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Wayside acoustic diagnosis of defective train bearings based on signal resampling and information enhancement

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ABSTRACT

The diagnosis of train bearing defects plays a significant role to maintain the safety of railway transport. Among various defect detection techniques, acoustic diagnosis is capable of detecting incipient defects of a train bearing as well as being suitable for wayside monitoring. However, the wayside acoustic signal will be corrupted by the Doppler effect and surrounding heavy noise. This paper proposes a solution to overcome these two difficulties in wayside acoustic diagnosis. In the solution, a dynamically resampling method is firstly presented to reduce the Doppler effect, and then an adaptive stochastic resonance (ASR) method is proposed to enhance the defective characteristic frequency automatically by the aid of noise. The resampling method is based on a frequency variation curve extracted from the time–frequency distribution (TFD) of an acoustic signal by dynamically minimizing the local cost functions. For the ASR method, the genetic algorithm is introduced to adaptively select the optimal parameter of the multiscale noise tuning (MST)-based stochastic resonance (SR) method. The proposed wayside acoustic diagnostic scheme combines signal resampling and information enhancement, and thus is expected to be effective in wayside defective bearing detection. The experimental study verifies the effectiveness of the proposed solution.

1. Introduction

Railway traffic plays a critically significant role in the transport system for rapid development of national economy. Currently, train speed increase is one of the main trends of railway development. For the speed increase, it is an important mission to guarantee the safety, the stability and uninterrupted operation of trains for passenger and freight transportation. There are hundreds of rolling bearings in a train with a significant relation for the train running. As reported, bearing failure is the most common type of train faults [1–4]. Hence it is of great importance to monitor the health conditions and detect the incipient defects of train bearings, to avoid costly train stoppages or even catastrophic derailments caused by bearing failure.

In bearing defect diagnosis, increasing attentions have been paid to diagnostic techniques without disassembling the train bearings, such as oil monitoring, hot-box detection, vibration signal analysis, acoustic emission (AE) and acoustic signal analysis methods. First, oil monitoring technique is to obtain the lubrication and wear conditions related to the defects through analyzing the oil sample of lubricant used in train bearings [5–7]. The technique is easy to be operated and effective to detect incipient fatigue damage of the bearing. However, it is only suitable for oil lubrication bearings, and not suitable for

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grease lubrication bearings. In addition, the rotating speed of the train bearing should also be slow [8,9]. Second, hot-box detection method is to judge the degree of bearing wear through detecting the temperature condition of bearing box. There are two kinds of hot-box detection systems: one is on-vehicle system with a temperature sensor being set on the bearing housing, the other is wayside infrared detection system. Only in severe faulty conditions will the temperature of the train bearing raise. Thus, the temperature monitoring method does not have the capability of early failure detection, which is dangerous for the high speed trains [1,10]. Third, vibration signal analysis is the most popular method for the diagnosis of rolling bearing defects [2,11]. There has been developing increasing diagnostic approaches based on vibration signals on account of its sensitivity to most of bearing defects [12–14]. However, the accelerometers should be attached on the bearing housing for vibration signal acquisition, which would make the measurement system enormous and expensive as for hundreds of bearings on a train. Fourth, AE technique is to measure the transient elastic waves generated by the interaction of bearing elements when a defect appears [11,15–18]. It has been proved that AE could offer an earlier and more reliable indication of bearing degradation than vibration signal and has the capability of detecting both surface and subsurface defects [11,16,17]. However, the AE measurement suffers from the drawback of signal attenuation and difficulty of signal processing, interpreting and classifying [15], as well as the difficulty of detecting inner race defects of a bearing [18]. The AE sensors also have to be placed as close as possible to the train bearings as the accelerometers do, which is also not convenient due to the complexity of the monitoring system. Finally, the train bearing acoustic signal with a frequency range from 3 Hz to 40 kHz can also be monitored by measuring sound pressure [19,20] or sound intensity [3,21] of the bearings. The sound amplitude is nearly proportional to vibration acceleration in the same direction [19] and is thus sensitive to incipient defects of the bearing, too. Due to non-contact measurement for acoustic signals [22,23], the acoustic signal analysis is economical and practicable in wayside real-time bearing defect detection. The acoustic detection systems could be placed at crucial locations on both sides of the railway track, and each system could monitor thousands of train bearings traveling through each day [4]. Therefore, this paper focuses on acoustic signal analysis for diagnosis of train bearing defects.

There are two main challenges in the wayside acoustic diagnosis of train bearing defects. The first one is the remedy for Doppler shift in the acquired acoustic signal. A dynamic resampling method based on Hilbert transform and analytical approach has been proposed to reduce the Doppler effect resulted from the relative motion [24]. However, for the Hilbert transform based resampling method, a band-pass filter should be first selected for the original signal, which may be unrealizable when confusion occurs between adjacent frequencies for the high-speed motion, or when the signal is buried in heavy noise for complex environment; while the analytical approach based resampling method strictly depends on the spatial and temporal parameters between the microphone and moving vehicle when measuring the acoustic signal. The second challenge is to enhance the weak defective information from heavy background noise coming from other coupled train components and measuring environment, especially in the low-frequency region [19], even when the Doppler effect has been removed, because the heavy noise would submerge some early signatures of bearing defects. In traditional de-noising solutions, an intuitive one is to remove unwanted noise [25], which, however, may also make the desired signal distorted simultaneously. Moreover, the blind source separation (BSS) technique has been employed to detect fault-related signal from corrupted machine sound by separating signal and noise [26,27]. In addition, the stochastic resonance (SR) is an opposite idea to make use of the noise to enhance the weak periodic signal and improve the signal-to-noise ratio (SNR) [28]. Because the defect-induced vibration response generally behaves as periodic transient impulses in a rotating machine, the SR theory has been developed by many researchers for periodic signature detection in the field of machine fault diagnosis [29–34] due to its special merit in noise utilization for signal processing. All of the developed SR methods including the SR with multiscale noise tuning (MST), proposed by our group [32–34], have been confirmed to be effective in vibration signal analysis. However, none of them has been applied to analysis of acoustic signals, such as the situation considered in the wayside acoustic diagnosis study.

This paper explores a wayside acoustic analysis solution for train bearing defect diagnosis. It is a combination of signal resampling and information enhancement. Specifically, the Doppler effect of acoustic signal is first reduced by a new resampling method according to a frequency variation curve extracted from the time–frequency domain. Then the weak defective information is enhanced by an adaptive SR (ASR) method. Considering that the noise in the resampled signal is no longer white noise, the SR with MST method is introduced because of its merit in utilizing colored noise [34]. Since the performance of SR with MST relies on the value of multiscale tuning parameter, this paper again proposes an intelligent optimization method based on genetic algorithm to adaptively deliver an optimal system output. The proposed solution takes advantages of signal resampling for Doppler effect reduction and information enhancement for noise treatment, and thus is expected to be effective in wayside defective bearing detection. In the following Section 2, a train bearing test rig is established and the wayside acoustic measurement experiments are carried out to formulate the problem to be studied. Then the proposed solution is presented in Sections 3 and 4 in detail. The experimental results as provided in Section 5 show that the proposed combination solution can well overcome the difficulties in Doppler effect and noise influence being involved in the wayside acoustic defective bearing diagnosis problem. Finally, Section 6 draws some concluding remarks.

2. Experimental setup and problem formulation

For the study of wayside acoustic diagnosis of train bearing defects, a train bearing test rig was first made by ourselves to acquire the static acoustic signals of train bearing with outer-race and inner-race defect, as shown in Fig. 1. The static