Journal of Sound and Vibration 432 (2018) 502–529

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Crack detection in the rotor ball bearing system using switching control strategy and Short Time Fourier Transform

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A R T I C L E I N F O

Article history:
Received 30 September 2017
Received in revised form 29 May 2018
Accepted 26 June 2018

Keywords:
Rotor dynamics
Crack detection
Short time Fourier transform
Robust control

A B S T R A C T

In case of simple Jeffcott rotors, bearings lie on edges of the rotors, hence bearing nonlinearities are not properly absorbed in the dynamic response. Real rotors containing multiple disks, flexible bearing supports, centrally located ball bearings and couplings are far more complex in terms of their dynamic response than simple Jeffcott rotors. Nonlinear dynamic modelling of the flexible rotor with centrally located ball bearing has been developed and used for simulation purposes. It has been observed that crack detection techniques based on the steady-state vibration response work well for simple Jeffcott rotors only. The presence of ball bearings and other system nonlinearities inhibit the direct application of steady-state dynamic response based crack detection techniques for real rotor-bearing systems condition monitoring. However, transient response based crack detection techniques can be successfully applied to work in the presence of system nonlinearities. Crack propagation is enhanced during high amplitude vibrations, hence, instead of working in the resonance region, working in pre-resonance regions is advantageous due to lower vibration amplitudes. Switching control strategy based on a combination of active vibration control and Short Time Fourier Transform is proposed in present work. The proposed technique basically operates on the signal in pre-resonance regions (with low vibration amplitude) hence avoids chances of the crack propagation. This technique can be used to detect the presence of even small cracks and works well in the presence of bearing nonlinearities and flexible bearing supports that are inherently present in real rotor-bearing systems and qualitatively change dynamics of the overall system.

1. Introduction

During the service life of rotating machinery, various faults like transverse cracks, rotor bow, misalignment and bolt loosening are quite common. Early diagnosis of these faults can prevent breakdown with significant economic losses. Due to the cyclic nature of the stress, fatigue failure in the rotating machinery is quite common. Transverse cracks are generally observed in rotor-bearing systems with fluctuating bending moments. In the last three decades, researchers have developed efficient crack detection techniques. Reference [1] gives a comprehensive introduction to this subject. Wauer [2], Gasch [3] and Dimarogonas [4] analyzed the nonlinear dynamics of rotor systems with fatigue cracks. It has been observed that nonlinear vibrations are produced in rotors in the presence of a transverse crack. Generally, two types of transverse cracks are

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https://doi.org/10.1016/j.jsv.2018.06.061

encountered in real rotors. These include open and breathing cracks. The permanently open cracks represent asymmetrical rotor and pose stability problems. These types of cracks are generally found in the rotors with low weight. Under the weight dominance, the crack opens as well as closes repeatedly representing a breathing crack. Hinge models of the cracked rotor were reviewed in Ref. [3]. Breathing crack model of the flexible rotor was proposed in the early time [5,6]. The comparison of these two models is available in Refs. [7,8]. In case of a cracked rotor system, the stability of periodic motion was used to detect the presence of crack [9–11]. Apart from simple two degrees-of-freedom systems used to model the rotors, various analytical, semi-analytical techniques, as well as finite element techniques (FET) have been used to model rotors with cracks.

In double row angular contact ball bearings, the restoring forces are function of quadratic terms of displacement (from equilibrium position). Ishida et al. [12] investigated forced oscillations of rotor-bearing systems in the presence of these nonlinearities. A simple Jeffcott type of rotors was considered in this work and the experimental results validated theoretical results regarding the shape of resonance curves. A detailed model of the ball bearing system considering the parametric excitation effect was however considered. Ji et al. [13] used the perturbation methods for the analysis of transient and steady state vibrations of the nonlinear rotor-bearing system. They used analytical methods for modelling the rotor system mounted on two bearings at the edges. A nonlinear model of restoring forces generated by bearings was considered in this work. However, parametric excitation considerations and other important modelling aspects of ball bearings were not studied in this work.

