Measurement 94 (2016) 630–644

Contents lists available at ScienceDirect

Measurement

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

A dual path optimization ridge estimation method for condition monitoring of planetary gearbox under varying-speed operation

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ARTICLE INFO

Article history:
Received 8 April 2016
Received in revised form 7 July 2016
Accepted 6 September 2016
Available online 7 September 2016

Keywords:
Condition monitoring
Ridge estimation
Planetary gearbox
Time-frequency representation
Planet bearing

ABSTRACT

Tacholess order tracking method is an effective tool for condition monitoring of planetary gearbox under varying-speed operation to reduce the measurement cost and avoid the inconvenience in the installation and adjustment. The robust ridge estimation is an indispensable procedure in the tacholess order tracking. However, conventional ridge estimation methods are difficult to extract the targeted ridge from the highly nonstationary signals. In this paper, we propose a novel method, termed dual path optimization ridge estimation (DPORE), which implants the idea of local integration to adapt with the intensively oscillated ridge. An in-situ vibration signal collected from a wind turbine planetary gearbox provided by the contest during the conference CMMNO December 2014 is employed to validate the proposed method. As a result, an important time-frequency ridge with weak energy and intricate shape is successfully extracted by the proposed method, while two popular ridge estimation methods cannot well track the complete time-frequency ridge. Moreover, the results obtained by the proposed method outperform those provided by the contestants in the conference contest. Finally, the accuracy of estimated ridge is further demonstrated by order analysis and one of the planet bearings in planetary gearbox with an inner race defect can be detected based on the order spectrum.

1. Introduction

Planetary gearboxes are applied in wide varieties of machines such as automobiles, wind turbines, mining machinery, and helicopters [1–5]. The structure and motion type of planetary gearboxes are more complex in comparison with a fixed-shaft one and planetary gearboxes often work under time-variant running condition, all of which make the condition monitoring and fault diagnosis of planetary gearbox being a challenge in the practical application. To date, the planetary gearbox condition monitoring is still an important research topic.

In most cases, the gear transmission systems are not accessible or difficult to inspect directly due to the restriction of disassembly, huge machine size or environmental limitation. Alternatively, vibration analysis is known as an effective and powerful tool for condition monitoring and fault diagnosis of rotary machinery [6–9]. However, the health condition monitoring of gearbox using vibration signals requires the knowledge of reference rotational speed, the number of stages as well as their arrangement and the number of gear teeth. The geometry parameter of gearbox is usually available to the vibration analysis by the manufacturer's details of gearbox [10]. Of course, a tachometer/encoder is installed at a reference shaft to enable the shaft speed estimation. However, the installation of speed sensor for each machine component is not always technically feasible due to the limited space and accessibility, and not always economically viable because of the costs incurred in investment, operation and maintenance of such sensors [11]. As a conclusion in [12], several tasks for monitoring the rotary machines under non-stationary operating condition are listed as: estimation of instantaneous angular speed (IAS); analysis of defect signature by order analysis; identification of rotary system parameters. It could be found that the IAS estimation is the first task and also a key procedure for health monitoring of gearboxes running on non-stationary operating condition. Currently, many constructive methods, such as wavelet ridge extraction method and its improved algorithm [13,14], multicomponent AM-FM demodulation method [15,16], the multiple stages order tracking scheme [17], the multi-order probabilistic approach [18], the coarse-fine instantaneous frequency estimation technique [19], and the ridge estimation method based on the cost function [20,21], have employed to calculate the instantaneous frequency and delivered the good performances for different mechanical signals. However, some of these methods leave something to be desired in processing the time-frequency ridge with weak energy and intricate shape. In this paper, we focus on the two-step method: (1) Map one dimension signal

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http://dx.doi.org/10.1016/j.measurement.2016.09.009
0263-2241/

into time-frequency plane by the time-frequency representation (TFR) method; (2) Track the targeted ridge curve in time-frequency plane through defining some criterions. If we can track correctly the time-frequency ridge, the IAS of the corresponding shaft could be calculated by dividing the number of gear teeth.

Many TFR methods which give insights into the complex structure of multi-component and time-variant frequency signals have been developed to deal with non-stationary signals, including short time Fourier transform (STFT) [22], Wigner-Ville distribution (WVD) [23] and wavelet transform (WT) [24], synchrosqueezing transform (SST) [22,25], parameterized time-frequency analysis method [26,27], etc. A larger number of researches have indicated that the TFR methods could be a perfect solution for processing non-stationary signals [28]. However, all TFR methods have their own merits and deficiencies. The individual TFR method may be suitable for analyzing a specific class of signals. For quadratic TFR, *e.g.* WVD, it is the Fourier transform of instantaneous autocorrelation function of a signal [23] and creates TFR with high time-frequency resolution for mono-component signal, but the cross-terms are introduced inevitably for analyzing multi-component signal. Abundance of wavelet functions, which can be used in WT for signal analysis, has been developed over the past decades. Since the choice of wavelet function in the first place may affect the result of WT at the end, such abundance raises a natural question as to how to choose a wavelet function that is best suited for analyzing a specific signal [24]. The SST technology is highly dependent on the original TFR [29]. The parameterized TFR methods [30–32] show a powerful ability to achieve the high time-frequency resolution when the analyzed signal shows the strongly non-linear instantaneous frequency. However, its several limitations should not be neglected, such as computational complexity and suitable matching mathematical models. Among them, the expensive computation is a crucial limitation for the use of parameterized TFR method in the industrial field. Considering that the analyzed vibration data are numerous and the complicated multi-components are buried in the signal, we utilize the simplest linear time-frequency transform, i.e., STFT as the TFR technique in this paper. Although the STFT which belongs to a linear TFR could not achieve an arbitrarily high time-frequency resolution at the same time, Refs. [20,33] indicate that the window width of STFT could be large enough to achieve a high frequency resolution on the TFR, which can distinguish the adjacent ridge curves from each other and is suitable for the time-frequency ridge estimation. Note that STFT may not be the best one but rational one in this paper.

