Renewable Energy 66 (2014) 468–477

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Fault diagnosis of wind turbine planetary gearbox under nonstationary conditions via adaptive optimal kernel time–frequency analysis

Zhipeng Feng [a], Ming Liang [b,*]

[a] School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China
[b] Department of Mechanical Engineering, University of Ottawa, Ottawa ON K1N 6N5, Canada

ARTICLE INFO

Article history:
Received 11 July 2013
Accepted 31 December 2013
Available online 24 January 2014

Keywords:
Fault diagnosis
Planetary gearbox
Wind turbine
Nonstationary
Time–frequency analysis
Adaptive optimal kernel

ABSTRACT

Planetary gearboxes play an important role in wind turbine (WT) drivetrains. WTs usually work under time-varying running conditions due to the volatile wind conditions. The planetary gearbox vibration signals in such an environment are hence highly nonstationary. Conventional spectral analysis and demodulation analysis methods are unable to identify the characteristic frequency of gear fault from such nonstationary signals. As such, this paper presents a time–frequency analysis methods to reveal the constituent frequency components of nonstationary signals and their time-varying features for WT planetary gearbox monitoring. More specifically, we exploit the adaptive optimal kernel (AOK) method for this challenging application because of its fine time–frequency resolution and cross-term free nature, as demonstrated by our simulation analysis. In this study, the AOK method has been applied to identify the time-varying characteristic frequencies of gear fault or to extract different levels of impulses induced by gear faults from lab WT experimental signals and in-situ WT signals under time-varying running conditions. We have demonstrated that the AOK is effective diagnosis of: (a) both the local damage (a single chipped tooth) and distributed faults (wear of all teeth), (b) both sun gear and planet gear faults, and (c) faults with very weak signature (e.g., the sun gear fault at the low speed stage of a WT planetary gearbox).

1. Introduction

Planetary gearboxes are widely used in the drivetrains of wind turbines (WTs) for its large power transmission capacity in a compact structure. Due to the highly volatile rough working conditions in wind farms due to, e.g., wind gust, dust, corrosion and heavy yet unpredictable load, WT planetary gearboxes are particularly prone to damage. Such damage can lead to a catastrophic failure of the entire WT, and consequently heavy investment and productivity losses. Therefore, planetary gearbox fault diagnosis is an important topic for WTs.

Researchers have proposed various statistical indices to detect planetary gearbox fault [1]. Lei et al. [2] presented two new indicators, i.e. root mean square of the filtered signal and normalized summation of the difference spectrum. To diagnose faults via spectral analysis, it is important to have a thorough understanding of the vibration spectral properties of planetary gearboxes. For this purpose, McFadden [3], McNames [4], and Mosher [5] investigated the spectral characteristics of planetary gearbox vibration signals, and found that they are typically asymmetric due to the planet carrier rotation. Inalpolat and Kahraman [6, 7] studied the sidebands of planetary gearbox vibration signals, considering the modulation effects caused by planet carrier rotation and manufacturing errors of gears. Mark and Hines [8,9] investigated the sideband characteristics caused by non-uniform planet loading and planet carrier torque modulation. Patrick et al [10] studied the effect of unequal planet spacing on vibration signal spectra, for identifying the cracks of planet carrier plate. Researchers have also applied other methods to fault diagnosis of planetary gearbox. For example, McFadden [11,12], Samuel and Pines [13] suggested vibration separation methods to discern the fault signatures from planet and sun gears by time domain averaging. Samuel and Pines [14] further proposed a constrained adaptive lifting wavelet transform to analyze individual tooth mesh waveforms, thereby detecting the damage in helicopter planetary transmissions. Bartelmus and Zimroz [15] recently used the cyclostationary analysis method to study the modulation characteristics of planetary gearbox vibration signals for condition monitoring. Barszcz and

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* Corresponding author. Tel.: +1 613 562 5800x6269; fax: +1 613 562 5177.
E-mail address: liang@eng.uottawa.ca (M. Liang).

0960-1481/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2013.12.047

Randall [16] applied the spectral kurtosis method for the detection of tooth crack in the planetary gearbox of a wind turbine. Lei et al. [17] extracted the weak fault symptoms of a planetary gearbox using an improved adaptive stochastic resonance method. Sun et al. [18] proposed a method to construct customized multiwavelets based on the redundant symmetric lifting scheme, and applied it to detect damage-induced impulses for fault diagnosis of a planetary gearbox. Though the above studies have made important contributions to this field, they nevertheless focus on the detection problems under constant running conditions, and most of them rely on the assumption of signal stationarity.

As mentioned earlier, WTs often work under time-varying running conditions due to the variations in wind velocity and directions, thus resulting in nonstationary vibration signals. Extracting fault information of planetary gearbox from such nonstationary signals is the key to the success in WT monitoring. However, to our best knowledge, the research on this topic has been very limited in the literature. A few publications include the recent work by Bartelmus and Zimroz [19,20]. They presented an indicator for monitoring planetary gearboxes under time-varying running conditions. This indicator reflects the linear dependence between the meshing frequency amplitude and the operating condition. The proposed method is helpful to monitor the health status of planetary gearboxes, but the fault diagnosis issue under time-varying running conditions still needs further investigation.

