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Wayside acoustic defective bearing detection based on improved Dopplerlet transform and Doppler transient matching

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ABSTRACT

The diagnosis of train bearing defects plays a significant role in maintaining the safety of railway transport. However, the phenomenon of Doppler Effect in the acoustic signal recorded by the wayside Acoustic Defective Bearing Detector (ADBD) system leads to the difficulty for fault diagnosis of train bearings with a high moving speed. This paper proposes a double-searching solution based on improved Dopplerlet transform and Doppler transient matching to overcome the difficulty in wayside acoustic bearing diagnosis. In the solution, the first searching procedure is to extract necessary parameters of Doppler Effect under the situation with very low signal-to-noise ratio (SNR) based on an improved Dopplerlet transform. Using the obtained parameters, the Doppler Effect can be embedded into the constructed periodic Laplace wavelet transient models. Subsequently, the second searching procedure is conducted to search fault impact period of the defective bearing through an operation, called Doppler transient matching, which is to calculate the correlation coefficient between the Doppler transient model and the filtered raw signal with the Doppler Effect. The proposed double-searching algorithm can adapt to the real Doppler Effect situation and extract the exact fault impact period from the Doppler distorted signal, and thus shows powerful capability to analyze wayside acoustic signals from train bearings. The proposed wayside acoustic diagnostic scheme is verified by means of a simulated Doppler distorted signal with a very low SNR (−20 dB) and the experiments conducted on train bearings. The results indicate that the proposed algorithm is effective and has obvious advantages for ADBD system.

1. Introduction

Railway transportation has played a significant role in the transport system because of its strong transporting capability and high speeds. With the rapid development and speed up of modern rail transports, both the economy and human safety become more and more important. Bearing defects are the dominant failure type of the mechanical equipments with rotary constructions [1–4], and it is especially apparent for the railway transport system. There are hundreds of bearings in a train with a significant relation for the train running, and the bearing failure is the most common type of train faults [5–8]. Therefore, it is an essential for developing the techniques of condition monitoring and fault diagnosis of bearings to guarantee the safety and continuous operation of the rail transports. The wayside Acoustic Defective Bearing Detector (ADBD) system [9] was developed in the 1980s to detect bearing flaws before overheated operation occurs or earlier in the failure process so that bearing maintenance can be performed on a scheduled basis. It collects acoustic signals as the train passes by the monitoring microphones that are wayside rail-mounted. According to the data processing and analysis of the signal acquired, the status of the bearings could be achieved and some derailment accidents could be avoided based on these results. In comparison with the On-Board Monitoring (OBM) system [1] and the Hot Bearing Detector (HBD) system [10], the ADBD system shows stronger versatility and economic benefits. What's more, being contrast to the vibration-based method, the acoustic signal analysis is economical and practicable in wayside real-time bearing defect detection because of its non-contact measurement [11,12]. However, there are some key techniques to be developed, one of which is the analysis of the acquired acoustic signal with strong Doppler Effect. Doppler Effect embedded in the acquired signal would cause high frequency shift, band expansion and amplitude modulation, which would badly reduce the effectiveness of diagnosis [13]. In order to improve the effectiveness of bearing condition monitoring and fault diagnosis of a high speed train, the ingenious and effective processing of the acquired acoustic signal with Doppler Effect is the crux.

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The most common method for overcoming the problem is to resample the received signal at a different sample rate so that the Doppler Effect embedded in the signal could be eliminated, and there are some studies committed to this field. Yang [14] 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, Dybala [13,15] proposed a disturbance-oriented dynamic signal re-sampling method based on Hilbert Transform to remove the Doppler Effect for wayside monitoring system. However, the application of this method is limited for that the frequency domain processing should just contain a single frequency, while in the practical situation the frequency alias is inevitable for the Doppler Effect. To solve the problems in [13,15], Zhang et al. [16] proposed a Doppler shift removal method based on Instantaneous Frequency Estimation (IFE) for wayside fault diagnosis of train bearings. Nevertheless, the noise immunity, which is a key factor to influence the accuracy of the IFE, still needs to be improved for this method. He et al. [17] explored a Doppler Effect removal method for ADBD system based on signal re-sampling and de-noising processing with stochastic resonance, and achieved good results. However, the de-noising processing in [17] is employed to enhance the SNR of the signal after rather than before the Doppler Effect is corrected. In practical situation the background noise coming from other coupled train components and measuring environment is so heavy that the weak defective information of the bearing is usually submerged and we cannot easily find the exact IF containing useful information for re-sampling.

