Measurement 50 (2014) 346–355

Contents lists available at ScienceDirect

Measurement

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

Doppler Effect removal based on instantaneous frequency estimation and time domain re-sampling for wayside acoustic defective bearing detector system

Chao Wang, Fanrang Kong, Qingbo He *, Fei Hu, Fang Liu

Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei, Anhui 230026, PR China

ARTICLE INFO

Article history:
Received 24 April 2013
Received in revised form 7 November 2013
Accepted 10 January 2014
Available online 18 January 2014

Keywords:
Acoustic signal
Doppler Effect
Instantaneous frequency estimation
Re-sampling
Fault diagnosis
Train bearing

ABSTRACT

The phenomenon of Doppler Effect in the acoustic signal recorded by the wayside acoustic defective bearing detector (ADBD) leads to the difficulty for fault diagnosis of train bearings with a high moving speed, which is a barrier that would badly reduce the effectiveness of online defect detection. In order to improve the performance of condition monitoring of the bearings on a passing train with microphones amounted besides the railway, the elimination of the Doppler Effect should be solved firstly. An effective method for removing the Doppler Effect embedded in the source signal is presented in this paper. The Short Time Fourier Transform-Viterbi Algorithm (STFT-VA) is applied to obtain instantaneous frequency estimation of the distorted signal. According to the acoustic theory of Morse, the non-linear data fitting is then carried out to get the fitting instantaneous frequencies. The necessary parameters for time domain interpolation re-sampling, which is totally based on the kinematic analysis, are acquired from the fitting curve and the re-sampling sequence could be established in the time domain. As a result of the preceding steps, the fault diagnosis for the train bearings could be implemented with the restored signal. The effectiveness of this proposed method is verified by means of a simulation with three adjacent frequencies and an experiment with practical acoustic signals of train bearings with a crack on the outer race and the inner race. The results of the simulation and the experiment indicate that the proposed method has an excellent performance in removing Doppler Effect, and could be well employed to the condition monitoring and fault diagnosis of train bearings with a high moving speed.

1. Introduction

With the rapid development and speed up of modern rail transports, the safety of the rail transports becomes more and more important. Since the defect of the bearing is the main reason for the failure of mechanical equipments with rotary constructions [1–4], it is essential to develop the techniques of condition monitoring and fault diagnosis of bearings to guarantee the safety and operation of the rail transports. The wayside acoustic defective bearing detector (ADBD) system [5] has performed well in detecting bearing flaws before overheated operation occurs or earlier in the failure process since its development in 1980s. It collects acoustic signal as the train passes by the monitoring microphone wayside rail-mounted. According to the analysis of the acquired signal, the status of the bearings could be evaluated. In comparison with the On-Board Monitoring (OBM) system [6] and the Hot Bearing Detector (HBD) system [7], the ADBD system costs lower and shows stronger versatility [4].

However, the ADBD still needs to be improved. The effectiveness of ADBD has decreased when vehicles pass

* Corresponding author. Address: Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, 96 Jinzhai Road, Hefei 230026, PR China. Tel.: +86 551 63607985.
E-mail address: qbhe@ustc.edu.cn (Q. He).

0263-2241/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.measurement.2014.01.004

with high speeds. One of the problems caused by the high relative move is the Doppler Effect, as it brings in high frequency shift, which badly reduces the effectiveness of diagnosis [8]. In order to increase the effectiveness of fault diagnosis and condition monitoring of a high speed moving train with microphones, the reduction and elimination of Doppler Effect is necessary.

There are some studies aiming at the Doppler Effect elimination. Yang and Wang [9] established the time–space relation between the measurement field, the radiating field and the acoustic holography field, and put forward a method of nonlinear time-mapping between the sound source and the measured signal, in which the Doppler Effect was eliminated. However, the method is based on the pre-measured parameters, such as the vertical distance between the sensors and the railway, the speed and the original position of the vehicle. Recently, Dybała et al. [8,10] proposed a disturbance-oriented dynamic signal re-sampling method based on Hilbert transform to remove the Doppler Effect for wayside monitoring system. While the application of this method is greatly limited for that the frequency domain processing could just contain a single frequency, which is contradictory to the practical application. What is more, the end effect of the Hilbert transform is also a severe threat to the validity of instantaneous frequency (IF) estimation (IFE).

