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Fault detection in rotor bearing systems using time frequency techniques

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ABSTRACT

Faults such as misalignment, rotor cracks and rotor to stator rub can exist collectively in rotor bearing systems. It is an important task for rotor dynamic personnel to monitor and detect faults in rotating machinery. In this paper, the rotor startup vibrations are utilized to solve the fault identification problem using time frequency techniques. Numerical simulations are performed through finite element analysis of the rotor bearing system with individual and collective combinations of faults as mentioned above. Three signal processing tools namely Short Time Fourier Transform (STFT), Continuous Wavelet Transform (CWT) and Hilbert Huang Transform (HHT) are compared to evaluate their detection performance. The effect of addition of Signal to Noise ratio (SNR) on three time frequency techniques is presented. The comparative study is focused towards detecting the least possible level of the fault induced and the computational time consumed. The computation time consumed by HHT is very less when compared to CWT based diagnosis. However, for noisy data CWT is more preferred over HHT. To identify fault characteristics using wavelets a procedure to adjust resolution of the mother wavelet is presented in detail. Experiments are conducted to obtain the run-up data of a rotor bearing setup for diagnosis of shaft misalignment and rotor stator rubbing faults.

1. Introduction

To identify existing faults in rotor bearing systems, several researchers have proposed theories and methods based on Fourier spectrum analysis, Orbit analysis, Wavelet Transforms and Hilbert Huang Transform [1,2]. In general common faults like the unbalance, shaft cracks, coupling misalignment and rotor–stator rub are identified based on the vibration data acquired. To identify these faults many researchers have focused on steady state vibration data [3] and few have presented their observations based on run-up and run-down vibration data [1,2,4,5]. Prabhakar et al. [6] have considered two individual cases of misalignment and shaft crack and presented their findings. The present study focuses on using run-up vibration responses for identifying coupling misalignment, shaft crack and rotor–stator rub faults. These three faults are expected to develop during the operation. Also, during operation secondary faults like rotor–stator rub [7] or impact can be caused due to the presence of primary faults like misalignment and unbalance. Many fault classification approaches based on neural networks and support vector machines are also based on steady-state vibration data. These require baseline or the healthy machine's data to reveal the fault information.

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Many researchers have presented model based methods for identification of faults such as fatigue crack [8] and coupling misalignment [9]. For large rotating machinery Pennacchi et al. [10,11] have presented a model based method for fault identification. A least square identification technique is introduced to identify faults in frequency domain. Model based approaches are useful not only for fault diagnosis but also have been applied to other technical processes [12]. A review on model based fault detection and quantification methods is reported by Lees et al. [13]. In a rotor bearing system misalignment may extent to premature failure of other components like bearing, seals and couplings. Rotating machinery with excessive misalignment causes high vibration and lowers the life of the components.

Alignment estimation methods based on optical laser or dial indicators are applicable only when the rotor system is stationary and the misalignment correction based on these instruments is based on the stationary data of the machine. Also, most of the industrial rotating machinery may not be available directly for examination due to limitations on deconstruction or size. Thus, to obtain a promising alignment, diagnosis based on vibration based data is unavoidable. Steady state or run-up vibration responses can be utilized to detect the misalignment present in the system [3,6]. Usually, steady state vibration based method leads to a confounding spectral information [14] and consumes more time when compared to run-up response based diagnosis. Based on steady state vibration data, the spectral information obtained for a particular fault configuration can be confusing as per the available literature [3]. The vibration with high $2\times$ and $4\times$ harmonics are commonly agreed for the presence of misalignment fault [15]. However, defects like fatigue crack and stiffening effects on shafts (due to rubbing), also show high $2\times$ harmonic vibrations. Sekhar and Prabhu [16] used higher order FEM to study the effect of misalignment. Using the theory based on kinematic model of the couplings Xu and Marangoni [17] reported a detection method based on the higher harmonics developed in the response due to misalignment. Under similar alignment conditions it is possible that for different types of couplings different spectral information can exist [14]. The spectral information of the steady state vibration response clearly cannot distinguish the existence faults.

For rotor supported on fluid film bearing, faults such as oil whirl, oil whip or dry whip can exist. Using run-up vibration data of such rotors Fan et al. [18] reported the diagnosis procedure for rotor supported on journal bearings. Since theoretical methods for fault detection include many assumptions results based on such methods may not be directly applicable for signals obtained from actual systems. Thus, experimental study is always necessary for examining new methods. Identification of multiple faults in rotor bearing systems is presented by Bachschmid et al. [19]. They have reported a least squares identification technique in frequency domain for crack diagnosis.

Many vibration based fault diagnosis tools such as full Fourier transform [3], Wavelet transform [20], empirical mode decomposition (EMD) [21], Hilbert Huang Transform (HHT) [1] and algorithms based on support vector machines (SVM) or Classifiers [22] are available. It is necessary to understand every tool, to choose an appropriate diagnosis method for the fault detection.

In rotating machinery fatigue cracks can develop due to varying loads and continuous operation. In order to develop techniques to detect existing cracks in rotor-bearing systems based on the vibration response of machinery, crack shafts have to be modeled accurately and its response needs to be studied thoroughly. Cracks in structures such as beams or shafts are modeled in many ways. The presence of crack causes local flexibility i.e., decreases its stiffness, reduces its natural frequency and also affects its vibration behavior. The added flexibility due to the presence crack can be expressed in the form of a matrix which is very suitable for FEM modeling of cracked rotors. This matrix was developed by Papadopoulos and Dimarogonas [23]. The stiffness of the cracked element varies with respect to the shaft rotation continuously, due to breathing behavior of the crack. This behavior is modeled by expressing stiffness variation by a truncated cosine series, which results in higher harmonics of running frequency in the FFT of vibration response.

The probability of rotor–stator rubbing is also high due to the presence of small clearances. Beatty [24] reported that to evaluate a rotor to stator rub contact phenomenon, monitoring steady state vibration response is not sufficient. Since, a transient signal like start-up response covers possible range of amplitudes it contains more information when compared to steady state vibration data. Also, monitoring through run-up vibration data consumed less time and facilitates early detection of the rub fault. Torkhani et al. [25] presented an experimental investigation to detect light, medium and heavy partial rub impacts using transient excitation. Muszynska [26] reported a detailed literature review on rotor to stator contact problems. Recently, Patel and Darpe [2] solved the rub initiation diagnosis problem using Hilbert–Huang Transform and compared the results with wavelet transforms.

The objective of this study is to detect multiple faults existing in a rotor system, using run-up vibrations. In this study both simulations and experimental investigations of misalignment, shaft crack and rotor–stator rub fault detection are considered. Use of HHT algorithm is highlighted along with a comparative study using the STFT and CWT approaches. The effect of signal to noise ratio for detecting faults using the three time frequency techniques is investigated.

The fault parameters considered for simulation study and experimental study are different. The objective of the simulation study is to identify least possible fault diagnosis features. For example for the simulation study, 0.075 mm rub clearance is considered as the heavy rub case, on the other hand for experiments 0.1 mm rub clearance case is considered as heavy rub. The reason being that for experiments, for rub clearance below 0.1 mm, the response obtained was very unstable and the rotor could not reach or cross the critical speed. In case of experiments, the vibration data corresponding to the least measurable fault parameter is considered for study. The vibration data recorded is considered for testing only if repeatability of harmonic signature is observed. In Section 2, the finite element model of the rotor bearing system is presented, which includes the theoretical modeling of faults. A brief overview of the time frequency techniques adopted in this study is

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