In this paper, a double-searching algorithm is proposed based on the improved Dopplerlet transform and Doppler transient matching for wayside fault diagnosis of train bearings. This algorithm is totally based on the intrinsic transient characteristics of defective bearings [18,19]. The main idea of the proposed algorithm is to embed the Doppler Effect carried in the signal to be analyzed into the periodic Laplace wavelet transient models, which could well match the Doppler shifted fault bearing signal, rather than correcting the distorted signal directly so that we could achieve more information about the defective bearing to do further research on it, i.e. time domain signal based bearing performance degradation assessment [20]. A most recent study conducted in our group presents a Doppler transient model that embeds the Doppler Effect into the periodic Laplace wavelet transient models [21]. However, this model has a weakness that the pre-measured work should be required for Doppler parameters determination and the whole model is conducted based on the premise that all the necessary parameters are known in advance. It is the parameter pre-measurement work that limits the popularization of the model in [21], as the measurement of all these parameters in ADBD system is quite difficult and the accuracy of the measurement results, which have direct influence on the model's result [22], cannot be guaranteed. Moreover, the real measurement environment abounds with various noises disturbing the measure process. Thus, it is essential to develop a practical method to improve the model and algorithm in [21]. In this paper, the proposed double-searching algorithm could overcome this weakness so that it can be more practical for the ADBD system. To realize the idea, an improved Dopplerlet transform is first carried out, as the first searching procedure, to obtain necessary Doppler parameters for the subsequent processing. Then, a band-pass filter is constructed to enhance the SNR of the received Doppler distorted signal and then the Doppler Effect is embedded into the constructed Doppler transient models to match the fault impact period of filtered signal later. After that, correlation assessment between the constructed Doppler transient model and the filtered signal, as the second searching procedure called Doppler transient matching, is executed to find out the maximal correlation coefficient representing the fault period of the defective bearing. Furthermore, the matched period Laplace wavelet transient model is obtained to represent the original information of the defective bearing in time domain. In the proposed double-searching algorithm, the combination of improved Dopplerlet transform and Doppler transient matching is the highlight. The improved Dopplerlet transform has the merit of no pre-measured work needed in this method so that the practicality of this method can be guaranteed. The Doppler transient matching enables us to deal with the Doppler Effect problem in the ADBD system in an unusual way. The whole algorithm is hoped to perform satisfied diagnostic effect for ADBD system.

The rest of this paper is arranged as follows. Section 2 briefly describes the theoretical background which focuses on the Doppler Effect, the improved Dopplerlet transform, the Doppler distorted transient model based on Laplace wavelet and correlation analysis. In Section 3, the scheme and detailed procedures of the proposed double-searching algorithm for wayside train bearings acoustic signal analysis is presented. Section 4 shows the analysis result of a simulated Doppler Effect embedded signal with very low SNR (−20 dB). The experimental results provided in Section 5 show that the proposed combination algorithm achieves satisfied diagnostic results for the wayside ADBD system. Section 6 discusses and compares the proposed method with previous techniques for ADBD system. Finally, Section 7 draws concluding remarks.

2. Theoretical background

2.1. Doppler Effect

The Doppler Effect was first proposed in 1842 by Austrian physicist Christian Doppler. The schematic diagram of generating Doppler Effect is illustrated in Fig. 1, where the notations are explained as follows: R represents the distance between the sound source and the microphone; θ denotes the angle between the connection from source to microphone and the direction of movement; S represents the horizontal distance between the start point of the source and the microphone; r denotes vertical distance between the motion trail and the microphone; and v denotes the speed of the acoustic source.

According to the Morse acoustic theory [23], the sound intensity acquired by the microphone could be achieved under the assumption that the acoustic source of the train bearing with subsonic velocity is a monopole point source and the medium is the ideal fluid. Moreover, the portion of high order with little effect is ignored [24] and the sound source is given as harmonic with the

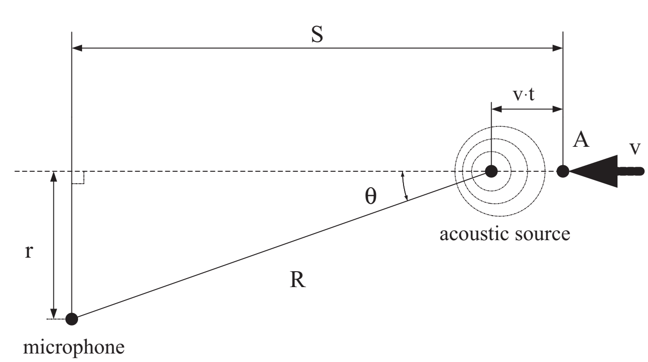

Fig. 1. Schematic diagram of the experiment scene.