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Amplitude and frequency demodulation analysis for fault diagnosis of planet bearings

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ABSTRACT

The vibration signals of planet bearings feature more complex amplitude modulation and frequency modulation (AM-FM) than those of fixed-axis bearings, due to the effects of time-varying vibration transfer path, load zone passing and time-varying angles between gear pair mesh lines of action and impact force vector, in addition to that of bearing fault. Their Fourier spectra have a complex sideband structure, leading to difficulty in feature extraction and fault diagnosis. In order to address this issue, a joint amplitude and frequency demodulation analysis method is proposed to reveal the fault features, by considering the modulation characteristics. To thoroughly understand planet bearing vibration characteristics, the explicit equations for amplitude and frequency demodulated spectra of outer race, rolling element and inner race fault cases are derived, and the fault symptoms are summarized respectively. The signal is firstly decomposed into intrinsic mode functions (IMFs) by empirical mode decomposition (EMD), thus meeting the monocomponent requirement by instantaneous frequency calculation. Then a sensitive component with the instantaneous frequency fluctuating around the resonance frequency is chosen for further frequency demodulation analysis. Finally, planet bearing fault can be diagnosed by matching the peaks identified in amplitude and frequency demodulated spectra with the theoretical fault characteristic frequencies. The proposed method is validated with both numerical simulated and lab experimental signal analyses.

1. Introduction

Planetary gearboxes are widely used in many sorts of machinery, for their unique merits of large transmission ratio and high loading capacity in a compact structure. For such a key unit in a drive train, once fault occurs, it could lead to transmission deficiency, or even shut-down of the entire machinery. Therefore, planetary gearbox fault diagnosis is an important topic, and has attracted more and more researchers' attention [1–3]. Reported literature range from dynamics modeling, fault feature extraction, to fault pattern identification. These include the works described in [4–18], to name a few for example. In order to understand the fault vibration characteristics of planetary gearboxes, Chaari et al. [4,5], Mark [6,7], and Inalpolat and Kahraman [8,9] respectively investigated the effects of gear fault, external loading and manufacturing errors on the vibration responses through dynamics modeling and analysis. In order to extract fault vibration signatures,

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McFadden [10,11] studied the spectral characteristics of planetary gearbox vibrations, and generalized the time domain averaging method for planetary gearbox vibration signal analysis. Samuel and Pines [12,13] proposed a vibration separation method for planet and sun gears, and a constrained adaptive wavelet lifting method to analyze individual tooth mesh vibration waveform. Lei et al. [14] improved adaptive stochastic resonance method for planetary gearbox weak fault symptom extraction. Sun et al. [15] constructed customized multiwavelets based on the redundant symmetric lifting scheme, to detect damage-induced impulses for planetary gearbox fault diagnosis. In order to identify fault pattern automatically, Qu et al. [16] presented a feature selection method based on support vector machine, and applied it to damage degree classification of planet gears. To assess gear fault degree in a planetary gearbox, Zhao et al. [17] proposed to preserve the ordinal information by ordinal ranking, and improved the accuracy of ordinal ranking by a correlation coefficients based feature selection method. Lei et al. [18] adopted multiclass relevance vector machine as a classifier to identify planetary gearbox health condition. These researches have enriched the literature on planetary gearbox fault diagnosis.

While most of the above reported works focus on the sun, the planet and the ring (annular) gears, few literature concerns bearings in planetary gearboxes. Rolling element bearings play an important role in planetary gearboxes. They are used to support the sun gear shaft and the planet carrier shaft, in a fixed-axis way. In the meantime, they are also deployed to connect planet gears to the planet carrier, in a planetary manner. Among them, planet bearings are more prone to faults than fixed-axis bearings, because they have to bear an additional loading due to the torque transmitted by the planet carrier, in addition to the radial centrifugal force caused by the planet gear rotation. Once fault occurs to planet bearings, it will reduce transmission efficiency and even lead to breakdown of the planetary gearbox. Hence, planet bearing fault diagnosis is an important topic [1].

