Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A new rolling bearing fault diagnosis method based on GFT impulse component extraction

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ARTICLE INFO

Article history:
Received 12 October 2015
Received in revised form
11 March 2016
Accepted 18 March 2016

Keywords:
Fault diagnosis
Rolling bearing
Graph Fourier Transform
Impulse component
Component extraction

ABSTRACT

Periodic impulses are vital indicators of rolling bearing faults. The extraction of impulse components from rolling bearing vibration signals is of great importance for fault diagnosis. In this paper, vibration signals are taken as the path graph signals in a manifold perspective, and the Graph Fourier Transform (GFT) of vibration signals are investigated from the graph spectrum domain, which are both introduced into the vibration signal analysis. To extract the impulse components efficiently, a new adjacency weight matrix is defined, and then the GFT of the impulse component and harmonic component in the rolling bearing vibration signals are analyzed. Furthermore, as the GFT graph spectrum of the impulse component is mainly concentrated in the high-order region, a new rolling bearing fault diagnosis method based on GFT impulse component extraction is proposed. In the proposed method, the GFT of a vibration signal is firstly performed, and its graph spectrum coefficients in the high-order region are extracted to reconstruct different impulse components. Next, the Hilbert envelope spectra of these impulse components are calculated, and the envelope spectrum values at the fault characteristic frequency are arranged in order. Furthermore, the envelope spectrum with the maximum value at the fault characteristic frequency is selected as the final result, from which the rolling bearing fault can be diagnosed. Finally, an index KR, which is the product of the kurtosis and Hilbert envelope spectrum fault feature ratio of the extracted impulse component, is put forward to measure the performance of the proposed method. Simulations and experiments are utilized to demonstrate the feasibility and effectiveness of the proposed method.

1. Introduction

Rolling bearings are widely used in rotating machines and bearing failure is one of the most common causes of machine breakdown and accidents. As a result, the identification of bearing faults is of great significance in practice [1–3]. Vibration signal analysis is a preferred approach to diagnose a bearing's localized defects [4,5]. When a localized defect is induced on the bearing, periodic impulses will be generated due to the pass of rolling over the defect [6]. The impact between the rolling and raceway will excite the bearing natural frequency, and the fault characteristic frequency is modulated as a series of harmonics. However, this useful fault feature information is often immersed in heavy background noise. Hence, the key in rolling bearing fault diagnosis is to extract the fault characteristic frequency from the modulated vibration signals.

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http://dx.doi.org/10.1016/j.ymssp.2016.03.009
0888-3270/

Please cite this article as: L. Ou, et al., A new rolling bearing fault diagnosis method based on GFT impulse component extraction, Mech. Syst. Signal Process. (2016), http://dx.doi.org/10.1016/j.ymssp.2016.03.009

To accurately identify the fault characteristic frequency, the transient impulses related to the faults should be first extracted from the raw vibration signals.

There are three typical approaches to address this problem. One of them is from the frequency domain. Band-pass filtering is popularly combined with an enveloping technique to remove irrelevant components, and then the demodulating signal is extracted [7–10]. For example, spectral kurtosis (SK) [11–12] and kurtogram-based methods have proven to be powerful and practical to detect impulse components in a signal. The basic idea of the kurtogram-based methods is to use the kurtosis as a measure to discover the presence of impulse components and to indicate the frequency band where these occur. However, the kurtogram is based on short time Fourier transform (STFT) or FIR filters, which are sensitive to irrelevant sporadic impulsive vibration components. That may cause the incorrect selection of the optimal analyzing parameters and thereby restrict the performance improvement of the kurtogram in identifying machinery faults [13,14]. Another approach is from the time domain. Commonly, time-domain averaging has been presented to extract periodic components by suppressing the asynchronous components in several segments from a vibration signal [15,16]. The last approach is from the time–frequency domain. These processing approaches are mainly dedicated to highlighting the periodic impulses in a time–frequency representation using various techniques [17–21]. However, this paper focuses on an unconventional approach and intends to explore a new effective method for impulse component extraction from the graph spectrum domain.

