Detection Method for Polygonalization of Wheel Treads Based on Dynamic Response

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Abstract. When the train runs at high speed, the polygonalization of wheel treads will produce high-frequency wheel-rail impact, which will have a bad impact on the fatigue life of the vehicle system and the rail system components such as axles, wheels and rails. Based on the vehicle dynamic response, this paper uses the generalized resonance demodulation method to realize the online diagnosis of polygonalization of wheel treads. The main idea is to obtain the time-spectrum of the signal by synchrosquezed short-time Fourier transform, wherein the window length of the time-frequency transform is determined by the maximum concentration metric; then the time-energy information is automatically extracted from the time spectrum which is caused by the impact. Frequency vibration and low-frequency signal separation; after determining the band-pass filtering range by L^p norm criterion, the generalized Hilbert envelope demodulation method is used to demodulate the dynamic response signal of the band-passed signal, and the polygonalization information of the wheel treads is extracted. The analysis result show that this method can effectively diagnose polygonalization of wheel treads.

Keywords: polygonalization of wheel treads, out-of-roundness of wheels, generalized resonance demodulation

1 Introduction

The abrasive wear of wheel mainly includes wear of flange, wheel flats, abrasion of wheel tread groove, abrasion of wheel tread concave, abrasion of wheel polygonization, and etc. [1]. Abrasion of wheel polygonization is the wear and tear of wheel along the circumferential direction of tread. High-order wheel polygonization is equivalent to short-wave irregularity of rail [2]. Wheel polygonization abrasion will produce high-frequency wheel-rail impact, which will have a bad impact on the fatigue life of the vehicle system and the rail system components such as axles, wheels and rails. To ensure the safety and comfort of train, the study in wheel polygonization is of great significance. The circular curves in Fig. 1 is defined as first-order (eccentricity), secondorder (ellipse), third-order polygon and eighteenth-order polygon, and by analogy, higher-order polygon.

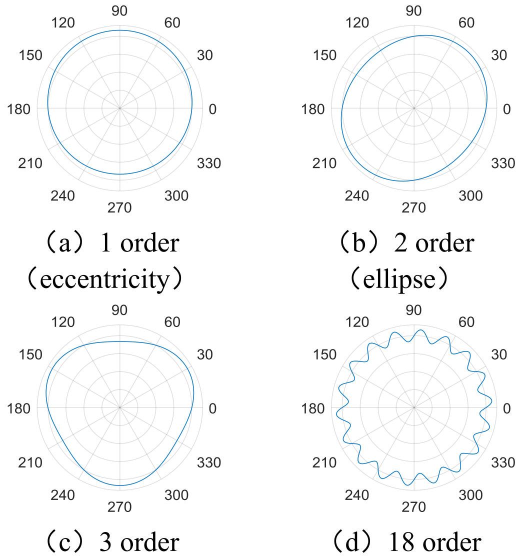

Fig. 1 Different order of polygonal wheel wear

In 2016, Li Yifan et al. [3]. proposed the method of fault diagnosis of out-of-round wheel based on Hilbert-Huang transformation [3]. It shows that there are significant differences among normal wheels, fault wheels and different types of fault wheel in Hilbert spectrum, through morphological filter-energy principle algorithm. Bo Chen et al. proposed a diagnosis method based on improved EEMD and genetic algorithm support vector machine in 2018 to identify wheel polygon faults [4].

High order wheel polygon wear corresponds to high exciting frequency, and make it easier to arouse high-energy system resonance [5]. In the vehicle dynamic response signal with local faults, the stationary component and the fault component will appear at the same time, but they are distributed in different frequency bands. Stationary components are generally distributed in low frequency, while transient components containing fault information are generally distributed in high frequency. High frequency resonance demodulation technology is based on the actual situation to select a certain natural vibration frequency as the research object, through the center frequency is equal to the natural frequency of the band pass filter to separate the natural vibration component of the signal, so as to clearly see the hidden fault information. References [6] and [7] used adaptive resonance demodulation method and STFT based vibration signal demodulation method to diagnose bearing faults in 2007 and 2008 respectively. Inspired by the above ideals, this paper proposes an adaptive resonance demodulation method based on synchronous compression STFT. The method is used to diagnose the out-of-round wear of high-speed train by analyzing the vehicle dynamic response data.