Recently, Jain and Hunt [19,20] developed a dynamics model for a planetary gearbox in a scenario of ring gear deformation and a planet bearing defect, and summarized the vibration spectral characteristics. Bonnardot et al. [21] designed a signal denoising method based on angle domain resampling for planet bearing fault detection. Fan and Li [22] proposed to mount a sensor on the planet carrier to eliminate modulation effects due to time-varying vibration transmission path, and presented a hybrid approach based on cepstrum whitening, minimum entropy deconvolution, spectral kurtosis and squared envelope analysis for planet bearing diagnostics. These works made important contributions to planet bearing fault diagnosis.

Although there are a large body of research publications on fixed-axis bearing fault diagnosis [23], reported literatures on the topic of planet bearing diagnostics have been very limited so far. This situation is mainly caused by the dynamics complexity of planet bearings. Planet bearings work in a special manner far different from that of fixed-axis bearings. They have unique kinematics involving both revolving around the sun gear and spinning around its own axis. Such a complex motion results in additional dynamic effects on the fault induced vibration, such as the time-varying vibration transfer path, loading zone passing and angle between bearing fault induced impact force vector and action line of gear pair mesh. These factors lead to high complexity of planet bearing vibration signals, result in intricate fault characteristics completely different from those of commonly used fixed-axis bearings [19–22]. This causes difficulty in planet bearing fault diagnosis. Therefore, well understanding the vibration characteristics of planet bearing fault and effectively extracting the planet bearing fault feature, still needs further investigation in in-depth.

In order to address this issue, we [24] have modeled planet bearing vibration signals as amplitude modulation and frequency modulation (AM-FM) processes, considered the modulation effects due to bearing fault, time-varying vibration transfer path, loading zone passing and angle between bearing fault induced impact force vector and action line of gear pair mesh, and further derived the explicit equations of vibration signal Fourier spectrum and summarized the spectral characteristics for each fault case, i.e. localized fault on the outer race, rolling element or inner race. These results are useful for us to understand the vibration characteristics of planet bearing vibrations and thereby are helpful for fault diagnosis.

For the planet bearing vibration signal as modeled in [24], because of the multiplication between the amplitude modulation (AM) part and the frequency modulation (FM) part in the time domain, their Fourier spectra amounts to convolution between the Fourier spectra of the AM part and the FM part in the frequency domain. This leads to a very intricate Fourier spectrum, featuring complex sideband clusters around the carrier frequency (resonance frequency) and even sidebands within a sideband cluster. One has to identify the sideband spacing first, and then conduct fault diagnosis by matching it with the bearing fault characteristic frequency. However, the multiple modulation sources (i.e. time-varying transfer path, load zone passing, time-varying angle, and fault induced modulation) may result in different sideband spacing values, thus confusing sideband identification and even hindering fault diagnosis.

Both the AM and FM parts contain the bearing fault information, because their modulating frequency is related to the bearing fault. Analysis of the AM and the FM parts separately in the frequency domain can reveal the modulating frequencies. More importantly, the Fourier spectrum of both AM and FM part alone is free from complex sidebands. Such a merit makes it easier to exhibit the bearing fault characteristic frequency, and thereby to reveal the planet bearing fault signature, than traditional Fourier spectrum. This inspires our idea of joint amplitude and frequency demodulation analysis for planet bearing fault diagnosis. In this paper, we aim to achieve two objectives and make two major corresponding contributions: (1) to reveal the characteristics of amplitude and frequency demodulated spectra, we will derive explicit equations of these spectra for the outer race fault, the inner race fault, and the rolling element fault of planet bearings. The characteristics of these spectra will be summarized as well. (2) utilizing the discovered characteristics, we will propose an amplitude and frequency demodulation analysis method for planet bearing fault feature extraction. In comparison with