Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 21.8
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.21.8

An On-board Detection Method for Polygonal Wear of Railway Wheel based on Modern Spectral Estimation

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Abstract

The contact friction between the railway wheel and track will cause the wheel polygonal wear, then producing the strong quasi-periodic wheel-rail excitation force and accelerating the fatigue failure of critical components and infrastructure. However, the specific generation mechanisms of wheel polygonal wear are still controversial. The timely wheel re-profiling process to the severe polygonal wheel is still the most frequently used solution. Therefore, it is essential to detect the wheels during their service process to provide a real-time wear status for the wheel re-profiling scheme. Nevertheless, the wheel fault signals are usually challenging to be identified by the traditional spectral estimation method, making the order and the level of wheel polygonal wear detected hardly. An on-board dynamic detection method of wheel polygonal wear based on modern power spectral estimation is proposed firstly in this paper. Taking the measured vertical axle-box vibration acceleration signal of a metro vehicle as a case study, the orders of polygonal wear for the studied wheel are clearly detected. And then, compared the proposed method and traditional method, the results show that the detection method can avoid the inherent defects of traditional methods, weaken the interference of random background noise, and is highly advantageous to detecting the polygonal wear of the railway wheel, even the initial wear state. Provide essential theoretical and methodological support for the dynamic detection method of polygonal wear of railway wheel. The actual field tests and the probability density analysis verify its feasibility and effectiveness.

Keywords: railway, polygonal wear, modern spectral estimation, detection

1 Introduction

Wheel polygonal wear is a kind of non-uniform wear in the circumferential direction of the wheel. The wheel radius changes periodically along the wheel circumference, which will cause the strong quasi-periodic wheel-rail excitation force, and accelerate the fatigue failure of critical components [1]. But the generation mechanism of wheel polygonal wear is still controversial [2]. Before it is wholly clarified, adopting the timely re-profiling process to the severe polygonal wear is still a helpful solution [3]. Monitoring the wheels during their service is essential to the re-profiling scheme to avoid structural fracture caused by the severe polygonal wheel.

The wheel polygonal wear detection methods are usually divided into the track-side and on-board. The track-side detection method refers to the detection system installed near the track to collect the signals generated when the wheels pass by [4,5]. However, limited by the number and location of sensors, it is impossible to achieve real-time monitoring of wheel wear status. The on-board detection method is to install the detection system on the vehicle to track the wheel wear state [6].

Whether the track-side detection method or on-board detection method is selected, analyzing the signals generated by the defective wheels passing through the track is the core to identify polygonal wear state on the wheels. Due to the strong non-stationarity of vehicle vibration signals, it isn't easy to obtain adequate wheel polygonal feature information through simple time-domain or frequency-domain analysis. Most of these analysis methods are essentially based on the traditional method, which seriously limits the evaluation accuracy of the wheel wear state [7,8]. Only a few vibrations with high polygonal wear levels can be observed. It is hard to detect some initial stages of wheel polygonal wear in time because of these inherent defects below, such as:

(1) The inability to consider the higher time resolution ratio and frequency resolution ratio at the same time;

(2) The frequency estimation deviation caused by the fence effect and window function.

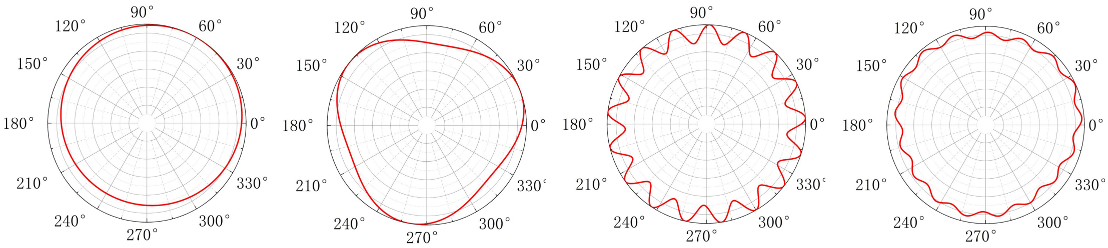
In addition, the wheel fault signals easily overlap with some random background noises and radiated vibrations from track and vehicle components, making the traditional analysis methods unable to reflect all the wheel polygonal wear characteristics accurately. Restrict the development of wheel maintenance management.

This paper, based on the modern power spectral estimation theory, proposes a more accurate analysis method to identify the wheel polygonal characteristics with the vertical vibration acceleration signal of the axle box.

