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Application of wavelet energy and Shannon entropy for feature extraction in gearbox fault detection under varying speed conditions

Hojat Heidari Bafroui, Abdolreza Ohadi *

Acoustics Research Lab., Mechanical Engineering Department, Amirkabir University of Technology (Tehran Polytechnic), Hafez Ave. 424, Tehran, Iran

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ABSTRACT

The fault detection and feature extraction of varying speed machinery with multi-component signals are full of difficulties caused by non-stationary machine dynamics and vibrations. In monitoring the vibrations of varying speed machinery, mainly formal signal processing methods based on digital sampling accomplished in equal time intervals become unsuitable. On the other hand, energy and Shannon entropy distribution of gear vibration signals measured in time–frequency plane would be different from the distribution under the normal state, when faults occur in the gear. Therefore, it is possible to detect a fault by comparing the energy and Shannon entropy distribution of gear vibration signals with and without fault conditions. In this paper, for fault diagnosis of gearbox in the run-up condition, primarily the obtained vibration signals from an acceleration sensor of automotive gearbox test setup are sampled at constant time increment by an acquisition card. To process the non-stationary vibration signals, the re-sampling technique at constant angle increment is combined with the continuous wavelet transform (CWT) and the wavelet coefficients of the signals are obtained. The Morlet wavelet is used; because impulses in many mechanical dynamic signals are always the indication of faults and the Morlet wavelet is exceedingly comparable to an impulse component. Then, statistical parameters of the wavelet coefficients are extracted that constitute the feature vectors. As a new method, the optimal range of wavelet scales is selected based on the maximum energy to Shannon entropy ratio criteria and consequently feature vectors are reduced. In addition, energy and Shannon entropy of the wavelet coefficients are used as two new features along other statistical parameters as input of the classifier. Finally, a feed-forward multilayer perceptron (MLP) neural network uses the extracted features for classification. The experimental results show that the presented method can diagnose the faults of the gear chip and wear efficiently.

1. Introduction

Gearbox has been remarkably operated in various industrial equipments and so is one of the core components in rotating machinery and research areas in the field of condition monitoring. Bearings and gears defects are common faults that occurring in gearbox and must be detected as early as possible to reduce maintenance costs, improve productivity, increase machine availability and prevent human casualties [1].

Numerous researches have been concentrated on the stationary process for the fault diagnosis of the rotating machinery at this time. Nonetheless, a small number of researches have been carried out for the run-up or run-down process. However, non-stationary vibration signals from varying speed machinery, especially during run-up or run-down process of gears drive, may have plenty of information about its condition. While in the transient region, all stimulation forces change both in amplitude and in frequency. Hence, some event and phenomena can become more obvious under varying speed conditions that are usually not evident at constant speed operation [2]. Some works have been concentrated on non-stationary signals and have used various methods to analyze them [3–5]. Li et al. [2] used angle domain average technique for fault diagnosis of gear crack faults during run-up of gear drives and converted non-stationary vibration signals in time domain into stationary signals in the angle domain. Meltzer and Ivanov [6,7] presented the time-frequency approach and the time-quefrency approach to recognition of faults in gear tooth of planetary gear drives during non-stationary start-up and run-down. Wu et al. [8] used adaptive Kalman filtering algorithm with a high-resolution order tracking to diagnose the fault in a gear set and damaged engine turbocharger wheel blades under various conditions. Computed order tracking, cepstrum analysis and radial basis function (RBF) artificial neural network (ANN) were combined

* Corresponding author. Tel.: +98 21 64543484; fax: +98 21 66419736.
E-mail addresses: hojat.heidari@gmail.com (H. Heidari Bafroui), a_r_ohadi@aut.ac.ir (A. Ohadi).

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for gear fault detection during the speed-up process and has been studied by Li et al. [9]. Referring to limit works in non-stationary signals, in this study, the re-sampling technique at constant angle increment is used to analyze the non-stationary signals that convert them into stationary ones.

Continuous wavelet transform (CWT), as a time–frequency representation of signal, provides an effective tool for vibration-based signal in fault detection. CWT provides a multi-resolution capability in analyzing the transitory features of non-stationary signals. Behind the advantages of CWT, there are some drawbacks; one of these is that CWT provides redundant data, so it makes feature extraction more complicated. Due to this data redundancy, data mining and feature reduction are extensively used [10]. Selection of wavelet bases is very important to indicate the maximal capability of features extraction for the desired faults. As an alternative, Tse et al. [11] for selection of the best wavelet family member and reduction of data redundancy presented the exact wavelet analysis. Zamanian and Ohadi [10] conducted a new method for feature extraction that is based on maximization of the local Gaussian correlation function of wavelet coefficients and signal. Rafiee et al. [12] selected four statistical features and studied 324 mother wavelets and then showed that the Daubechies 44 wavelet is the most effective for both faulty gears and faulty bearings. Kankar et al. [13] considered seven different base wavelets for fault detection in roller bearings and complex Morlet wavelet was selected based on the minimum Shannon entropy criterion. They also considered six different base wavelets in which three are from real values and the other three from complex values [14]. Out of these six wavelets, the base wavelet was selected based on two wavelet selection criteria: maximum energy to Shannon entropy ratio and maximum relative wavelet energy. Statistical features of base wavelet coefficients were extracted from raw vibration signals. All of these methods are efficient but they waste much time in fault detection. In this research, to improve the speed of fault diagnosis with high efficiency performance, the optimal range of wavelet scales is selected based on the maximum Energy to Shannon Entropy ratio criteria and consequently feature vectors are reduced.

