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Time–frequency analysis based on Vold-Kalman filter and higher order energy separation for fault diagnosis of wind turbine planetary gearbox under nonstationary conditions

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ABSTRACT

Planetary gearbox fault diagnosis under nonstationary conditions is important for many engineering applications in general and for wind turbines in particular because of their time-varying operating conditions. This paper focuses on the identification of time-varying characteristic frequencies from complex nonstationary vibration signals for fault diagnosis of wind turbines under nonstationary conditions. We propose a time–frequency analysis method based on the Vold-Kalman filter and higher order energy separation (HOES) to extract fault symptoms. The Vold-Kalman filter is improved such that it is encoders/tachometers-free. It can decompose an arbitrarily complex signal into mono-components without resorting to speed inputs, thus satisfying the mono-component requirement by the HOES algorithm. The HOES is then used to accurately estimate the instantaneous frequency because of its high adaptability to local signal changes. The derived time–frequency distribution features fine resolution without cross-term interferences and thus facilitates extracting time-varying frequency components from highly complex and nonstationary signals. The method is illustrated and validated by analyzing simulated and experimental signals of a planetary gearbox in a wind turbine test rig under nonstationary running conditions. The results have shown that the method is effective in detecting both distributed (wear on every tooth) and localized (chipping on one tooth) gear faults.

1. Introduction

Planetary gearboxes are widely used in wind turbines and appear in helicopters and heavy trucks, for its large transmission capacity in a compact structure. In a wind farm, the planetary gearboxes are prone to fault because they usually work under heavy, time-varying loading conditions due to the wind speed variations. Once a fault occurs in a planetary gearbox, it will result in reduction of transmission efficiency and even breakdown of the entire drivetrain. Hence, planetary fault diagnosis is a very important topic in the field of machinery diagnostics.

To date, researchers have made important contributions to planetary gearbox fault diagnosis [1,2], including fault induced vibration physics [3–9], statistical indices for condition monitoring [10–12], and various signal processing methods for fault feature extraction [13–18]. Regarding the topic of wind turbine gearbox diagnostics, Odgaard et al. [19] presented a benchmark model for simulation of wind turbine fault detection and accommodation schemes, at a system level containing sensors, actuators and systems faults in the pitch system, drive train, generator and converter system. Considering the fact that fault results in changes in the resonance frequency of gearboxes, Odgaard and Stoustrup [20] proposed a filter based algorithm to detect changes in a resonance frequency of a system, and thereby diagnosed wind turbine gearbox fault using only the generator speed measurement available in wind turbine control systems. Odgaard and Stoustrup [21] further designed a Karhunen-Loeve basis approach to detect changes in frequency response for wind turbine gearbox fault diagnostics. In order to exploit the information available in a standard wind turbine control system, thus potentially reducing the cost of additional condition motoring system, Nejad and Odgaard and their collaborators [22,23] defined an angular velocity error function based on gearbox input and output shaft speed, and proposed to detect gearbox fault via spectral analysis of such error function.

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Most of these researches concentrate on fault detection under constant running conditions, and rely on the assumption of signal stationarity. Nevertheless, real world planetary gearboxes often work under time-varying conditions, and their vibration signals are highly nonstationary. To the best of our knowledge, the research on nonstationary condition topic has been very limited in the literature. A few publications include the recent works by Bartelmus and his colleagues [10,11]. They found that gear fault is susceptible to external load, proposed an indicator that reflects the linear dependence between the amplitude of meshing frequency and the operating condition, and presented a procedure for load-dependent feature processing, to monitor planetary gearboxes and other machinery under time-varying running conditions. These studies have enriched the literature on planetary gearbox condition monitoring.

Machinery fault diagnosis not only includes condition monitoring, but also involves fault localization. To this end, the key task of planetary gearbox fault diagnosis is to identify the gear characteristic frequencies from vibration signals and track their magnitude changes [24–28]. Under nonstationary working conditions, the time-varying speed and/or load will result in time-variant gear characteristic frequencies as well as time-varying vibration magnitudes, because they are dependent on the speed and load. Therefore, time-varying fault feature extraction from nonstationary signals is an important topic for planetary gearbox fault diagnosis under nonstationary conditions. Time–frequency analysis offers a good approach to analysis of such nonstationary signals. We have proposed to extract the time-variant fault characteristic frequencies via joint time–frequency analysis including adaptive optimal kernel (AOK) [27] and iterative generalized synchrosqueezing transform (IGST) [28]. These works have laid a foundation for further research on planetary gearbox fault diagnosis under nonstationary conditions.