2 Detection method for out-of-round wear wheel based on dynamic response

In this section, vehicle dynamic response data are taken as the experimental object to study the effectiveness and practicability of diagnosing wheel non-roundness by using the generalized resonance demodulation method based on synchronous compression short-time Fourier transform. The speed of high-speed trains is between 200km/h and 350km/h; high frequency excitation is easy to occur on the wheel track system when the wheel is out-of-round wear. At the same time, there will be equal interval harmonic components in the corresponding frequency band. When the fault occurs, sometimes these harmonic components will be hidden in other components due to the change of working conditions. Through resonance demodulation, the corresponding relationship among the frequency interval Δf and the running speed and wheel circumference can be found out.

This section designs the following online automatic identification of out-of-round wheel wear. The automatic recognition process is shown in the following figure:

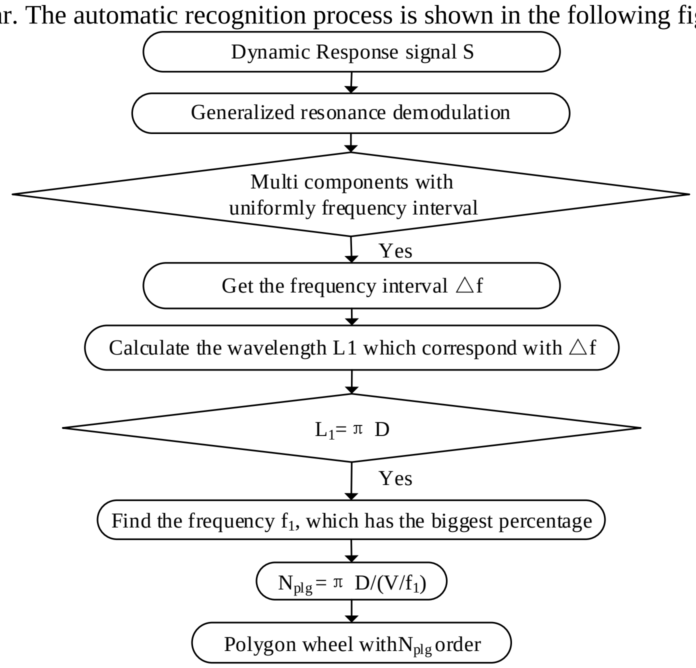

Fig. 2 Automatic identification of out-of-round wheel wear

2.1 Synchronously Compressed Short-time Fourier Transform

Assume f is the superposition of following K numbers of AM-FM components with the following forms:

$$f(t) = \sum_{n=1}^{K} A_n(t)\cos(2\pi\phi_n(t)) \tag{1}$$

where, $\phi'_n(t) > 0$, $1 \le n \le K$ Then the ideal instantaneous frequency $IIF(f, A_n, \phi_n)$ is the Function Set $\{\phi'_n(t)\}_{1 \le n \le K}$, $A_n(t)$ is the instantaneous amplitude.

The steps of instantaneous frequency extraction method based on Synchronously Compressed short-time Fourier Transform are as follows:

1）Conduct STFT transform for signal $f(t)$, and fixed window function g :

$$G_f(t,\eta) = (g(\cdot -)f)^\wedge(\eta) = \int f(t) g(t-\eta) e^{-i\xi t} \tag{2}$$

2）Calculate the instantaneous frequency of the signal, its function is as follow:

$$\omega(t,\eta) = \begin{cases} \dfrac{-i\partial_t G_{\tilde{f}}(t,\eta)}{2\pi G_{\tilde{f}}(t,\eta)} & \left|G_{\tilde{f}}(t,\eta)\right| > 0 \\ \infty & \left|G_{\tilde{f}}(t,\eta)\right| = 0 \end{cases} \tag{3}$$

3）Reassign the time-frequency plane obtained from STFT on the basis of the instantaneous frequency also known as synchronous compression, the process can be expressed as follow:

$$S_d^{\alpha,\gamma} \tilde{f}(t,\xi) = \mu(\eta : \left|\xi - \omega(t,\eta)\right| < \alpha, \left|G_{\tilde{f}}(t,\eta)\right| > \gamma) \tag{4}$$

Where threshold value $\gamma \ge 0$, $(t,\xi) \in R \times \alpha N$, resolving power $\alpha > 0$, μ is the Lebesgue measure on R .