Intelligent methods are used to classify healthy and faulty conditions such as artificial neural networks (ANN) that have potential applications in diagnosis of machine conditions and automated detection. Radial basis functions (RBFs) and multi-layer perceptions (MLPs) are the most prevalently used ANNs [7]. Rafiee et al. [15] developed a procedure which experimentally recognizes gears and bearings faults of a typical gearbox system using a multi-layer perceptron neural network. A comparative experimental study for the effectiveness of ANN and SVM in fault diagnosis of ball bearings has been presented by Kankar et al. [16]. Saravanan and Ramachandran [17] investigated the usage of discrete wavelets for feature extraction and application of artificial neural network for classification. In this study, a feed-forward multilayer perceptron (MLP) neural network is utilized for classification. Regarding the references that have shown that neural network can be effectively used in the diagnosis of various gear faults, in this study, a feed-forward multilayer perceptron (MLP) neural network is utilized for classification. In addition, two new neurons are considered as inputs of network to enhance the accuracy of ANN.

In this research, the re-sampled at constant angle increments technique and continuous wavelet transform (CWT) are introduced and applied specifically to gearbox fault diagnosis during the run-up condition. Morlet wavelet, as an effective wavelet, is selected to extract statistical features from wavelet coefficients of raw vibration signals. The statistical parameters of the wavelet coefficients are extracted and as a new method, to find very efficient features for classification, maximum energy to Shannon entropy is used to search optimal scales of CWT and consequently features are reduced. Finally, a feed-forward multilayer perceptron (MLP) neural network uses the extracted features for classification. To improve the accuracy of ANN performance, energy and Shannon entropy factors are used as two new features along with other statistical parameters. A flowchart is shown in Fig. 1 for summarizing the proposed fault diagnosis procedure that is used in this research. The next sections of this paper are devoted to the introduction of angle domain analysis, continuous wavelet transform, artificial neural network, experimental setup, experimental results and discussions, classification, and conclusions.

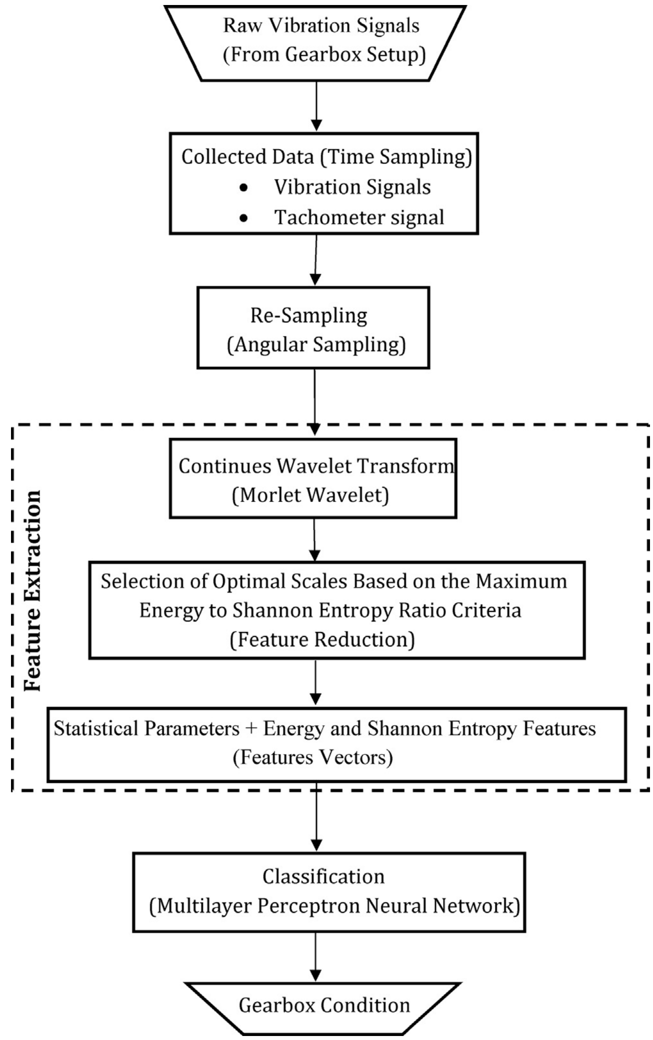

Fig. 1. Flowchart of fault diagnosis system.

2. Angle domain analysis

Data acquisition technique where digital sampling is done at equal angular displacements of the gearbox shaft is angular sampling [2]. Angle domain analysis can easily recognize vibration components from vibration signal that are proportional to multiples of the running speed concerning the vibration signal to the rotating speed of the shaft instead of an absolute frequency base [18].

Angular sampling technique prepares fixed order resolution, without spectral smearing and leakage. It makes practical and effective use of all the advantages of synchronous sampling. Angular sampling needs sampling of the vibration signal at constant angular increments from constant in time sampled signal and therefore it is related to the shaft speed [18]. This task could be solved by interpolation theory.