Chen [14] studied an ideal Jeffcott rotor considering three nonlinear factors of ball bearing systems. First being the nonlinear Hertzian contact force between balls and races, second is the clearance of bearings, and third being the varying compliance (VC) vibrations. These VC vibrations are generated because of the periodic change in contact positions between balls and races. Villa et al. [15] studied the stability of nonlinear systems in the frequency domain. A finite element method was used to discretize equations of the motion. In the above study, the steady-state behaviour of nonlinear systems with a very large number of the degrees-of-freedoms was studied using condensation techniques. However, no attention was paid to calculate the transient response of the overall system.

Hou et al. [16] studied the dynamics of a simple Jeffcott rotor mounted on ball bearings in the presence of transverse crack. The main motivation of their research was to diagnose the nonlinear dynamic behaviour of an aircraft cracked rotor-ball bearing system under maneuver loads. In case of a Jeffcott rotor, bearings are mounted on the shaft/rotor edges, giving less contribution of nonlinear bearing effects to the overall dynamics of the system. This is probably the most recent paper in the field of rotor dynamics, investigating the combined effect of bearing nonlinearities and rotor cracks. It has also been observed that the Jeffcott rotor does not represent the real rotor-bearing system with multiple rigid disks, couplings, flexible bearing supports and centrally located ball bearings. All these parameters demand a high order model of the system to represent the exact dynamics of the real rotor.

The presence of cracks in a revolving rotor converts a linear system into a nonlinear system with varying system parameters due to the parametric excitation. Historically, the 2X (where X is the critical or resonance frequency) response of a revolving rotor system in sub-harmonic and super-harmonic regions has been used to detect the presence of cracks. This process can be used in both frequency and time domains. For analysis, Bachschmid et al. [17] used the method of least squares to study the system in the frequency domain. Markert et al. [18] applied the same approach in the time domain to identify a crack and its location in a flexible rotor. In this regard, Kulesza and Sawicki [19] designed a set of observers to find out the presence and location of a crack in a rotor. Sawicki et al. [20] used auxiliary harmonic excitations (AHE) to detect the presence of cracks in the rotors. They observed the dynamic response of the rotor under sinusoidal excitation. They noticed that the spectrum of vibration response of a cracked rotor contains multiple frequencies. These frequencies are function of the rotor spin speed and external excitation frequency. The parametric excitation effect caused by rotor crack is responsible for the generation of these frequencies. This is a form of nonlinearity. The same concept has been used by the authors and their co-workers in other publications [21,22]. These methods are quite recent and are being used quite frequently. On the other hand, some of the researchers tried to detect the rotor crack based on the transient response of the revolving rotor. Darpe et al. [23] studied the transient vibration behaviour of a cracked Jeffcott rotor while crossing the critical or resonance speed. They studied the orbit plots near sub-harmonic resonances to analyze the effect of critical speeds on the orbit orientation. Babu et al. [24] applied Hilbert-Huang Transformations (HHT) to analyze the transient response of the cracked Jeffcott rotor. They emphasized that HHT gives better results as compared to the continuous wavelet transform and Fast Fourier transform (FFT) for the crack detection in a rotor based on the transient response. The main emphasis was on the transient response of the rotor when passing through a critical frequency. Silani et al. [25] investigated the ability of the short time Fourier transform (STFT) to detect the presence of small cracks based on the transient response calculations. Yang et al. [26] investigated the role of Empirical Mode Decomposition for analyzing cracks based on the transient response. The existing research as mentioned in Refs. [24–26] is mainly based on the application of STFT for the response in resonance regions. This high amplitude in resonance regions can increase the crack propagation speed. However, working in pre-resonance regions (where the vibration amplitude is much less than the amplitude in resonance regions) is advantageous.

In the first part of our research, we investigated effects of the flexibility of bearing supports and ball bearing nonlinearities on the effectiveness of crack detection techniques. In the second part of the research, we developed a new technique to detect the presence of small cracks in a rotor ball bearing system. Based on the authors' best knowledge, this is the first study showing the negative impact of the ball bearings (in the rotor system) on the crack detection efficiency of techniques based on the vibration response. The contribution of the present research can be divided into three parts. Firstly, a nonlinear dynamic model of the cracked rotor ball bearing system is developed. A discrete mass-spring damper element based model (DMSDM)