Effective concentration measurement(CM) could depicts different distribution property of signals. The more the signal concentrated, the simpler the components contained. Therefore, it is rational to apply the maximum concentration measurement on time-frequency spectrum of the signal to determine the best transform window length. Let the concentration measurement of frequency band where ξ_i is in as:

$$CM(\xi_i, l) = \frac{\left(\sum_k \sum_i \left|\bar{C}_l(k,\xi_i)\right|^\beta\right)^{1/\beta}}{\left(\sum_k \sum_i \left|\bar{C}_l(k,\xi_i)\right|^\alpha\right)^{1/\alpha}}, \qquad 0<\alpha<1<\beta \tag{5}$$

Where

$$\bar{C}_l(k,\xi_i) = \frac{S_d^{\alpha,\gamma}(k,\xi_i)}{\sum_k \sum_i \left|S_d^{\alpha,\gamma}(k,\xi_i)\right|} \tag{6}$$

$S_d^{\alpha,\gamma}(k,\xi)$ is the discrete expression of function (4).

Then define the best transform window length of frequency band where ξ_i is in as:

$$l = \arg\max_l CM(\xi_i, l)$$

Based on the rules above, the best window length can be ascertained, and thus enable clearly access to the fault characteristic hidden in the signals.

2.2 L^p Norm Criteria

The purpose of demodulation analysis of vehicle dynamic response signals is to detect those periodic fault signals from vehicle dynamic response data, but it is unnecessary to completely demodulate all the modulated components. Therefore, we need a criterion in choosing the proper filtering bandwidth. The selected filtering bandwidth should contain the most abundant information of the modulated signals, and then we can analyze the signal by amplitude spectrum. The criterion selected in this paper is L^p Norm Criterion [6].

For vehicle dynamic response data $s(k), k = 1, 2, ..., N$, where N is the data length, applied synchronously compressed short-time Fourier Transform, the obtained time-frequency spectrum is $S(k, \omega_j), k = 1, 2, ..., N, j = 0, 2, ..., N/2$. Defined the time-frequency spectrum as：

$$EP(k, \omega_j) = |S(k, \omega_{j+N/4})|^2 \tag{7}$$

Base on above function, the time-frequency signal of the vehicle dynamic response data can be obtained applying L^p Norm Criterion.

$$E(k) = (\sum_{j=0}^{N/4} EP(k, \omega_j)^p/(N/4 + 1))^{1/p}, \quad p \in [1, \infty) \tag{8}$$

The constant term added in the formula above is to evade changing of results in the spectrum analysis of time-frequency signals when the sampling number changed. When $p > \infty$, Form (8) could be written as:

$$E(k) = \max_j EP(k, \omega_j), k = 1, 2, ..., N \tag{9}$$

Obviously, Form (8) and (9) have the same dimension.

2.3 Generalized Hilbert Envelop Demodulation Analysis

In practical applications. There is a specific corresponding relationship between the Hilbert Envelop and the theoretical fault frequency of abrasion of wheel polygonization. However, we only need to demodulate the periodic components contained in modulated signals, and do not have to restore the modulated signals completely. So the generalized Hilbert envelop demodulation method is chosen in this paper for analysis [7]:

Assume modulation signal is：

$$x_i(t) = c[1 + \sum_{i=1}^{L} b_i \cos(i\omega_r t + \varphi_i)]cos(\omega_n t + \theta) \tag{10}$$

Apply multiple analytical band pass filter to above signals. Assume the band pass contains frequency components $\omega_n + k\omega_r + i\omega_r$, $k \in [-L, L], i = 1, 2, ..., n$, Let $\omega_i = \omega_n + k\omega_r + i\omega_r$, Then the filtered signals can be expressed as:

$$y_i(t) = \sum_{i=1}^{n} a_i e^{j(\omega_i t + \Phi_i)} \tag{11}$$

As Hilbert Envelop demodulation method, we perform modulo operation on formula (11), take Taylor series expansion and with keeping only linear terms, we obtain:

$$g_i(t) = \left|\sum_{i=1}^{n} a_i e^{j(\omega_i t+\Phi_i)}\right| \approx \sum_{i=1}^{n} a_i\{1 + \frac{2\sum_{1\le i<k\le n} a_i a_k\{\cos[(\omega_i-\omega_k)t+\Phi_i-\Phi_k]-1\}}{(\sum_{i=1}^{n} a_i)^2}\} \tag{12}$$

