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De-noising of wayside acoustic signal from train bearings based on variable digital filtering

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ABSTRACT

In the wayside Acoustic Defective Bearing Detector (ADBD) system, the recorded signal usually includes both the sound from train bearings and the other disturbance sources. The fact of heavy noise corruption and the Doppler Effect of multi-source acoustic signals would badly reduce the effectiveness of online defect detection of the ADBD system. In order to extract useful information from the multi-source signal with Doppler Effect, this paper proposes an effective de-noising method based on the variable digital filter (VDF) for the ADBD system. Specifically, the ridge extraction based on Short-Time Fourier Transform (STFT) is applied to estimate the instantaneous frequencies (IFs), with which the fitting IF curves based on the Morse theory of theoretical acoustics could be achieved by using the nonlinear curve-fitting so that the parameters of the initial position of the acoustic sources could be calculated. By the aid of these parameters, the IFs according to the target train bearing could be then extracted. After that, the FIR variable digital filters could be designed with all the IFs which match the Morse theory with Doppler Shift so that the noise from the other parts could be effectively restrained after filtering the original signal. The effectiveness of this method is verified by means of a simulation with multi-frequency signals and applications to diagnosis of train roller bearing defects. Results indicate that the proposed method is effective.

1. Introduction

It is indispensable to develop the techniques of condition monitoring and fault diagnosis for the train bearings because the defect of roller bearing is the dominant type of faults for a train which would lead to serious accidents and significant costs for the rail transport industry [1–4].The wayside Acoustic Defective Bearing Detector (ADBD) system [5] was developed in the 1980's 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 uses wayside rail-mounted monitoring microphones to collect the acoustic signals as the train passes by the detector. According to the data processing and analysis of the signal acquired, the status of the bearings could be achieved and some derailment accidents are hoped to be avoided based on these results. The most significant advantage of this system is that thousands of bearings can be monitored with a single system everyday so that the costs are lower than the other systems and the early failure of the bearing can be detected [6–8]. What's more, in contrast with the vibration-based methods, the wayside acoustics-based techniques with the non-contact and non-disintegration advantages have extensively achieved attentions in recent years [9,10]. However, there are some key techniques that need to be developed, one of which is the de-noising processing. Audio signals are often contaminated by background environment noise [11], and the acoustic signal acquired by the microphone includes both the sound from the train bearings and the other disturbance sources, such as the rolling noise, the aerodynamic noise and the traction noise [12]. In addition, the facts of the huge magnitude of these noises (much larger than that of the signal from the train bearings) and the Doppler Shift of the acoustic signal (which is a pitch shift of a fasting moving sound [13]) make the condition monitoring and fault diagnosis for the bearings using the acoustic signal become a hard task with great difficulties.

There are some studies being committed to the problems mentioned above. Dybała [14,15] proposed a disturbance-oriented dynamic signal re-sampling method based on Hilbert Transform to remove the Doppler Effect for wayside monitoring system so that the Doppler Effect of the acoustic signal could be resolved to some extent. 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. He et al. [16] explored a Doppler Effect removal method for ADBD system based on signal re-sampling and

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de-noising processing with stochastic resonance, and achieved good results. The de-noising processing in [16] is employed to enhance the signal-to-noise ratio (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. Especially, multiple acoustic sources at different locations would cause different Doppler Effect in the wayside acquired acoustic signals. Removing the Doppler Effect of the measured signal directly in such a condition is usually difficult because we cannot easily find the exact IF containing useful information. In this condition, the reduction of the noise in the measuring environment should be intensively considered [17,18] and the de-noising processing can be seen as a good premise of the Doppler Effect removal. However, de-noising of such a noisy signal with Doppler Effect is also a huge challenge in the wayside acoustic diagnosis of train bearing defects [19].

Based on the present situation and difficulties of the de-noising problem for the wayside acoustic diagnosis of train bearing defects mentioned above, a novel and effective de-noising method based on the variable digital filter for ADBD system is proposed in this paper. The ridge extraction with the crazy climber detection algorithm (CCDA) based on Short-Time Fourier Transform (STFT) is applied to estimate the instantaneous frequencies (IFs) with relatively high values. Then the fitting IF curves based on the Morse theory of theoretical acoustics could be achieved by using the nonlinear curve-fitting with the result of the IF estimation. The parameters of the initial position of the acoustic sources are the key clues to determine whether the signal with a certain IF comes from the place near to the train bearings or not. After the loop calculation, all the IFs which match the Morse theory with Doppler Shift can be attained to design the FIR variable digital filters (VDFs). Due to the variable band-pass filtering, the noise from the other parts of the train could be effectively restrained. In the proposed method, the initial position of the bearing (useful acoustic source) is pre-measured to ensure that the exact IF containing useful information could be extracted, which means only the signals generated from around fault sources (bearings) could be taken into consideration. In this condition, the extracted signal certainly contains the fault information of the bearings and the SNR is much higher than that of the original signal. As a result, the weak defective information of the bearing could be effectively extracted even in a heavy noise background, which makes this method particularly suitable for the ADBD system.