In the last few years, techniques based on spectral graph theory [22,23] provide a “frequency” interpretation of graph data and have been proven to be quite popular in some application areas [24–26]. A growing amount of research works have been dedicated to extending and complementing the spectral graph techniques, leading to the emergence of the field of graph signal processing (GSP) [27]. The Graph Fourier Transform (GFT) [28] is the expansion of a graph signal function in terms of the eigenfunctions of the graph Laplacian matrix and is the foundation of GSP. The GFT is a data conversion method that is similar to the Fourier transform (FT). The GFT provides a “spectral analysis” perspective of GSP that focuses on the interplay between the graph structure (Laplacian matrix) and the characteristics of the corresponding graph signal. David I Shuman [27,28] outlined the main challenges of the field and discussed different ways to define the graph spectrum domain, which is the analog to the classical frequency domain, and highlighted the importance of incorporating the irregular structures of the graph data domain when processing the signals on a graph. Ameya Agaskar [29,30] justified the use of the graph Laplacian's eigenbasis as the surrogate of the Fourier basis for graphs, defined the notions of “spread” in the graph and spectral domains, and investigated the uncertainty principle and the localization of the graph signal in different domains. Xiaofan Zhu [31] provided a detailed theoretical analysis on why the graph Laplacian eigenbasis can be regarded as the Fourier transform of graphs and discussed whether the Laplacian eigenvectors are meaningful basis vectors for all graphs. Aliaksei Sandryhaila [32–34] extended the discrete signal processing (DSP) to “DSP on graphs” and combined it with the representation and processing of big data by the application of large-scale irregularly data compression.

The targets of these studies are generally all class graphs, but the detailed study of a particular class graph, namely, the path graph, is rare. Generally, the path graph is a sequence of vertices connected by edges in sequence, which is a special case of a bipartite graph [35]. The path graph is the graph with the simplest and most intuitive structure. Harmonic signals, mechanical vibration signals and ECG signals are some examples of time series signals with the structure of a path graph. In addition, periodic extensions of the time series signal would be analogous to a circle graph that is closely related to the path graph [36–37]. As the time series signal is one class of path graph signal, it is of important significance to introduce the path graph signal analysis into the time series analysis. In addition, there are structural relationships between the time series and the path graph, with the sequence structure of the time series signal corresponding to the structure of the path graph and the function value of the time series signal corresponding to the signal value of the path graph. The rolling bearing vibration signals are time series signals, and the signal processing in fault diagnosis is actually the signal processing in a time series [38]. Hence the GFT of a path graph can be used to analyze the rolling bearing vibration signals.

Because the GFT of a path graph, which is defined by the traditional adjacency matrix weight, cannot easily reflect the impulse fault characteristics of rolling bearing signals, in this paper, a new weighted matrix is defined by the Euclidean distance, and then the GFT is applied to analyze the impulse signal and harmonic signal. In fact, there is a large difference between the GFT graph spectra of the impulse signal and harmonic signal, namely, their distributions of spectrum lines. Therefore, according to the characteristic that the GFT graph spectra of the impulse signal are mainly concentrated in the high-order region, a new rolling bearing fault diagnosis method based on GFT impulse component extraction is proposed. There are four steps in the proposed method to extract the fault impulse components of the rolling bearing vibration signals. First, the GFT of a vibration signal is performed, and its graph spectrum coefficients are put in reverse order. Then, the graph spectrum coefficients in front are extracted to reconstruct a series of impulse components, where the coefficients for reconstruction are added one by one. Next, the envelope spectra of these impulse components are obtained by the Hilbert transform, and the envelope spectrum values at the fault characteristic frequency are arranged in order. Finally, the envelope spectrum with the maximum value at the fault characteristic frequency of the rolling bearing is selected as the final result, from which the faults in a rolling bearing can be diagnosed and the fault patterns can be identified. Simulated and actual rolling bearing vibration signals are analyzed by the proposed method. Further, an index KR, which is defined by the product of the kurtosis [39] and Hilbert envelope spectrum fault feature ratio [40], is applied to measure the performance of the proposed method. The results verify the effectiveness of the proposed method in extracting fault impulse characteristics and show that the proposed method is superior to some well-known impulse extraction methods.

This paper is organized as follows. In Section 2, the GFT is introduced. In Section 3, the GFT analysis of vibration signals is investigated. In Section 4, the rolling bearing fault diagnosis method based on GFT impulse component extraction