Recently, we have conducted a series of studies on fault diagnosis of planetary gearboxes [21–23]. We considered both the amplitude modulation and frequency modulation effects of a gear fault, as well as the amplitude modulation effects caused by the time-varying vibration transfer path or planet passing, in modeling planetary gearbox vibration signals, and summarized the spectral symptoms of both local and distributed faults of sun, planet and ring gears. We also derived the explicit equations for calculating the characteristic frequency of all the three types of gears with either local or distributed fault [21]. To mitigate the complexity problem with the traditional spectral analysis caused by the complicated sideband structure, we proposed a joint amplitude and frequency demodulation analysis based on ensemble empirical mode decomposition and energy separation methods [22]. To further reduce the amplitude modulation effects due to time-varying vibration transfer path or planet passing, a planetary gearbox fault diagnosis method was also proposed via torsional vibration signal analysis [23]. These works have laid a foundation for further investigation of planetary gearbox fault diagnosis under nonstationary running conditions.

Planetary gearbox fault diagnosis essentially relies on detecting the presence of gear fault characteristic frequency, monitoring its magnitude change or, in other words, analyzing the periodicity of gear fault induced impulses. The gear fault characteristic frequency is dependent on the rotating speed of planetary gearbox. The time variations in speed and/or load will result in time-varying rotating frequency of planetary gearbox and thereby a time-varying gear fault characteristic frequency, i.e., an irregular impulse train. Therefore, the key issue in fault diagnosis of planetary gearbox under nonstationary running conditions is to identify the time-varying gear fault characteristic frequency, track its magnitude change, or extract the gear fault induced impulses.

Time–frequency analysis can effectively reveal the constituent frequency components of nonstationary signals and their time variation features, as well as transient events such as impulses. To date, various time–frequency analysis methods have been proposed [24]. However, the inherent drawbacks of these time–frequency analysis methods limit their effectiveness in analyzing planetary gearbox vibration signals. For instance, linear transforms such as the short time Fourier transform (STFT) and wavelet transform are subject to Heisenberg uncertainty principle, i.e. the best time localization and highest frequency resolution cannot be achieved simultaneously. One of them can only be enhanced at the expense of the other and hence the time–frequency resolutions of linear transforms are limited [25]. In addition, the basis in either the Fourier or wavelet transform is fixed. Therefore they lack adaptability in simultaneously matching the complicated components inherent in planetary gear vibration signals, such as the gear meshing frequency and their harmonics, gear fault induced impulses, and other transient vibration. The well-known Hilbert-Huang transform has fine time–frequency resolution and is free of cross-term interferences, but it essentially relies on the empirical mode decomposition (EMD) using spline interpolation. It is susceptible to singularities in signals, and may produce pseudo intrinsic mode functions (IMF), thus masking or interfering the time–frequency structure of true signal components [26]. The recently proposed local mean decomposition (LMD) has the same merits but also suffers from the same shortcomings as EMD [27]. As a typical representative of bilinear time–frequency representations, Wigner-Ville distribution has the best time–frequency resolution, but it has the inevitable cross-term interferences for multiple component signals. Such cross-term interferences complicate the interpretation of signal features in the time–frequency domain and make it unsuitable to analyzing the complex planetary gearbox vibration signals. Various modified bilinear time–frequency distributions including Cohen and affine class distributions may suppress the negative effect of cross-terms, but will compromise time–frequency resolution and auto-term integrity [28,29].

In comparison with the Cohen and affine class distributions of fixed kernel functions, the adaptive optimal kernel (AOK) method can suppress the cross-terms more effectively with better time–frequency resolution [30,31]. Sun et al. [32] applied the optimal Gaussian kernel method to identifying the flow pattern of gas–liquid fluids. Their research demonstrated that the optimal Gaussian kernel method had clearly extracted the characteristics for explaining the law of flow. Although this method provides new insights into the nature of nonstationary signals, it has not been widely used in signal analysis for machinery fault diagnosis. In this paper, we will adopt the AOK approach to revealing the complicated time–frequency features of planetary gearbox vibration signals under time-varying running conditions and thus diagnosing the gear fault.

Hereafter, the paper is organized as follows. Section 2 provides a brief overview on the principle of the AOK method. Section 3 illustrates the method by numerical simulated signal analysis. Sections 4 and 5 show that the AOK method can be successfully applied to diagnose planetary gearbox faults as demonstrated using both the lab experimental signals of a WT planetary gearbox test rig and the in-situ measured signals of a real-world WT respectively. Section 6 draws conclusions.

2. Adaptive optimal kernel method

The Cohen and affine class bilinear distributions are the commonly used time–frequency analysis methods. Each of these distributions has a certain kernel function. The kernel function is fixed and it determines the ability to suppress cross-terms. One kind of kernel function is only effective for limited classes of signals. The corresponding distribution exhibits either interference components, amplitude distortion, or resolution reduction. Thus both the Cohen and affine class distributions with a fixed kernel function lack adaptability to changes in signals.

In order to overcome the limitations of the Cohen and affine class distributions, Baraniuk and Jones [30] proposed a method to