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Experimental study on the intrawave frequency modulation characteristic of rotor rub and crack fault

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ABSTRACT

Rub and crack are two important rotor faults. In this paper, the rub, crack and rub-crack coupled fault experiments are performed on a rotor test rig and the instantaneous frequency signatures of the faults are analyzed using Hilbert–Huang transform. The intrawave frequency modulation property of the rub and crack rotor is revealed through the response of Jeffcott rotor model and experiments. It is demonstrated that the intrawave frequency modulation produces extra harmonic components in FFT spectrum. The relationship between the FFT spectrum and the modulation frequency is supplied. The simulated and experimental analysis results show that the different composition of the modulation frequency can be the feature to detect the local rub, crack and crack-rub coupled rotor fault.

1. Introduction

The modern rotating machinery is more flexible and operates under tight clearances. It is an important task for rotor dynamic personnel to monitor and detect faults in rotating machinery. Rub and crack are two important faults in rotor system, which may cause the rotor to fail or even cause serious accidents. The rubbing fault is more likely to occur once the crack is developed in a rotor due to the increasing amplitude of the vibration. The vibration response of rub or crack rotor exhibits nonlinearities [1]. When these two faults happen at the same time, richer and more complex behavior of the rotor system will emerge. Thus, it is essential to understand its unique vibration signature in crack and rub fault detection.

Many researchers have presented model based dynamics analysis and signal processing methods in rotor rub or crack fault detection. Considering cross-coupling between the different direction stiffnesses, Varney [2] analyzed the nonlinear response of the two DOF rotor–stator contact model with asymmetric support stiffness. Chávez [3] presented a Jeffcott rotor within a snubber ring mathematical model under anisotropic support. A finite beam elements model and experimental results are supplied by Pennacchi [4] for real rotating machinery in rub conditions, the short arc rubs are particularly considered. Behzad [5] developed a finite element (FE)-based algorithm for partial rubbing vibration analysis. The synchronous and subsynchronous responses with different rotational speeds are reported. The Jeffcott rotor model with slant crack is presented by Lin [6] and Darpe [7] using open crack model and nonlinear breathing crack model respectively. Lin [8] analyzed the flexural vibrations of a rotor system with transverse or slant crack under torsional excitation by numerical simulation and experiment. Differences of the rotating speed and the torsional excitation frequency combination in a transverse or slant crack rotor are presented. Traditional signal process methods, rotor orbit, spectrum and cascade spectrum, for instance, are used in the dynamic response analysis in these works. However, the nonlinear characteristics of the rub or crack rotor system

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are proved at the same time. Thus, non-stationary signal processing methods are widely adopted in such nonlinear system response analysis, such as wavelet transform (WT), Hilbert–Huang transform (HHT), etc.

The run-up dynamic response data, which is based FE crack rotor model, are analyzed in reference [9–11]. Babu [9] pointed out that Hilbert–Huang transform (HHT) appears to be a better tool compared to continuous wavelet transform (CWT) for crack detection. Chandra [10] compared some time-frequency analysis methods in misalignment, rub and crack rotor startup vibrations and demonstrated that for noisy data CWT is more preferred. By using of HHT, the analysis of run up response around the resonance and sub-harmonic resonance for different crack ratio is presented by Guo [11]. The results show that the 2X and 3X components, which are produced around half and one-third of the critical speed respectively, are not purely harmonic, but with frequency oscillating periodically around the 2X or 3X. Model of a rotor with a breathing crack is established by Guo [12], empirical mode decomposition (EMD) is employed to obtain the intrinsic mode functions (IMFs) of the response data. The averaged amplitudes of the IMFs in the neighborhood of 1/2 and 1/3 of the first critical rotational speed are provided as vibration signatures of the early breathing crack presence. The theoretical result is verified in his later experimental investigation [13]. These works provide theoretical base for the experiment or real rotating machine study. But the time-frequency characteristics or instantaneous frequency analysis are mainly focused on the rotor model based run up data process.