The remainder of two-step method is to identify the targeted ridge curve from time-frequency plane. Generally speaking, if the TFR construction is well matched to the analyzed signal, then each latent component will appear as a unique peak sequence, named as "ridge". By searching the appropriate peak sequences, the time-varying characteristics (such as amplitude, phase and instantaneous frequency) of the corresponding components can be recovered. As a simplest technique, the direct ridge detection algorithm, also called as modulus maximum method [34,35] is usually used in ridge estimation and signal decomposition. The direct ridge detection algorithm, which is to detect the maximum magnitude point in the frequency direction for every time instant, only considers the magnitude of each point in time-frequency plane but ignores the smoothness of time frequency ridge. As many peaks exist in time-frequency plane at each time and their number also often varies in real cases, the location of maximum amplitude maybe not the actual ridge point. In this circumstances, it can be unclear which peak corresponds to which component, and which are just noise-induced artifacts, thus it is sensitive to noise and not suitable to estimate instantaneous frequency from TFR in real cases. Additionally, some popular ridge extraction methods based on simulated annealing [36], or crazy climber [37], etc. are presented for ridge estimation, signal decomposition and reconstruction in the early stage. However, these methods track the single or multi-ridges by searching the whole time-frequency plane, which brings about the expensive computation. Besides, the wavelet-based phase map and its derivative methods [38] are also employed into the ridge estimation and feature extraction. As introduced in above paragraph, the choice of wavelet function in the first place may affect the result of WT at the end. Therefore, the wavelet-based phase map could provide a failure result of the ridge curve for the unbefitting wavelet basis. Currently, the cost function method is regarded as a convenient, highly calculative efficient and relatively robust technique for the ridge estimation [21] and signal reconstruction [39]. Its main idea is that the constructed local cost function is dynamically minimized, where both the evident amplitude in local area and the continuity of ridge curve are considered to avoid the interference of local strong noise. As is well known, a ridge detection algorithm based on cost function was firstly proposed in [34] for extracting the phase information from moire interferograms by continuous wavelet transform (CWT). It utilizes the smoothness of instantaneous spatial fringe frequency to suppress the noise-induced strong magnitude and extract the ridge accurately in noisy interferograms, which is non-sensitive to noise compared with the direct maximum method. Then, a local cost function based on STFT was present to reduce the Doppler effect for wayside defective bearing detection [33], which further enhanced the computational cost by shrinking the search region. In follow-up work, an improved ridge detection algorithm [20,21] was presented to give an arbitrarily initial search point. However, these cost function methods called one-step method only utilize the information of one adjacently determined ridge point to define current ridge point. Hence, a remarkable point induced by strong noise could change the search result easily. In addition, the above cost function methods must give an initial search point which should be accurately localized in the position of actual ridge point, or else it could produce some deviations in the initial search region. For accurately extracting a vital ridge curve with some notable characteristics hidden in the analyzed signal, we will design a robust time-frequency ridge estimation method which is motivated by the cost function and takes over the advantage of cost function in following research.

The paper is organized as follows. A group of vibration data collected from a planetary gearbox operating in the industrial field is introduced in Section 2. In Section 3, we firstly describe the motivations for constructing a robust ridge curve estimation method, and then a novel dual path optimization ridge estimation method is proposed. In Section 4, the result of the ridge estimation is presented, and an accuracy of the estimated ridge curve is demonstrated by comparing with the two popular methods and the consequences of the contestants. The defective identification of planetary gearbox is performed based on the estimated rotational speed in Section 5. A discussion is given in Section 6. Finally, Section 7 draws a conclusion.

2. An in-situ planetary gearbox

A "challenge" about planetary gearbox condition monitoring is recently presented by the conference on condition monitoring of machinery in non-stationary operations (CMMNO) in December, 2014. Its aim is to make the most relevant diagnosis of a wind turbine planetary gearbox under non-stationary operating conditions in the industrial field. A schematic of the planetary gearbox is shown in Fig. 1, which is taken from an actual wind turbine. As described in Fig. 1, the red[1] shaft represents the input shaft. And

[1] For interpretation of color in Figs. 1 and 21, the reader is referred to the web version of this article.