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An adaptive and tacholess order analysis method based on enhanced empirical wavelet transform for fault detection of bearings with varying speeds

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ABSTRACT

The order tracking method based on time-frequency representation is regarded as an effective tool for fault detection of bearings with varying rotating speeds. In the traditional order tracking methods, a tachometer is required to obtain the instantaneous speed which is hardly satisfied in practice due to the technical and economical limitations. Some tacholess order tracking methods have been developed in recent years. In these methods, the instantaneous frequency ridge extraction is one of the most important parts. However, the current ridge extraction methods are sensitive to noise and may easily get trapped in a local optimum. Due to the presence of noise and other unrelated components of the signal, bearing fault features are difficult to be detected from the envelope spectrum or envelope order spectrum. To overcome the abovementioned drawbacks, an adaptive and tacholess order analysis method is proposed in this paper. In this method, a novel ridge extraction algorithm based on dynamic path optimization is adopted to estimate the instantaneous frequency. This algorithm can overcome the shortcomings of the current ridge extraction algorithms. Meanwhile, the enhanced empirical wavelet transform (EEWT) algorithm is applied to extract the bearing fault features. Both simulated and experimental results demonstrate that the proposed method is robust to noise and effective for bearing fault detection under variable speed conditions.

1. Introduction

The rolling bearing is one of the most vulnerable components in rotating machinery due to its harsh working environment, such as high rotating speed, heavy load and high temperature [1,2]. A simple defect, such as a crack on the inner race or the outer race of a bearing, would result in excessive vibration levels or even failures of the machine [3,4]. Therefore, it is crucial to monitor the bearing health status and detect bearing faults as early as possible.

The contact between the bearing defect and its mating surface generates a series of impulses [3]. If the rotating speed is constant, the impulses will occur periodically or quasi-periodically [5] with a repetition frequency of impulses called the fault characteristic frequency (FCF). Thus, the bearing fault detection can be conducted via directly identifying FCFs from the spectrum of the vibration signal [1]. Moreover, the time-domain methods [6,7], the frequency-domain methods [8,9],

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statistical methods [10,11], wavelet transform [12] and empirical mode decomposition [13] are usually applied for detecting bearing faults. The effectiveness of these methods have been verified when the shaft rotates at constant speeds.

In practical applications, bearings often operate at variable rotating speeds, such as wind turbines, mining equipment and other rotating machines during speed-up and speed-down processes. In these situations, impulses induced by the bearing defects do not occur at constant time intervals but at constant angle intervals [3]. Since the FCFs are proportional to the shaft rotating frequency, the fault features are no longer discrete frequency lines, but rather frequency bands related to the shaft rotating frequency. The speed variation would cause spectrum smearing. The abovementioned methods based on constant rotating speed would fail to detect faults of bearings with variable shaft rotating speeds.

A number of methods have been developed to diagnose the bearing faults at time-varying rotating speeds [1–3,14–26]. Among these methods, order tracking [14–17] is regarded as an effective tool. In the order tracking method, the original signal is resampled at constant angle intervals and, therefore, the fault-induced impulses are rearranged to be equal in angular domain [1]. The non-stationary signal in the time domain is transformed into a stationary one in the angular domain. The order tracking method can remove the effects of speed fluctuation and spectrum smearing. However, in the traditional order tracking method, a tachometer is required to obtain its instantaneous speeds for signal resampling. This requirement is hardly satisfied in many applications due to limited space and cost.

A rotating speed isolation method was introduced to extract the instantaneous rotating speed from the vibration signal in bearing diagnosis under speed variation conditions [19]. This method has an obvious limitation that the shaft speed component is required clear enough to be accurately extracted. The strong background noise may cover the shaft speed component, which leads to a mistaken instantaneous frequency (IF) ridge.

The instantaneous frequency ridge estimation is an indispensable part in the tacholess order tracking methods. In Ref. [17], the instantaneous frequency is estimated by searching the local maxima in the time-frequency representation (TFR). But this method is invalid in case of a low signal-to-noise ratio (SNR). A noise robust ridge detection algorithm based on the cost function is developed [27]. However, this algorithm may easily get trapped in a local optimum. A tacholess order tracking technique based on generalized demodulation is introduced for rolling bearing fault detection [20]. The starting point of the IF ridge is set as the local maximum at the beginning range on the time-frequency plane. This selection mainly depends on local information rather than the whole profile of the signal. Hence, an improper starting point would completely change the subsequent extracted ridge.

In vibration signal, the bearing fault features are usually masked by other components, such as rotor vibrations, shaft rotations, gear meshes and their corresponding harmonics [28,29]. Traditional envelope analysis fails to extract the bearing fault features [19]. It is necessary to develop effective and adaptive methods for the bearing fault diagnosis with variable rotor speeds.

In this study, an adaptive and tacholess order analysis method is proposed for detecting bearing faults under varying rotating speed conditions. A novel ridge extraction algorithm based on dynamic path optimization is applied to estimate the instantaneous rotating speed. This algorithm overcomes the shortcomings of the current ridge extraction algorithms, i.e. the noise interference and the local optima. The original signal is resampled based on the instantaneous phase information which is related to the instantaneous frequency extracted from the original signal. Since a correct diagnosis highly depends on a post-processing algorithm, the enhanced empirical wavelet transform (EEWT) is used to analyze the resampled signal. The core of EEWT is constructing an adaptive filter bank and decomposing the processed signal into a set of principal modes. The signatures of the bearing faults can be effectively separated from unrelated components via the EEWT method. Effectiveness of the proposed method on bearing fault detection under speed variation operations is verified by both simulated and experimental vibration signals.

The rest of this paper is organized as follows. Section 2 introduces the proposed method in detail, especially the instantaneous frequency estimation based on the dynamic path optimization and the enhanced empirical wavelet transform. Section 3 verifies the performance of the proposed method via a simulated signal. In Section 4, the proposed method is validated by two experiments. The first experiment is carried out on a SpectraQuest machinery fault simulator and the second one is performed on a complex civil aircraft engine. Finally, conclusions are drawn in Section 5.

2. The proposed method

To detect the bearing faults under variable rotating speed conditions, an adaptive and tacholess order analysis method is proposed in the present study. This method adopts a ridge extraction algorithm based on dynamic path optimization to estimate the IF and applies the EEWT approach to detect the fault characteristic order (FCO) and identify the fault type. The flowchart of the proposed method is shown in Fig. 1.

Procedure of this method is discussed as follows:

1) Calculate the time-frequency representation of the acquired signal.
   The time-frequency representation of the signal is calculated based on the windowed Fourier transform.
2) Estimate the shaft rotating speed based on dynamic path optimization.
   The accurate IF is required before resampling the signal. A new ridge extraction algorithm based on dynamic path optimization is adopted to estimate the IF. This algorithm is robust against noise and avoids the local optima.