Mechanical Systems and Signal Processing 70-71 (2016) 176–200

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Multi-bearing defect detection with trackside acoustic signal based on a pseudo time–frequency analysis and Dopplerlet filter

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A R T I C L E I N F O

Article history:
Received 8 July 2014
Received in revised form
11 August 2015
Accepted 27 September 2015
Available online 23 October 2015

Keywords:
Pseudo time–frequency analysis
Dopplerlet filter
Doppler distortion removal
Multi-bearing defect detection
Wayside acoustic diagnosis

A B S T R A C T

The diagnosis of train bearing defects based on the acoustic signal acquired by a trackside microphone plays a significant role in the transport system. However, the wayside acoustic signal suffers from the Doppler distortion due to the high moving speed and also contains the multi-source signals from different train bearings. This paper proposes a novel solution to overcome the two difficulties in trackside acoustic diagnosis. In the method a pseudo time–frequency analysis (PTFA) based on an improved Dopplerlet transform (IDT) is presented to acquire the time centers for different bearings. With the time centers, we design a series of Dopplerlet filters (DF) in time–frequency domain to work on the signal's time–frequency distribution (TFD) gained by the short time Fourier transform (STFT). Then an inverse STFT (ISTFT) is utilized to get the separated signals for each sound source which means bearing here. Later the resampling method based on certain motion parameters eliminates the Doppler Effect and finally the diagnosis can be made effectively according to the envelope spectrum of each separated signal. With the effectiveness of the technique validated by both simulated and experimental cases, the proposed wayside acoustic diagnostic scheme is expected to be available in wayside defective bearing detection.

1. Introduction

Condition monitoring and fault diagnosis of bearings is indispensable as the defect of the bearing is the dominant type of fault for mechanical equipment with rotary construction [1] especially for the railway transport industry. Currently, train speed increase is one of the main trends of railway development all over the world. So as the speed increases, it is a challenging mission to guarantee the safety, the stability and uninterrupted operation of train's transportation. With hundreds of rolling bearings in a train playing significant roles in the train safety condition, the defect of the roller bearing acts as a frequent type of fault, which may lead to serious accidents and great costs for the rail transport industry [2–4]. As reported by the department of the railway in the United State, approximately 50 bearing related derailments occur each year. And this rate has remained nearly constant for the last 10 years [3]. Consequently, it is of great importance and

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http://dx.doi.org/10.1016/j.ymssp.2015.09.042
0888-3270/

significance to monitor the health conditions and detect the incipient defects of train bearings, in order to avoid costly train stoppages or even catastrophic derailments caused by bearing failure.

In bearing defect diagnosis, many diagnostic techniques were proposed without disassembling the train bearings, such as oil monitoring, vibration signal analysis, and acoustic signal analysis methods [5]. Wayside Acoustic Defective Bearing Detector (ADBD) system [6] was firstly developed in the 1980s to detect the bearing flaws and attracted more and more attention due to its non-contact measurement. Comparing with the On-Board Monitoring (OBM) system like employing the accelerometer [2,7], the ADBD system has lower cost and shows better versatility as it sets all the devices on the wayside and thus hundreds of bearings can be detected when the vehicles pass by the device [4]. It uses wayside rail-mounted monitoring microphones to collect the acoustic signal as the train passes by the detector. According to the analysis of the acoustic signal we acquire, the status of the bearings could be evaluated and monitored [3,4]. However, there are several key difficulties that need to be overcome and only with getting over these problems can we have a satisfiable and accurate diagnosis result.

For the acoustic signals acquired by the microphone settled wayside, they would be severely disturbed resulting from the heavy background noise and Doppler Effect caused by the vehicle's high speed. In the past decades, many researchers paid so much attention to the denoising technic for rotating machinery diagnosis. Methods such as empirical mode decomposition (EMD) and Hilbert–Huang transform (HHT) [8], energy kurtosis demodulation [9], stochastic resonance (SR) [5,10,11], etc. offer us many choices and effective ways to overcome the influence of noise. Besides, more and more works focus on the reduction of Doppler distortion especially in the wayside acoustic diagnosis for train bearings [5,12,13]. As a widely existing phenomenon in the signal from a moving acoustic source, Dybala and his co-workers firstly proposed a disturbance-oriented dynamic signal resampling method [14,15]. But in the method, moving parameters need to be foreknown, while in the practical applications the frequency alias is inevitable for the Doppler Effect and most of the parameters are unknown. Another serious drawback of the method is that the end effect of the Hilbert transform (HT) is a severe threat to the validity of the Doppler shift removal. He combined this method with SR which overcome the difficulties in the Doppler Effect and noise influence being involved in the wayside acoustic defective bearing diagnosis problem [5]. But the application of this method is limited for that the frequency-domain processing should just contain a single source signal. Zhang proposed a Doppler shift removal based on instantaneous frequency estimation [12] which estimates the moving parameters with TFD spectrogram and Liu solved the same problem by time-domain interpolation resampling based on kinematic model analysis [13]. The HT is effectively avoided in these methods. Nevertheless, the accuracy of the parameters estimation affects the results severely which will be restricted by the resolution of the STFT.

Note that all the methods mentioned above are in assumption that the characteristic signals are from one bearing source which means there will be only one time center. But in fact, the signals acquired by microphones contain the sound from different train bearings. If we process the signal with the parameters confirming to one of the sources, the frequency shift, frequency band expansion due to the Doppler Effect of other sources will not be eliminated and they will affect our diagnosis work badly. So we have to be faced with the challenge of multi-source separation to make an accurate diagnosis for different bearings as two or more of them might be in defect condition at the same time. This paper focuses on multi-bearing defect detection with trackside acoustic signal based on a pseudo time–frequency analysis (PTFA) and Dopplerlet filter (DF). The PTFA here is used to estimate the time centers of different sound sources so we can design the different filters. The technique is based on the Dopplerlet transform (DT) proposed by Zou et al. [16,17]. We optimized the model and proposed an improve DT (IDT) to calculate a pseudo time–frequency distribution (PTFD) for a Doppler signal with which we can confirm the different time centers of all sound sources. With these time centers, we can design the peculiar filters in time–frequency domain which we call DF to filter out all the other sources remaining the only one we want. The filters work on the signal's time–frequency distribution (TFD) gained by the short time Fourier transform (STFT) [18,19] which can be inversely transformed easily. Then we take the inverse STFT (ISTFT) to recover the separated time-domain signal with only one sound source. Lately, a dynamically resampling method [5,14] is utilized to eliminate the signal's Doppler distortion. Finally, we make a diagnosis with the resampled signals of different bearings or sound sources whose characteristic frequency is corrected and highlighted effectively.

The rest of the paper is arranged as follows. In Section 2, some background knowledge will be introduced such as the Doppler Effect and its relevant parameters, IDT and the dynamically resampling method. Afterwards, PTFA and DF based on IDT are described in detail in Section 3. Later Section 4 provides us the scheme of the proposed method and its application to simulated signal. The experimental results are presented in Section 5. All the results show that the proposed technique can overcome the difficulties in multi-bearing defect detection with trackside acoustic signal under Doppler distortion. Finally we draw some conclusions in Section 6.

2. Background knowledge

2.1. Wayside acoustic diagnosis model

The geometrical model of wayside acoustic testing can be illustrated as Fig. 1. There are two sound sources numbered 1 and 2 which stand for the different train bearings. The microphone is held in position by a bracket with some vertical distance to the path of vehicle. It is obvious that the signal acquired by the microphone will be disturbed by the Doppler