Identification of Abnormal Wheel and Rail Wear Faults Based on Short-time Fourier Transforms

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Abstract. Wheel polygon and rail wave abrasion in railroad wheel-rail system are two common abnormal wheel-rail abrasion faults, which can easily affect the safety and stability of train operation. In order to understand the current situation of wheel-rail abnormal wear, and to detect and distinguish these two kinds of abnormal faults, this paper proposes a time-frequency analysis method based on short-time Fourier transform (STFT). At the same time, considering that the train is usually running under variable speed conditions, it is proposed to use the spatial spectrum instead of the time spectrum to collect and process the acceleration data of the train axlebox, and then use the STFT to analyze the time-frequency analysis of the axlebox vertical vibration acceleration signal. At the same time, this paper deduces the calculation formulae for the wavelength of rail wave abrasion and the order of wheel polygon under train variable speed conditions, and quantitatively identifies the physical characteristics of the faults by collecting the frequency amplitude of the spectrogram of the segmented signals. The results show that the accuracy of the Simpack simulation test set reaches more than 92%, and the research results provide a new technical means for the diagnosis of railroad faults.

Keywords: wheel polygon; rail wave abrasion; short-time Fourier transform; spatial spectrum

1 INTRODUCTION

With the increasing speed of train operation, rail wave wear and wheel polygonal phenomenon become more and more prominent in the rail transportation system. These abnormal abrasion failures will not only aggravate the wear and tear of the wheel and rail, but also cause train vibration, which in the long run will lead to fatigue failure of key functional parts of the wheel and rail system, affecting the stability of train operation[1]. The traditional rail bobbing and train vibration. The traditional rail wave wear and wheel polygon detection methods are less efficient, with a single type of detection, limited accuracy and other problems, which can not meet the high requirements of safety and stability of the train. Therefore, there is an urgent need for a method to efficiently differentiate the abnormal wear types of wheel and rail as well as to measure the physical characteristics.

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At present, numerous scholars have conducted research on the detection of rail corrugation and wheel polygonal wear. In the area of rail corrugation wear, Zhao et al. [2] employed various feature extraction methods such as Short-Time Fourier Transform (STFT), wavelet packet analysis, and empirical mode decomposition to extract comprehensive and accurate rail corrugation features from multiple perspectives. By integrating Bayesian classifiers and convolutional neural networks, they achieved online identification of corrugation wavelengths, though the influence of variable train speeds on the identification results was not considered. Nieslen [3] used wavelet packet energy entropy to analyze axle-box vibration data, and the simulation results indicated that wavelet packet time-frequency maps can effectively locate rail corrugation and determine the corrugation wavelength with high measurement accuracy.In the area of wheel polygonal wear, SUN [4] proposed a filtering method in the angular domain to reduce noise in the measured axle-box vibration signals, successfully identifying the orders of the wheel polygonal wear. However, their research only focused on the identification and analysis of single faults.

Appellate literature from the signal processing, fault characteristics of the perspective of the rail wave grinding and wheel polygon detection and identification, although able to identify the wheel and rail abnormal abrasion faults, but also able to roughly reflect the severity of the fault, but in the two kinds of faults at the same time how to effectively distinguish between the types of faults as well as in the train speed conditions under the characteristics of faults accurately identify the research is still there is a certain gap.

Therefore, to address the above problems, this paper proposes a fault type identification method based on short-time Fourier transform. The wheel polygonal abnormal wear, rail wave grinding abnormal wear and train speed driving at the same time to consider, first of all through the use of spatial instead of temporal spectrum on the train axle box vertical vibration acceleration signal acquisition, and then the signal for the short-time Fourier transform for the spectral characteristics of the segment extraction, and then realize the speed conditions of rail wave grinding and wheel polygonal two kinds of abnormal wear fault discrimination.

2 MECHANISMS FOR DISTINGUISHING ABNORMAL WEAR TYPES ON WHEEL AND RAIL

In order to effectively analyze the wheel polygon and rail wave abrasion faults, this paper uses the Short-Time Fourier Transform to process the vertical vibration acceleration signal of the train axlebox. Short-Time Fourier Transform (STFT) is a time-frequency signal processing method used for[5] The STFT is a time-frequency signal processing method used in time-frequency signal processing. Through the segmentation advantage of this method, the time-frequency map is generated by Fourier transforming each segment of the signal, so that the local frequency characteristics of the signal can be analyzed, and the frequency components of the vibration signals caused by wheel polygons and rail wave abrasion can be clearly distinguished[6].

Then through the fault frequency of the number of occurrences of statistics, due to the wheel polygon abnormal abrasion in the signal persistent, while the rail wave wear for non-persistent occurrence, can be judged by the frequency of the occurrence of fault frequency in the signal to distinguish between the wheel polygon and the rail wave wear wheel rail abnormal abrasion, so as to realize the real-time monitoring of the train operating status and fault prediction.