Several rub or crack experiments are carried out and the collected vibration data are analyzed with different signal processing methods. Peng [14] extracted rub features by means of wavelet. Different harmonic components are excited by slight or severe rub impact in the experiments. Yang [15] put forward ensemble local mean decomposition (ELMD) to decompose the local rub-impact fault signal into product functions (PFs), and then the spectrum of each PF is supplied. Wang [16] performs rub-impact experiment in a gas turbine test rig and the 1/3X, 1X and super harmonics are obtained by variational mode decomposition (VMD). Zeng [17] proposed the normalized complex teager energy operator (NCTEO) method. The instantaneous frequency of rub fault is extracted. The changes of the instantaneous amplitude and frequency of the 1X harmonic component are observed. Nembhard [18] showed the detail experimental observations in the shaft orbits of different rotor related faults (unbalance, bow, looseness, misalignment, rub, crack) in a single machine. From the literatures, the factors that influence rub-impact and crack in rotor system are complicated, and the dynamic behavior of such rotor system is often non-linear. The periodic, quasi-periodic and chaotic motion of the rotor system presents a rich diversity of rotor responses. As the fault aggravates, the integral and fractional harmonic components in spectrum of the vibration will become more complicated due to the nature of non-linear response. Therefore, the time-frequency-energy representation methods are potentially viable for the non-linear dynamic properties analysis of rotors.

Compare to the study of the single rub or crack rotor fault, only a few papers provided results for the rub and crack rotor. With full spectrum analysis, Patel [19] investigated the distinctive directional feature of the higher harmonics of the rub and crack rotor. The full spectrum characteristics of the two faults at 1/3 and 1/2 of the critical rotational speed are revealed. Hui [20] studied the crack coupled with rub-impact and oil-film instability coupled with bearing rub-impact, the changing of the system motion when the crack coupled with rub fault in both the run up and slowing down process is described through reassigned wavelet scalogram. Patel [1] investigated the rotor–stator interaction effects on the response of a transverse crack rotor using finite element model. The vibration response at one third of the first bending natural frequency is processed by HHT. Some unique features of these faults are unraveled with instantaneous frequency plot.

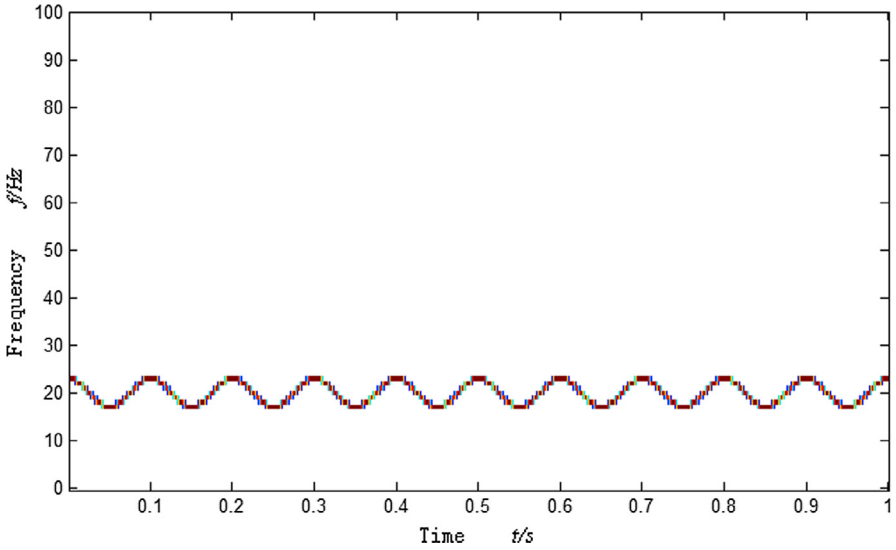

Fig. 1. Hilbert spectrum of the intrawave FM model.