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Time-varying demodulation analysis for rolling bearing fault diagnosis under variable speed conditions

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ABSTRACT

Rolling bearings often work under variable speed conditions, resulting in nonstationary vibrations. How to effectively extract the time-varying fault frequency from nonstationary vibration signals is a key issue in rolling bearing fault diagnosis. To address this issue, a quality time–frequency analysis of excellent time–frequency readability and robust to noise is necessary. To this end, the concentration of frequency and time (ConceFT) method is exploited. Based on this time–frequency analysis method, and considering the modulation feature of rolling bearing vibrations, we propose joint time-varying amplitude and frequency demodulated spectra to reveal the time-varying fault characteristic frequency. Firstly, the optimal frequency band sensitive to rolling bearing fault is selected by spectral kurtosis. Then, both the amplitude envelope and instantaneous frequency of the sensitive signal component within the selected optimal frequency band are calculated. Next, the ConceFT method is applied to the amplitude envelope and instantaneous frequency to generate the time-varying amplitude and frequency demodulated spectra. Finally, rolling bearing fault can be diagnosed by analysis of the time-varying frequency revealed by the time-varying demodulated spectra. This method is free from complex time-varying sidebands, and is robust to noise interference. It is illustrated by numerical simulated signal analysis, and is further validated via lab experimental rolling bearing vibration signal analyses. The localized defects on both inner and outer race are successfully diagnosed.

1. Introduction

Rolling bearings are widely used in many sorts of machinery, and they often work under variable speed conditions in practice. In such circumstances, their vibration signals will exhibit strong nonstationarity. Therefore, how to effectively extract fault features from nonstationary signals is an important topic for rolling bearing fault diagnosis [1–3].

This challenging topic has attracted researchers' attention. Most of their works exploit order tracking to remove the effect of speed time variation. To name a few for example, Borghesani et al. [4] designed a reversed sequence squared envelope spectrum and a reversed sequence envelope spectrogram based on computed order tracking and cepstrum pre-whitening, to remove transient condition effects for rolling bearing diagnostics under nonstationary conditions. Zhao et al. [5] devised an envelope order analysis method by exploiting the generalized demodulation and computed order tracking to detect

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rolling bearing fault under variable speeds. Wang et al. [6] presented a fault characteristic frequency order analysis to remove the smearing effect due to speed variation, and thereby extract rolling bearing fault features from nonstationary signals. Mishra et al. [7] denoised signals via wavelet transform and then used envelope order tracking to diagnose rolling bearing fault under variable speeds. Order tracking essentially relies on an equi-angular resampling, but the resampling suffers from interpolation error. More importantly, tachometers or encoders are necessary to provide a reference signal for resampling in angular domain, whereas they are not always available in real applications due to cost concerns and design reasons.

Time–frequency analysis can reveal the frequency components and their temporal evolution of nonstationary signals. Some researchers have also tried it to extract the time-varying fault features of rolling bearing vibrations. For example, Li et al. [8] used time–frequency ridges to further enhance the time–frequency analysis via generalized synchrosqueezing transform, and applied it to rolling bearing fault feature extraction in both lower and resonance frequency bands under variable speeds. Shi et al. [9] defined a generalized stepwise demodulation based on iterative generalized demodulation, and combined it with synchrosqueezing transform for time-varying fault feature extraction of rolling bearings under time-varying speed conditions. These publications have enriched the literature on and made contributions to rolling bearing fault diagnosis.

Rolling bearing fault signatures are usually contaminated or even overwhelmed by interfering noise. Moreover, under variable speeds, the fault features are often manifested by highly time-varying frequency components. In such circumstances, a higher quality time–frequency analysis method (better time–frequency resolution and readability, and robust to strong noise) is needed. However, reported studies in this direction have not been adequately explored, thus the topic under variable speeds still needs further in-depth investigation.

Usually, rolling bearing fault diagnosis relies on effective identification of the fault characteristic frequency from vibration signals. When a localized fault occurs to a rolling bearing, the defective point will strike the mating parts during running, resulting in impulses. Under constant speed, such impulses will be generated almost periodically. The repeating frequency of such periodical impulses links to the defective part of a rolling bearing, thus is called fault characteristic frequency. Given the rolling bearing geometry and running speed, the fault characteristic frequency can be calculated following explicit equations [10,11]. In practice, rolling bearing localized fault is usually detected and located by the presence of fault characteristic frequency in vibration signals.

Rolling bearing fault vibration signals have both amplitude modulation (AM) and frequency modulation (FM) features. The fault induced impulses excite the resonance of bearing assembly repetitively. In terms of amplitude, the resonance damps out rapidly before the next resonance arises, resulting in the AM feature. In terms of frequency, in one cycle, the resonance exists in the early portion of the cycle and the instantaneous frequency equals approximately the resonance frequency, while in the later portion, the resonance vanishes due to damping and the instantaneous frequency becomes 0 (as illustrated in Fig. 3(a2)). This means the instantaneous frequency changes repetitively, resulting in FM feature.

Because of the AM-FM nature of rolling bearing fault vibration signals, it is somewhat difficult to pinpoint the fault characteristic frequency from the Fourier spectrum of raw signals, even under constant speed conditions. In time domain, the relationship between the AM part and the resonance carrier signal is multiplicative. According to the convolution property of Fourier transform, this results in complex spectral characteristics, i.e. intricate sidebands around the resonance frequency. One has to figure out fault characteristic frequency according to the sideband spacing. This leads to difficulty in rolling bearing fault diagnosis via traditional Fourier spectrum analysis.

Amplitude demodulation is one of the most prevalent and effective methods for rolling bearing fault diagnosis [12], because it can avoid the complex sidebands around the resonance frequency and can extract the fault characteristic frequency directly. The amplitude modulating frequency of rolling bearing fault vibration signals links to the fault characteristic frequency. Hence, envelope spectrum is developed to pinpoint the modulating frequency and thereby the fault characteristic frequency. However, envelope spectrum still involves some sidebands around the fault characteristic frequency due to the additional AM effect caused by loading zone passing. The sideband spacing is irrelevant to the rolling bearing fault, such as the shaft rotating frequency in the inner race fault case, and the cage rotating frequency in the rolling element fault case. These irrelevant frequencies may mislead fault diagnosis.

Frequency demodulation can also reveal the fault characteristic frequency effectively. The instantaneous frequency of fault induced impulse series repeats a cycle every time when the defective point strikes the mating parts. More importantly, the frequency modulating frequency corresponds to the fault characteristic frequency only, independent of loading zone passing effect. Hence, frequency demodulation may reveal the fault characteristic frequency directly, free from irrelevant frequency interferences. Unfortunately, the FM information is usually discarded and has not been fully exploited.

Under variable speed conditions, the rolling bearing fault characteristic frequency is not constant, but time-varying, because it is proportional to the running speed and follows its time-varying profile. Therefore, the key to success in rolling bearing fault diagnosis under variable speed conditions lies in effective extraction of the time-varying fault characteristic frequency.

Meanwhile, both the amplitude envelope and the instantaneous frequency of rolling bearing fault vibration signals under variable speed conditions will exhibit time-varying features. To reveal the temporal evolution information of constituent components in nonstationary signals, one effective approach is time–frequency analysis. We can treat the amplitude envelope and the instantaneous frequency as signals and extend time–frequency analysis to them, thus resolving the time-varying modulating frequency and thereby identifying the fault characteristic frequency. This inspires the idea of