2. Problem formulation and theoretical background

2.1. Experimental setup and problem formulation

In order to obtain the multi-source noise acoustic signal with Doppler Shift, four speakers are mounted at different locations in the car as shown in Fig. 1. Four speakers would play different acoustic signals while the car passes by the microphone, which is placed about 1.7 m away from the running track of the car, along a straight line with a constant speed. During the pass-by test, the microphone receives the multi-source acoustic signal with Doppler Shift and then recorded by data acquisition device.

The schematic diagram of the experiment is shown in Fig. 2, where the notations and parameters are explained as follows: S is the location of signal source (represents the train bearing); A, B and C represent locations of noise sources and the spacing between the signal source and each noise source is: $d_{sa} = 2.46$ m, $d_{sb} = 1.56$ m, $d_{sc} = 2.30$ m; the microphone and the photoelectric sensor are placed parallel with the vector of the car's velocity and the distance between them is $r_s = 1.7$ m; the height of the

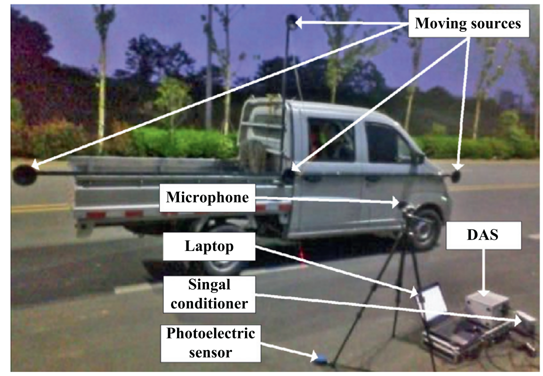

Fig. 1. Scene of experiment.

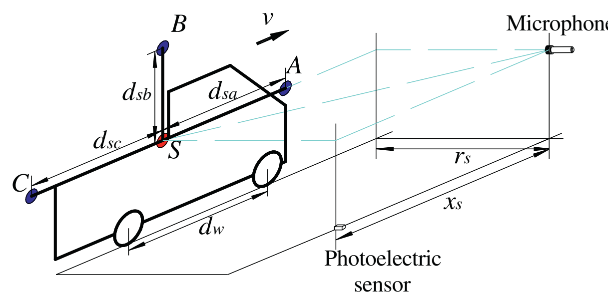

Fig. 2. Schematic diagram of the experiment.

microphone is equal to that of S; $x_s = 4$ m is the distance between the microphone and the photoelectric sensor; the distance between two wheels is $d_w = 2.75$ m. The photoelectric sensor records the signal between two wheels when the car passes by so that we can calculate the exact velocity of the car.

There are two experiments implemented using the testing equipment designed by our group to get the required signals. In Experiment 1, both of the signal source (S) and three noise sources (A, B and C) play two different frequency sinusoidal signals so that the microphone would record eight different frequency signals at the same time. In Experiment 2, three noise sources (A, B and C) still play two different frequency sinusoidal signals, while the signal source (S) plays the real acoustic signal of a defected train bearing (Type: NJ(P)3226X1), which is the dominated type in use. The first experiment is designed to verify the effectiveness of the de-noising algorithm for extracting required useful information from multi-source heavy noise background. The second experiment aims at verifying the algorithm in the actual defected roller bearing situation so that the proposed method could be practically and effectively operated in the ADBD system.

To conduct the second experiment, the static acoustic signal was acquired continuously by a microphone being mounted beside the outer race of the bearing. The artificial crack was set by the wire-electrode cutting machine with the width of 0.18 mm on the outer race as shown in Fig. 3(a). Fig. 3(b) is the test bench of the train bearing, where the bearing could be applied with the mechanical load while being driven by the motor, which was controlled by a frequency converter to match the anticipant rotating speed. The acoustic signal acquired through the microphone was preprocessed by the signal conditioner and then recorded by the data acquisition device. The rotating speed was set at 572 r/min, with a load of 2.5 t. The specification of the train bearing used in this experiment is given in Table 1. The sampling frequency of these two experiments was set as 50 kHz.