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Time–frequency demodulation analysis based on iterative generalized demodulation for fault diagnosis of planetary gearbox under nonstationary conditions

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ABSTRACT

The vibration signal of planetary gearboxes exhibits the characteristics of both amplitude modulation (AM) and frequency modulation (FM), and thus has a complex sideband structure. Time-varying speed and/or load will result in time variant characteristic frequency components. Since the modulating frequency is related to the gear fault characteristic frequency, the AM and FM parts each alone contains the information of the gear fault. We propose a time–frequency amplitude and frequency demodulation analysis metbhod to avoid the complex time-variant sideband analysis, and thereby identify the time-variant gear fault characteristic frequency. We enhance the time–frequency analysis via iterative generalized demodulation (IGD). The time-varying amplitude and frequency demodulated spectra have fine time–frequency resolution and are free of cross term interferences. They do not involve complex time-variant sidebands, thus considerably facilitating fault diagnosis of planetary gearboxes under nonstationary conditions. The method is validated using both numerically simulated data and experimental signals.

1. Introduction

Planetary gearboxes are widely used in the drivetrain of many types of machinery such as helicopters, automobiles and wind turbines, because of its large transmission ratio in a compact structure. Once fault occurs to planetary gearboxes, it will ultimately lead to breakdown of the entire drivetrain and cause catastrophic loss. Therefore, planetary gearbox fault diagnosis is an important topic.

To date, researchers have made important contributions to planetary gearbox fault diagnosis in terms of gear fault induced vibration physics, statistical indices for condition monitoring, and various signal processing methods for fault feature extraction [1–15]. For example, Inalpolat and Kahraman [3,4] considered the configuration of planetary gearboxes (such as the number of planets, the planet position phasing and the number of gear teeth), and the amplitude modulation (AM) and frequency modulation (FM) effects due to gear manufacturing errors as well, to develop the dynamic model of planetary gearboxes. They also summarized the vibration sideband characteristics. Mark and Hines [5,6] studied the effects

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of non-uniform planet loading caused by gear imperfections on the sidebands of vibration response, and further the modulation effects of planet carrier torque. Chaari et al. [7,8] analyzed the effect of gear fault on the meshing stiffness, and modeled a planetary gearbox with sun tooth pitting and crack. They also analyzed the dynamic response of a healthy planetary gearbox in the presence of gear eccentricity and gear tooth profile error. Lei et al. [9] proposed two new indicators, i.e. root mean square of the filtered signal and normalized summation of the difference spectrum, for planetary gearbox fault detection. McFadden [10], McNames [11], and Mosher [12] investigated the spectral structure of planetary gearbox vibration signals, and found that the vibration signal spectrum is typically asymmetric. McFadden [13] further suggested vibration separation methods to discern the fault signatures from planet and sun gears by time domain averaging. Samuel and Pines [14] proposed a constrained adaptive lifting wavelet transform to analyze individual tooth mesh waveforms, thereby detecting the damage in helicopter planetary transmissions. More recently, Lei et al. [15] extracted the weak fault symptoms of a planetary gearbox using an improved adaptive stochastic resonance method. The above studies have contributed to fault diagnosis of planetary gearboxes. Nevertheless, they focus on the detection problems under constant running conditions, and most of them rely on the assumption of signal stationarity.

However, in engineering applications, planetary gearboxes often work under time-variant running conditions, thus resulting in nonstationary vibration signals. Therefore, how to effectively extract planetary gearbox fault features from nonstationary vibration signals is a key topic. Unfortunately, to the best of our knowledge, the reported research on this topic has been very limited in the literature. A few publications include the recent works by Bartelmus and Zimroz [16,17]. An indicator, which reflects the linear dependence between the meshing frequency amplitude and the operating condition, was presented for condition monitoring of planetary gearboxes under time-variant running conditions.

It should also be pointed out that machinery fault diagnosis not only includes condition monitoring, but also involves fault detection and localization. Therefore, fault diagnosis of planetary gearbox under nonstationary conditions requires further investigation. To this end, we have proposed to extract the time-variant fault characteristic frequencies via adaptive optimal kernel (AOK) time–frequency analysis [18] and iterative generalized synchrosqueezing transform (IGST) [19]. Although the AOK and IGST methods can effectively reveal the time–frequency structure of planetary gearbox vibration signals, they involve the complex time-variant sideband analysis. If the sideband analysis can be avoided, fault diagnosis of planetary gearboxes under nonstationary conditions will be much easier.

In our earlier works [20–23], we have explained that the complex sidebands of planetary gearbox vibration signals are resulted from the multiplicative relationship between the AM effects due to gear fault and time variant vibration transfer path and the FM effect induced by gear fault. Under nonstationary running conditions, the problem is further complicated by the time variation of frequency components. A closer examination of the AM–FM model of planetary gearbox vibration signals shows that both the AM and FM parts contain the gear fault characteristic frequency components. This has inspired us to propose a joint amplitude and frequency demodulation analysis method [22,23]. The derived amplitude and frequency demodulated spectra avoid the complex sidebands, and have a simpler spectral structure than the Fourier spectrum of original signal, thus yielding a more effective approach. However, our early proposed method is suitable for constant running conditions only, and it cannot track the time-variant fault characteristic frequencies of planetary gearboxes under nonstationary conditions.

Time–frequency analysis has been demonstrated to be effective for time-variant fault characteristic frequency extraction. As such, in this study we extend the application of the original amplitude and frequency demodulated spectra concept from frequency domain to joint time–frequency domain. This naturally results in the time-varying amplitude and frequency demodulated spectra which can be used to extract time variant fault characteristic frequency components from nonstationary signals. However, this involves some challenging issues such as mono-component decomposition for accurate estimation of amplitude envelope and instantaneous frequency, as well as constructing time–frequency representation that is of fine time–frequency resolution and free of cross term interferences.

So far, some multi-component AM–FM signal demodulation analysis methods have been proposed. For example, Feldman [24] presented Hilbert vibration decomposition to decompose a multi-component signal into a sum of mono-components with slow varying amplitude envelope and instantaneous frequency. It can estimate the instantaneous frequency and amplitude envelope via Hilbert transform and synchronous detection, and is suitable to analyze quasi and almost periodic oscillating-like signals. In order to analyze nonstationary AM–FM speech signals, Gianfelici et al. [25] proposed iterated Hilbert transform based on an asymptotically exact multi-component sinusoidal model, and developed an a posteriori adaptive segmentation algorithm to limit the phase estimation error in FM decomposition. Via this method, the amplitude envelope and instantaneous frequency can also be calculated. Motivated by the relationship between the total mechanical energy of a vibrator and its amplitude and frequency, Kaiser [26] defined energy operator as a nonlinear combination of the instantaneous signal values and its derivatives. Maragos et al. [27,28] further developed energy separation algorithm for AM–FM signal demodulation analysis. This algorithm is effective in estimating the instantaneous frequency and envelope amplitude of arbitrary time-varying modulated signals. It has attractive features such as high time–frequency resolution, adaptability to instantaneous feature, and low computational complexity. However, it requires that the signal to be analyzed is mono-component, but by itself, it cannot decompose a multi-component signal into mono-components. In fact, all the above methods rely on a proper filtering. In order to improve multi-component AM–FM signal demodulation analysis, considering the spectral characteristics of amplitude envelope and instantaneous frequency, Qin [29] proposed an adaptive filter design method to select the pass-band and stop-band corner frequencies. These researches made important contributions to demodulation analysis of multi-component modulated signals. However, under time-varying