3 IDENTIFICATION OF RAIL WAVE ABRASION WAVELENGTH AND WHEEL POLYGON ORDER

To accurately identify fault characteristics under variable-speed conditions, this paper converts the time-acceleration signal into a wheel rotation angle-acceleration signal and derives the relevant formulas for calculating wavelength and order under variable-speed conditions[7] .

3.1 Derivation of the formula for the polygonal order of a wheel under variable speeds

The relationship between wheel polygon and train speed under uniform speed conditions is:

$$n = \frac{2\pi R \cdot f}{v} \tag{1}$$

Where n is the polygon order;f is the wheel polygon distribution frequency, Hz ;v is the vehicle running speed, m/s;R is the wheel radius, m.

Under variable speed conditions, by converting the time-acceleration signal to a wheel rotation angle-acceleration signal, the formula for calculating the wheel polygon order is modified as:

$$f = \frac{n}{2\pi} \tag{2}$$

where f is the wheel polygon failure frequency in 1/rad and n is the polygon order.

3.2 Derivation of the Formula for the Wavelength of Rail Wave Abrasion at Variable Speeds

Under uniform speed conditions, the relationship between rail wave wear and train speed is:

$$\lambda = \frac{v}{f} \tag{3}$$

where.λ is the wave mill wavelength, m;v is the train running speed, m/s;f is the wave mill distribution frequency, Hz.

Under variable speed conditions, after signal conversion, the formula for the wave mill wavelength is corrected to:

$$\lambda = \frac{R}{f} \tag{4}$$

where.λ is the wave mill wavelength, m;R is the train running speed, m;f is the wave mill distribution frequency, 1/rad.

4 EXPERIMENTAL VALIDATION AND ANALYSIS OF RESULTS

4.1 Simulation Test

The wheel rotation angle-axlebox vertical vibration acceleration signal under variable-speed conditions of the train, containing both rail corrugation and wheel polygonal wear faults, was obtained through Simpack simulation, as shown in Figure 1

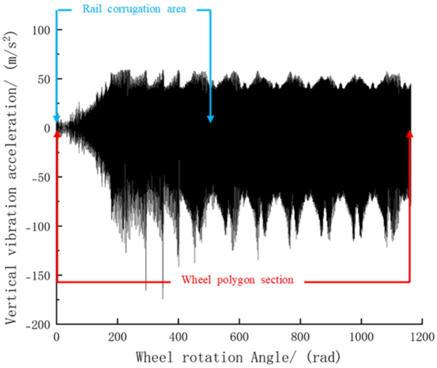
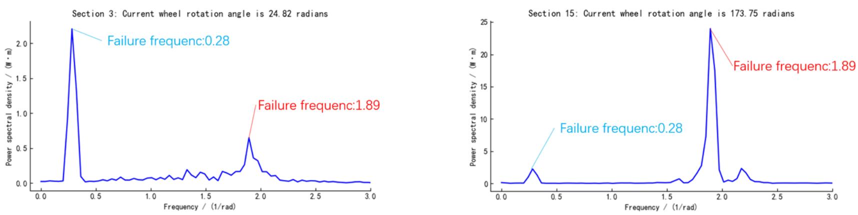


Fig. 1. Wheel rotation angle-axlebox vertical vibration acceleration signal

By randomly selecting some of the angular segments of the spatial spectrum to frequency domain diagrams after the short-time Fourier transform of this signal as shown in Fig. 2, we can obtain the value of the fault frequency corresponding to the largest magnitude in each segment of the signal.



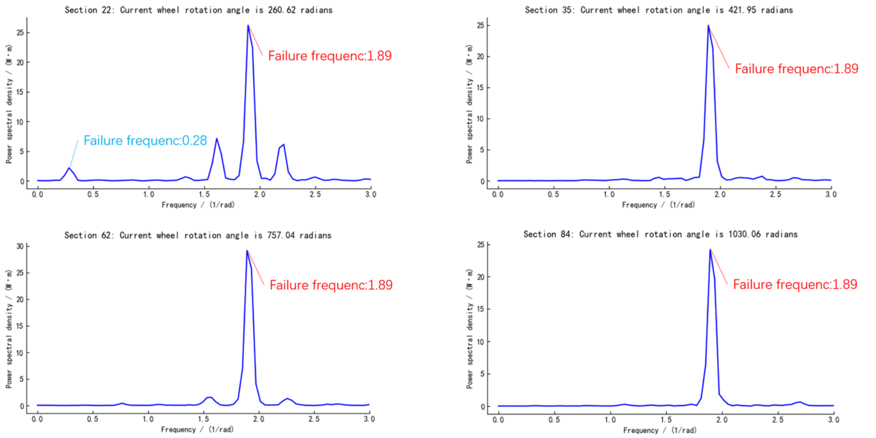


Fig. 2. STFT transformed spatial spectrum of vertical vibration of the shaft box in each angular section to frequency domain plot

Eventually, by counting the frequency of each fault frequency is shown in Table 1:

Table 1. . Frequency table of fault frequency

Fault frequency/(1/rad)	frequency
1.89	75
0.28	16
0.12	3
0.16	2
0.08	2

4.2 Analysis of Results

As can be seen from the identification results, the frequency of the most frequent failure is 1.89, corresponding to a frequency of 75, according to chapter 2 mentioned in the failure type differentiation mechanism to determine its frequency of wheel polygon failure, by substituting into the calculation of formula (2) can be calculated as wheel polygon order is 11.89, the relative error is 0.8%; and the frequency of the second frequency of failure is 0.28, corresponding to a frequency of 16, according to chapter 2 mentioned the fault type differentiation mechanism to judge it as the rail wave grinding fault frequency, by substituting into the formula (4) calculation can get the rail wave grinding wavelength is 1.52m, the relative error is 1.33%, which proves the accuracy of the method.

