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Bearing fault diagnosis under variable rotational speed via the joint application of windowed fractal dimension transform and generalized demodulation: A method free from prefiltering and resampling

Juanjuan Shi *, Ming Liang, Yunpeng Guan

Department of Mechanical Engineering, University of Ottawa, Ottawa, Canada K1N 6N5

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ABSTRACT

The conventional way for bearing fault diagnosis under variable rotational speed generally includes prefiltering, resampling based on shaft rotating frequency and order spectrum analysis. However, its application is confined by three major obstacles: a) knowledge-demanding parameter determination required by prefiltering, b) unavailable shaft rotating frequency for resampling as it is coupled with instantaneous fault characteristic frequency (IFCF) by a fault characteristic coefficient (FCC) which cannot be decided without knowing what fault actually exists, and c) complicated and error-prone resampling process. As such, we propose a new method to address these problems. The proposed method free from prefiltering and resampling mainly contains the following steps: a) extracting envelope by windowed fractal dimension (FD) transform, requiring no prefiltering, b) with the envelope signal, performing short time Fourier transform (STFT) to get a clear time frequency representation (TFR), from which the IFCF and the basic demodulator for generalized demodulation (GD) can be obtained, c) applying the generalized demodulation to the envelope signal with the current demodulator, converting the trajectory of the current time-frequency component into a linear path parallel to the time axis, d) frequency analyzing the demodulated signal, followed by searching the amplitude of the constant frequency where the linear path is situated. Updating demodulator via multiplying the basic demodulator by different real numbers (i.e., coefficient λ) and repeating the steps (c)–(d), the resampling-free order spectrum is then obtained. Based on the resulting spectrum, the final diagnosis decision can be made. The proposed method for its implementation on the example of simulated data is presented. Finally, experimental data are employed to validate the effectiveness of the proposed technique.

1. Introduction

The development of fault detection and diagnosis in rotating machinery has long been investigated, for the goal of preventing severe equipment damage and unscheduled downtime. When a fault in one surface of a bearing interacts another surface, an impulse is generated which excites resonances in the system. These successive impulses are the main

* Corresponding author. Tel.: +1 613 562 5800x6293; fax: +1 613 562 5177.
E-mail address: jshi091@uOttawa.ca (J. Shi).

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Nomenclature

FCC	Fault characteristic coefficient
FD	Fractal dimension
FT	Fourier transform
GD	Generalized demodulation
GFT	Generalized Fourier transform
IF	Instantaneous frequency
IFCF	Instantaneous fault characteristic frequency
STFT	Short time Fourier transform
TFR	Time frequency representation

features to be detected. Once these impulses are extracted, the frequency of repetition of these impulses can be obtained by envelope demodulation and frequency analysis, which is related to the existence of faults as well as the type of faults [1,2]. However, this is the case for bearings of time-invariant rotational speed. In reality, bearings in wind turbine, mining equipment and ordinary machines during speed-up and ramp-down processes often run at a variable speed. When the rotational speed is variable, such speed fluctuation may cause "smearing" of the discrete frequencies in the frequency representation, indicating that these frequencies will no longer be observable and detected as discrete frequency lines [3]. As a result, signal process approaches that are developed for signal analysis at a constant speed in bearings would be ineffective.

Fault detection of bearing under time-varying rotational speed has therefore been a challenge and attracted considerable attention in recent decades [4–6]. Order analysis has proven effective in variable speed bearing fault detection as it can remove the effect of speed variations and convert the vibration signal into a stationary one in angular domain [7–9]. In this way, the traditional frequency analysis techniques, such as Fourier transform, become applicable. To obtain order spectrum, the vibration signal must be resampled at a rate proportional to the shaft rotational speed, which in turn means that the shaft rotational speed has to be known beforehand. The straightforward method of obtaining the shaft speed is to use tachometers, encoders etc. As reported in [10], with the aid of tachometers, the vibration signal is resampled and the effect of small speed variation is hence eliminated, making the squared envelope spectrum applicable. However, speed measuring devices are not always allowed to be installed in every case due to the design reason and cost concerns. Consequently, it is highly desirable to extract instantaneous rotational speed information from vibration signals. Combet and Zimroz are among the first who originally develop the method for this purpose [11]. Recently Urbanek et al. [4] advanced this idea by proposing a two-step procedure to predict instantaneous speed with large fluctuations based on phase demodulation and TFR. Along this line, order tracking without speed measuring devices has been extensively used for gear fault detection, as presented in [9,12], in which the rotational speed can be directly extracted based on TFR. However, there are two issues related to this kind of techniques, which are described as follows. First of all, the clear TFR is not always available. Usually, collected vibration signals are contaminated by strong background noise and cycle interferences which are called discrete frequency noise resulted by other electrical or/and mechanical components [13]; hence, the weak fault-induced impacts are submerged. To obtain a clear TFR, prefiltering is required to process raw vibration signals, which inevitably involves the time-consuming and knowledge-demanding filter parameter determination. Moreover, even if the filter is firstly designed properly, it may become ineffective in a rotational speed changing environment. Next, this kind of methods is more effective for gear fault detection under unstable speed because the relationship between TFR and instantaneous frequency (IF) of the shaft is explicit, as presented in [9,12]. However, in the bearing case, although the clear TFR is successfully acquired, such a method may become less effective. This is because, despite the IFCF being successfully obtained from the TFR, the IF of the shaft cannot be determined yet because the IF and IFCF are coupled by a fault characteristic coefficient which is still unknown without knowing the type of fault. To address this problem, Wang et al. [14] propose a new method which utilizes the fault characteristic order to detect fault of bearings. Specifically, they re-sample the raw signal at a rate proportional to the IFCF, instead of IF which is not easy to know beforehand. It is reported that this method performs well in variable speed bearing fault detection.

However, it is worth mentioning that all the methods mentioned above rely upon resampling technique. For bearing case, the design of a new resampling algorithm based on IFCF is required, which complicates the detection method. An approach that directly extracts fault features from the non-stationary signal without resampling will be better suited to real applications due to the simplified process, and computational efficiency is accordingly improved. Furthermore, the accuracy of the resampling algorithm is affected by several factors. As stated in [15], order tracking inevitably propagates error to the result as the resampling is achieved via polynomial interpolations, while vibration signals are generated by cyclic phenomena and thus sinusoidal not polynomial in nature. Besides, filtering, rotational speed, interpolation method, noise and block size also have effects on the accuracy of resampling. Therefore, a technique without resampling process is preferred. However, such an approach has not yet been reported in the accessible literature.

In view of the above, a novel method is proposed in this paper. To begin with, a windowed FD transform which is effective in interference and noise suppression is applied to extract the envelope of the signal. With the aid of windowed FD transform, the design of band-pass filter is avoided, easing the difficulty of parameter selection. With the extracted envelope, a clearer TFR can be obtained, from which the IFCF can then be accurately estimated. Next, the resampling-free detection strategy is proposed relying on the joint application of STFT and GD. An important step of GD is to approximate the demodulator, which can be done by STFT based on the extracted envelope. Signals can then be generalized demodulated,