In this paper, the Short Time Fourier Transform-Viterbi Algorithm (STFT-VA) based IFE is applied to obtain the fitting IFs, which are employed with the Morse theory to attain parameters necessary for re-sampling of the signal in the time domain. Consequently, the Doppler Effect could be eliminated based on the kinematic model analysis and the re-sampling in the time domain. The STFT-based IFE is widely employed because its advantages in linear time–frequency transform and no cross-term, which is particularly suitable for the diagnosis of ADBD system. What is more, the Viterbi algorithm for hidden state estimation has been adopted to diverse applications in various scientific fields and has shown excellent performance for high noise environment [11–13]. According to the adaptability and advantages of STFT-VA mentioned above, it is a suitable combined algorithm to deal with the Doppler Effect problem embedded in ADBD system.

The combination of superiorities in frequency and time domain is the highlight in this method, where the re-sampling of the signal in the time domain is based on the analysis of IFs in time–frequency domain. The time and frequency domain complement each other so that the effectiveness of this method is improved as compared with other methods [8–10]. The advantages of this method are obvious: The IFs could be extracted from the other adjacent components even if the signal is disturbed by the Doppler Effect so that the end effect resulted from the Hilbert transform is cleverly avoided. The parameters utilized in the method are totally based on the signal collected by the microphone, which means we do not need to do any pre-measurement so that this method is more efficient and economic for practical application.

The rest of this paper is outlined as follows. In Section 2, the acoustic kinematic model analysis and the time domain re-sampling method are presented. In Section 3, the proposed STFT-VA based IFE method is introduced. Section 4 shows the wayside bearing fault diagnosis scheme and the analysis results of a simulated signal. Section 5 presents experimental verification tests using defective train roller bearings with inner race and outer race faults. Finally, Section 6 draws concluding remarks.

2. Time domain re-sampling method

The most common method for eliminating the Doppler Effect is to resample the original signal at a different sample rate, in which the key technique is to establish a set of re-sampling sequences in time domain. Recently, Dybała and Radkowski [8] proposed a disturbance-oriented dynamic signal re-sampling method based on Hilbert transform to remove the Doppler Effect for wayside monitoring system. This method needs to know the characteristic frequency beforehand and its frequency domain processing just contains a single frequency. Different from the method in [8], the time domain re-sampling method is totally based on the acoustic kinematic model analysis, and it is more visual and easy to understand.

The schematic diagram of the train passing the microphone is illustrated in Fig. 1. We assume that the train moves with a constant speed along a straight rail, and one single moving acoustic source and one stationary microphone receiver is considered.

According to Fig. 1, it is obvious that there is a delay between the acoustic source and the microphone, and the delay will be shorter as the acoustic source and the microphone get closer, which means the signal is compressed in the time axis and vice versa. In order to restore the signal modulated by the Doppler Effect, we need to get a new time sequence and resample the signal. Point A represents the initial position where the time t is set to be zero. Assuming that the amplitude of the acoustic source is $x(t_s)$ at time t_s and it will arrive at the microphone at time t_r, which can be calculated through the below equation:

$$t_r = t_s + \Delta_t \tag{1}$$

where Δ_t denotes the sound propagation time in the air and it can be calculated as

$$\Delta_t = R/c = \sqrt{Y^2 + (S - vt)^2}/c \tag{2}$$

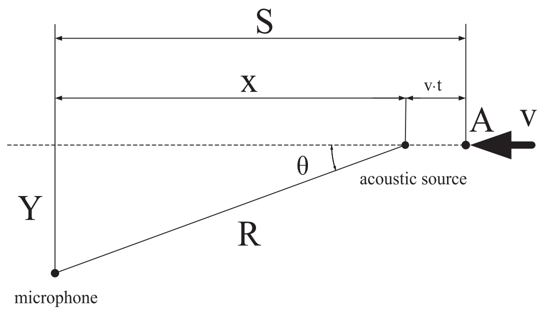

Fig. 1. Schematic diagram of the train passing the microphone.