In order to further verify the accuracy and robustness of the method, the use of different driving speeds at the same time contains different degrees of polygonal order of the working conditions and rail wave grinding wheel rail abnormal wear failure conditions for Simpack simulation tests, to obtain the vertical vibration acceleration of the train in each group of data, in accordance with the above method of data processing and calculation of the polygonal order and the wavelength of the rail wave grinding, and at the same time, the relative error in the results of the calculation of the relative error in the various faults. Comparison of simulation results for each fault type is shown in Table 2 and Table 3:

Table 2. . Experimental simulation of wheel polygon order error results

Test No.	Train speed/(m/s)	Setting the polygon order	Calculate polygon order	relative error
1	40-60	6	6.1575	2.63%
2	40-60	12	12.1454	1.21%
3	40-60	18	18.2212	-1.23%
4	40-60	24	24.5547	2.31%
5	60-80	6	6.1135	1.89%
6	60-80	12	12.2346	-1.96%
7	60-80	18	18.1396	-0.78%
8	60-80	24	24.0483	0.20%

Table 3. . Experimental simulation of rail wave abrasion wavelength error results

Test No.	Train speed/(m/s)	Setting wave wavelength/(m)	Calculation wave wavelength/(m)	relative error
1	40-60	2	2.1500	7.50%
2	40-60	1.5	1.5357	2.38%
3	40-60	1	0.9773	-2.27%
4	40-60	0.5	0.5059	1.18%
5	60-80	2	2.1500	7.50%
6	60-80	1.5	1.4333	-4.44%
7	60-80	1	0.9773	-2.27%
8	60-80	0.5	0.5119	2.38%

The polygonal order and the wavelength of the rail wave abrasion in the simulation results of each test and the relative error of the results are shown graphically, as shown in Fig. 3 and Fig. 4, respectively:

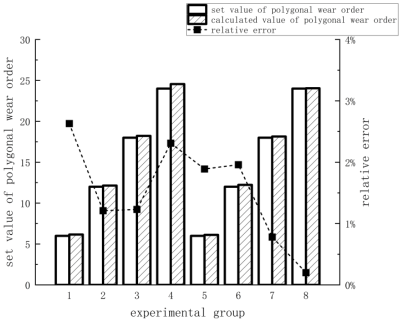


Fig. 3. Comparison of wheel polygon order simulation results

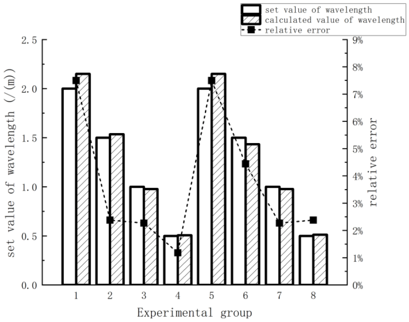


Fig. 4. Comparison of simulation results of rail wave abrasion wavelengths

The experimental results show that the STFT method can accurately distinguish between wheel polygon and rail wave wear faults, and the error between the derived polygon order and wave wear wavelength and the actual value under the variable speed condition is under 8%, which indicates that the method has high recognition accuracy and application value, and verifies the accuracy of the identification method for distinguishing and physically characterizing the abnormal wear faults of rail wave wear and wheel polygon through the STFT under the variable speed condition of the train. The accuracy of the identification method is verified.

5 CONCLUSIONS AND PERSPECTIVES

This paper investigates typical wheel and rail abnormal wear failures in railroad wheel and rail systems, focusing on the differentiation and identification of wheel polygons and rail wave wear, with the main conclusions as follows:

1. The time-frequency analysis of wheel rotation angle-train axlebox vibration acceleration signal by short-time Fourier transform (STFT) can effectively extract the fault frequency caused by wheel polygon and rail wave abrasion, and differentiate different types of abnormal abrasion through the fault frequency frequency.
2. Under the condition of train variable speed, this paper derives the order of wheel polygon and the wavelength calculation formula of rail wave abrasion, and verifies the accuracy of the quantitative calculation formula for these two fault characteristics through frequency analysis and amplitude calculation.

The method proposed in this paper holds significant value in terms of resource savings, reducing labor costs, and improving detection efficiency, as well as offering promising application prospects. In future research, the following perspectives may be explored:

During actual vehicle operation, the axlebox vibration signals collected may contain other fault signals. A key area of future research will focus on how to identify and separate these signals and extract the specific signals related to particular faults.

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