. In our previous paper [17], a new function of the cross-coupling stiffness was developed to complete the breathing model in Ref. [15] so that the breathing mechanism of the crack could be fully represented. The proposed function was applied to a Jeffcott rotor, the typical whirl orbits [17] and stability region [18] of which were investigated, respectively.

Based on the accurate development of time-varying stiffness functions, the governing equations of the cracked rotor system can be built and the dynamic behaviors are studied for crack identification by numerous researchers. Haji et al. [19]

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used orthogonal natural frequencies (ONFs) to identify the crack for a non-rotating cracked rotor. The simulated results showed that the unique characteristics was the appearance of the sharp, notched peaks at the crack location of the normalized ONF curve but round peaks at non-cracked locations. Silani et al. [20] modeled the crack breathing behavior with a finite element method, and the dynamic response of the cracked rotor was examined with the short time Fourier transform for small crack detection based on the presence of higher harmonics. Sekhar [21] used the continuous wavelet transform (CWT) to detect transverse cracks during a rotor system passing through its critical speed. The subcritical response peaks appeared in the CWT coefficient plots but not in the time-history plots, which was used as the indicator of the presence of cracks. Sinou [22] detected the breathing crack in a nonlinear rotor system by numerically using the 2X and 3X super-harmonic frequency components at the associated subcritical resonant peaks. Babu et al. [23] applied the Hilbert–Huang transform (HHT) to transient response of a cracked rotor. In the HHT spectrum, the instantaneous frequency fluctuations showed up as a result of the sub-harmonics which is a typical characteristic of a crack. In the former paper [17], we used empirical mode decomposition (EMD) to extract the fault feature of a transverse crack in a Jeffcott rotor by investigating the variations of super-harmonic components. Other researches [24–28] also focused on this topic and several methods have been proposed to detect the crack in rotor systems based on the typical dynamic behavior including the whirl orbits, spectrums of FFT, WT and HHT during passing through the subcritical speed zones. However, most of these researches are based on the simulation without any experimental verification.

Only few papers provided experiment results for the cracked rotor. In Ref. [29], Darpe et al. set up experiments on both slotted and cracked shafts to verify the analytical findings. A slot of width 1 mm was machined on the rotor near the disc using a slitter to simulate the open crack. In terms of the real breathing crack, a three-point-fatigue machine was used to generate a fatigue crack by adding cyclic loading to an initiate slit at a desired location. The orbits and FFT spectra during the rotor passing through 1/3 and 1/2 critical speed were consistently matching with theoretical findings. Similar method was adopted to make fatigue crack in Refs. [30,31]. However, in [30] the typical orbits in the subcritical speed zones were not as regular as the analytical results, and in [31] the frequency analysis was performed by the wavelet transform while none typical orbit was provided. Dong et al. [32] and Lin et al. [33] used the wire-cut electrical discharge machine to make a slit on the rotor which was treated as an open crack. Therefore, it is still necessary to experimentally verify the dynamic behavior and the crack detecting method for breathing cracks.

In this paper, based on the theoretical research of the dynamic analysis and the crack diagnostic method provided in Ref. [17], an experiment was set up on a rotor testbed. A real fatigue was made near the middle location of the shaft. The experiment results are compared with the analytical findings to investigate whether the proposed crack detecting method is feasible in practice.

2. Equations of motion of a cracked Jeffcott rotor

A Jeffcott rotor with a transverse crack considered in Ref. [17] is adopted in the present study which is shown as Fig. 1. A brief description of the modeling process for the cracked rotor is given below.

The coordinates built on the cross-section where the crack is located are shown in Fig. 2.

The equations of motion of the cracked rotor system can be given as

$$\begin{aligned} m\ddot{u} + c\dot{u} + k_1(t)u + k_{12}(t)v &= m_{ed}\Omega^2 \sin(\Omega t + \beta) \\ m\ddot{v} + c\dot{v} + k_{21}(t)u + k_2(t)v &= m_{ed}\Omega^2 \cos(\Omega t + \beta) - mg \end{aligned} \tag{1}$$

where u is the shaft displacement in the x_1 direction, v is the shaft displacement in the y_1 direction, m is the mass of the rigid disk, c is the external damping, m_{ed} is the mass unbalance, β is the angle between the mass unbalance and the weak direction of the crack, Ω is the rotating speed, and g is the gravitational acceleration.

Considering the neutral axis shift, the time-varying moment of inertia of the cross-section at the crack location is approximated by the Fourier series expansion. The independent functions of the moment of inertia and production of inertia (cross-moment of inertia) were given as

$$I_{\bar{X}} \cong I - f_1(t) I_{11} \tag{2}$$

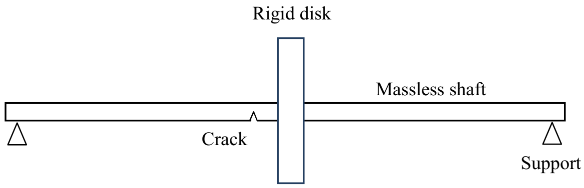

Fig. 1. Cracked Jeffcott rotor system [17].

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