Because

$$\omega_i - \omega_k = (i-k)\omega_r, 1 \le |i-k| \le n-1 \tag{13}$$

So the demodulated signals contains frequency of ω_r, $2\omega_r$, …, $(n-1)\omega_r$ and etc.

The above conclusion proves that even if the center frequency of the band-pass filter of vehicle dynamic response signals is different from modulated signals' carrier frequency, the periodic components of the modulated signals could still be demodulated. However, because this method is not strictly Hilbert Envelop demodulation method, the modulated signal could not be fully recovered. [7]

3 Experimental Result

The generalized resonance demodulation method is used to analyze the vehicle dynamic response data, and the original data is shown in FIG. 3. Following the resonant demodulation of the method proposed herein, the envelope spectrum of the signal is shown in FIG. 4. By using the method proposed in this paper, the vehicle dynamic response fault frequency and its frequency multiplier can be clearly seen. The peak interval is exactly equal to the wheel polygon wear response period. That is:

$$\pi D = \frac{v}{\Delta f}$$

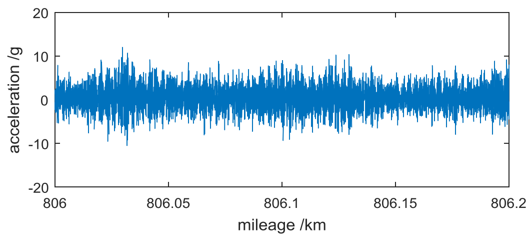

Fig. 3 Axle box acceleration

Through the data of the power spectrum and time-frequency diagram shows that the analysis of vehicle dynamic response data of frequency is 548 Hz, through calculating the data corresponding to the existence of higher order wheel polygon. According to the calculation, the polygon order of the test wheel is 16.

By testing the wheelset, it is known that the wheel has a 16 order polygon, as shown in FIG. 5, having a roughness level of more than 10 $dB\ re\ 1\mu m$.

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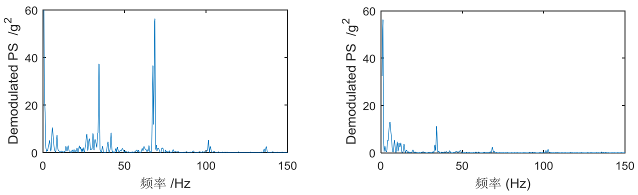
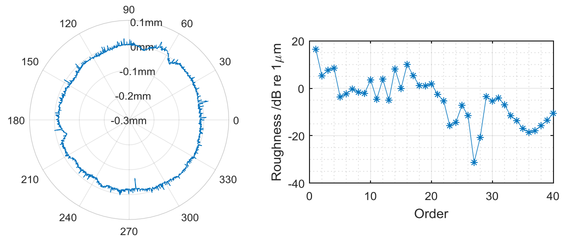


Fig. 4 Spectral envelope



(a) Amplitude in polar coordinates **(b) Polygonalization level**

Fig. 5 Wheel surface wear data

4 Conclusion

In the paper, we applied the generalized resonance demodulation method based on synchronously compressed short-time Fourier transform to diagnose polygonalization of wheel treads of high-speed train, and proposed the automatic detection method. The calculation results prove that this method can effectively diagnose the polygonalization of wheel.

The generalized resonance demodulation method used in this paper selects the band-pass filtering range of vehicle dynamic response data based on time-energy criterion through time-frequency analysis of time-vibration signals, which can accurately separate the frequency band containing abundant fault information and avoid the difficulty of determining the center frequency and bandwidth of traditional band-pass filtering.

Based on the method of automatic recognition of wheel polygonization of dynamic vehicle response, by analyzing the data, the wheel condition of high-speed train and the abrasion of wheel polygonization can be detected in time.

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