Since planetary gearbox vibration signals are composed of very complex frequencies including meshing frequency, gear (sun, planet and ring) characteristic frequency, sun and/or planet carrier rotating frequency, their harmonics and even combinations. Under nonstationary conditions, especially time-varying speed conditions, such complex signals will present much more intricate structure, i.e. time-variant complex sidebands on the time–frequency plane. To pinpoint the time-varying gear characteristic frequencies from such complex nonstationary signals, an effective time–frequency analysis method that can provide fine time–frequency resolution and is free from cross term interferences is necessary.

To achieve fine time–frequency resolution and to be free from cross term interferences, it is necessary to accurately estimate instantaneous frequency and to separate complex signals into mono-components. The energy separation algorithm [29–32] has been demonstrated as an effective approach to estimation of instantaneous frequency. It does not need any basis functions, but uses nonlinear combination of the instantaneous signal values and its derivatives to estimate the instantaneous frequency of a signal. It is therefore completely data driven and highly adaptive to the signal local structure. Compared with the commonly used Hilbert transform method, it has attractive features such as higher time–frequency resolution and lower computational complexity. The recently proposed higher order energy operator and energy separation method inherits the advantages of energy separation algorithm, and also has unique merits such as higher precision in amplitude envelope and instantaneous frequency estimation and robustness to noise [33–35].

However, the energy separation algorithms including higher order ones are subject to the mono-component and narrow band requirements. It usually assumes that amplitude envelope and instantaneous frequency signals do not vary too fast or too widely compared to the signal carrier frequency [29–35]. For planetary gearbox vibration signals, these requirements are not directly satisfied, since they are usually composed of complex multi-components. To satisfy the requirement of the energy separation algorithm, it is crucial to decompose planetary gearbox vibration signals into mono-components. Although the widely known empirical mode decomposition (EMD) [36] and local mean decomposition (LMD) [37] methods as well as their derivatives offer an approach to mono-component decomposition, they are susceptible to singularities in signals and ineffective to decompose such highly complex signals (closely spaced sidebands varying in a wide frequency band) from planetary gearboxes into the true constituent mono-components.

Recently, Vold et al. [38,39] proposed the Vold-Kalman filter for extraction of time history of harmonics relative to one or more independently rotating mechanical components. Compared with conventional filters, Vold-Kalman filter extracts the signal components of interest in time domain directly, thus eliminating the phase distortions due to the transformation from time domain to frequency domain. In contrast to EMD or LMD method, it is more effective in separating signal components which are close to each other or even overlap on the time–frequency plane. In this sense, the Vold-Kalman filter has the potential to effectively decompose a complex multi-component signal into mono-components, thus satisfying the mono-component requirement of the energy separation algorithm. However, the original Vold-Kalman filter method assumes that the instantaneous rotating speed of the target is given, while this requirement is difficult to be met in planetary gearbox and other machinery fault diagnosis applications, because encoder or tachometer data is usually unavailable in practice.

This paper aims to address the issues with Vold-Kalman filter and energy separation algorithm sequentially, and exploit their combined advantages for the construction of a high quality time–frequency distribution for planetary gearbox fault diagnosis under nonstationary conditions. In order to address the speed-dependent issue with the Vold-Kalman filter, we propose to estimate the instantaneous speed by time–frequency analysis. Through such an improvement, the Vold-Kalman filter would become encoder/tachometer-free, and can separate any multi-component signal with curvilinear instantaneous frequency trajectories on the time–frequency plane into mono-components, thus meeting the mono-component requirement of a higher order energy separation algorithm. By exploiting the advantages of higher order energy separation such as high precision and robustness to noise, we could estimate the instantaneous frequency accurately. Given the instantaneous frequency and higher order energy at each instant, we could construct a time–frequency representation with high time–frequency resolution and without cross-term interferences. This would be helpful to clearly identify the time–frequency structure of complex nonstationary signals, thus providing an effective way to pinpoint the gear characteristic frequency from the time-varying complex sidebands of planetary gearbox vibration signals.

Fault diagnosis of wind turbine planetary gearbox under nonstationary conditions is an important yet very challenging topic, and but has not been adequately well investigated yet. In essence, it relies mainly on an effective identification of time-varying frequency components from complex nonstationary signals. To this end, we propose a new time–frequency analysis method based on Vold-Kalman filter and higher order energy separation algorithm, with which have unique advantages merits, such as fine time–frequency resolution and free from cross-term interferences. The proposed method, and is effective in revealing the time–frequency structure of complex signals, thus representing a novel providing an approach to reliable fault diagnosis of