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An improved AE detection method of rail defect based on multi-level ANC with VSS-LMS

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A B S T R A C T

In order to ensure the safety and reliability of railway system, Acoustic Emission (AE) method is employed to investigate rail defect detection. However, little attention has been paid to the defect detection at high speed, especially for noise interference suppression. Based on AE technology, this paper presents an improved rail defect detection method by multi-level ANC with VSS-LMS. Multi-level noise cancellation based on SANC and ANC is utilized to eliminate complex noises at high speed, and tongue-shaped curve with index adjustment factor is proposed to enhance the performance of variable step-size algorithm. Defect signals and reference signals are acquired by the rail-wheel test rig. The features of noise signals and defect signals are analyzed for effective detection. The effectiveness of the proposed method is demonstrated by comparing with the previous study, and different filter lengths are investigated to obtain a better noise suppression performance. Meanwhile, the detection ability of the proposed method is verified at the top speed of the test rig. The results clearly illustrate that the proposed method is effective in detecting rail defects at high speed, especially for noise interference suppression.

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1. Introduction

With the rapid development of railway transportation, the higher speed and busier track bring more requirements in the safety of railway system [1]. Rail defect is one of the most important reasons for track degradation, and how to ensure the safety and reliability of rail becomes a significant problem for railway system. Recently, Acoustic Emission (AE) technology is employed to investigate the rail defect detection, which is an effective nondestructive detecting method for real-time and dynamic detection [2]. Growing defects can generate AE signals which carry the defect information. AE technology passively receives signals from the rapid release of energy associated with initial defect development and growth, and it only requires the receiving transducers [3,4]. Based on the acquired AE signals in real-time, the whole historical process of rail defects can be monitored. AE technology has the advantages of dynamic crack detection, unlimited geometric shape, high sensitivity and real-time online monitoring [5], and it has been utilized successfully in various applications from aerospace to welding [6].

Based on AE method, the initial investigations of rail defect detection have been carried out by several researchers. The normal rolling AE signals with natural rail defects were investigated by Thakkar [7], and the propagation feature of AE in rail was analyzed by a test rig which includes a circular mild steel track and a scale model wheel. Bruzelius and Mba [8]

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examined the potential of applying AE in rail track defect detection with different speeds and loads, a surface defect was seeded onto the test-rig by a notch and AE activities from the rail track were picked up successfully. This research was also based on a simulated test rig with a rail track wheel and a rail wheel, and the maximum speed was 25 km/h. In the field conditions, Bollas's work [9] verified the ability of AE method in detecting wheel defects which included the flat surfaces on wheel circumference. The frequency and mounting position of AE sensors were analyzed under 40 km/h. The combination of AE and Lamb wave was used to investigate defect detection and location in switch rails by Zhang et al. [10], and continuous wavelet transform was employed to select the characteristic points which were utilized to locate the defects. Bianchi et al. [11] investigated the rail contact fatigue by a wavelet packet decomposition within the framework of multi-resolution analysis theory, and the detection of single events in AE signals was used to investigate the cracks in rail.

The contribution of these studies demonstrates the ability of applying AE in rail defect detection. However, one of the major challenges in AE detection of rail defects is the noise interference at high speed. The present research works are at low speed with the maximum speed of 40 km/h, thus AE signals have high signal to noise ratio. Many details need to be worked out for the AE detection of rail defects with noises at high speed, where the traditional method with AE parameter analysis is invalid. In our previous work [12], the Shannon entropy method with time window was proposed to extract AE features of defect signals. In this method, the simple wavelet hard threshold de-noising is employed for noise suppression, and this method leads to the loss of available signal information and cannot adapt to the changes of noises. As a result, the rail defects can be detected at 124 km/h, but the results suffer a serious noise interference which can easily cause errors in detection.

Due to the complex noises at high speed, especially for the frequency overlaps between noise signals and defect signals, the traditional methods are limited because they will lose the useful information of signals or cannot adapt to the noise changing, such as filtering method and wavelet method. The de-noising can be achieved by the Adaptive Noise Cancellation (ANC) which is a special case of optimal filtering based on the information of reference noise signals [13,14]. An appropriate adaptive process is employed to control the filtering and extraction, thus de-noising can be accomplished with little risk of distorting the defect signals and adapting to the noise changing [15]. In order to detect rail defects effectively, some conditions of this method should be considered, such as calculation efficiency, convergence rate and steady-state estimation error.

Therefore, ANC method is utilized and improved to eliminate noises in order to detect rail defects at high speed, and then the time-Shannon entropy is employed to detect the defect signals in order to verify the validity of the proposed method. Based on AE technology, this paper presents an improved rail defect detection method based on multi-level ANC with VSS-LMS (VSS-LMS means variable step-size least mean square) at high speed. The rest of this paper is organized as follows. Section 2 presents the improved ANC method including multi-level adaptive noise cancellation and variable step-size algorithm based on tongue-shaped curve with index adjustment factor, and the Shannon entropy method with time window proposed in the previous work is described simply. Section 3 introduces the rail-wheel test rig and test procedure. In Section 4, the noise influence on detection is analyzed at different speeds, the selection of filter length is discussed for noise suppression and the effectiveness of the proposed method is verified at the maximum speed of 140 km/h by the rail-wheel test rig. Section 5 gives the concluding remarks.

2. Improved rail defect detection method by multi-level ANC with VSS-LMS

2.1. Multi-level noise cancellation based on SANC and ANC

In the conventional ANC method, reference signals are used directly to eliminate noises. In rail defect detection, the main noise signals with the same generating mechanism, which are from friction and wear, are used as the reference signals. However, there are a lot of random noises in reference signals due to the complex noises at high speed, these reference signals cannot be used directly as the input of ANC system (Note: the influence of the main noise signals and random noises will be analyzed in detail in Section 4.1). The random noises will bring a serious interference, and it should be eliminated at first. Similarly, the defect signals should also be pre-processed in order to suppress the random noises. Due to the random noises without correlation in time, Self-Adaptive Noise Cancellation (SANC) method, which uses a finite number delay signal as the reference signal, is utilized to eliminate random noises from input signals and reference signals of ANC [16,17], then the pre-processed input signals and reference signals are used to eliminate the main noises based on ANC method [18]. Therefore, the multi-level de-noising method combined of SANC and ANC has been adopted and improved to the detection of defect signals in this paper. The schematic diagram of this method is shown in Fig. 1. It includes two levels: the first level is used to eliminate the random noises and the second level is used to eliminate the main noises. The process can be expressed as follows.

Input signal $u(n)$ is composed of defect signal $s(n)$, main noise signal $c(n)$ and random noise signal $n(n)$. Reference signal $r(n)$ includes reference main noise signal $rc(n)$ and random noise signal $rn(n)$. Based on the random noises without correlation in time, SANC is used to eliminate the random noises in $u(n)$ and $r(n)$, respectively. For the input signal $u(n)$, the delayed signal $u'(n)$ is given by:

$$u'(n) = s'(n) + c'(n) + n'(n) \tag{1}$$

where $s'(n)$, $c'(n)$ and $n'(n)$ represent the delayed signals of $s(n)$, $c(n)$ and $n(n)$, respectively. $u'(n)$ is the input of Adaptive filter 1, the output signal is $o_1(n)$ and the error signal can be calculated by:

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