2 Methods

2.1. Calculation method of harmonic frequency

Generally, the railway wheel has multiple order polygonal wear at the same time. Figure 1(d) comprises the 1st, 3rd, and 17th order polygon wear characteristics. Now, suppose this wheel runs on a smooth track at a stable speed. The axle box's acceleration vibration signal generated by the polygonal feature can be regarded as the superposition of 3 different harmonics.



(a) 1st order polygon (eccentric) (b) 3rd order polygon (c) 17th order polygon (d) 1st, 3rd and 17th order polygon

Figure 1: Polygonal wear of railway wheel.

The time-domain signal of vertical axle-box vibration acceleration generated by the 1st order polygon of this wheel can be discretized into a time-series signal:

$$x(n) = \sin(2\pi f \cdot n + \varphi), (n = 0, 1, 2, ...) \tag{1}$$

Then get the second-order difference equation of this process:

$$x(n) - 2\cos(2\pi f)x(n-1) + x(n-2) = 0 \tag{2}$$

Take the Z transformation to formula (2) and the complex eigenvalue can be solved out:

$$z = \cos(2\pi f) \pm j\sin(2\pi f) = e^{\pm j2\pi f} \tag{3}$$

In general, consider this system as causal system. Only the positive frequency is picked. The frequency of the harmonic vibration signal generated by the 1st order polygon of the wheel can be obtained:

$$f = \left| \frac{1}{2\pi} \arctan\left[\frac{\mathrm{Im}(z)}{\mathrm{Re}(z)} \right] \right| \tag{4}$$

Where: Im(z) and Re(z) are the imaginary and real part of the eigenvalue z.

2.2. Establishment of harmonic frequency recovery model

Nevertheless, the railway wheels not only have the 1st order polygon feature. Hence, it is more realistic to re-suppose the time-series signal $x(n)$ is composed of p

different harmonic vibration signals. Each harmonic vibration signal is caused by a specific wheel polygon feature.

$$x(n)=\sum_{i=1}^{p} A_i \sin(2\pi f_i \cdot n+\varphi_i) \tag{5}$$

According to the characteristics of the conjugate complex eigenvalues in formula (3), the harmonic frequency recovery model can be established:

$$\prod_{i=1}^{p}(z-z_i)(z-z_i^*)=\sum_{i=0}^{2p} a_i z^{2p-i}=0 \tag{6}$$

Taking the inverse Z transformation to formula (6), the difference equation of process (5) can be derived:

$$x(n)+\sum_{i=1}^{2p} a_i \cdot x(n-i)=0 \tag{7}$$

Then, multiply the formula (7) by $x(n\text{-}k)$ and calculate the expectation $E[\cdot]$ to obtain the relationship of auto-correlation function:

$$R_x(k)+\sum_{i=1}^{2p} a_i \cdot R_x(k-i)=0\,,\forall\, k \tag{8}$$

However, the collected signals usually contain some random noise. Hence, assumed the signal $x(n)$ is observed under an additive noise background $w(n)$. The noise is the Gaussian white noise with mean is 0 and variance is σ_w^2.

Meanwhile, since the relationship between harmonic signal $x(n)$ and white noise $w(n)$ is statistically independent, that is $R_y(k)= R_x(k)+ \sigma_w^2\cdot\delta(k)$. Substitute it into formula (8) can get:

$$R_y(k)+\sum_{\mathrm{i}=1}^{2p} a_i R_y(k-i)=\sigma_w^2\sum_{\mathrm{i}=1}^{2p} a_i\delta(k-i)=\sigma_w^2\cdot a_k \tag{9}$$

According to the Yule-Walker equation [9], establish the linear equations of this process. And its analytical solution is unique.

$$\begin{bmatrix} R_y(2p+1) & R_y(2p) & \cdots & R_y(1) \\ R_y(2p+2) & R_y(2p+1) & \cdots & R_y(2) \\ \vdots & \vdots & \ddots & \vdots \\ R_y(2p+2p) & R_y(2p+2p-1) & \cdots & R_y(2p) \end{bmatrix} \cdot \begin{bmatrix} 1 \\ a_1 \\ \vdots \\ a_{2p} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{10}$$

2.3. Determination of the order $2p$ and Parameter a_i (i=1...) of ARMA(2p,2p) model

Then, based on singular value decomposition method, the $2p$ can be determined.

And based on total least square method, the model parameters a_i (i=1...) can be determined. Substituting them into the formula (6), obtain each complex eigenvalue. Then, according to formula (4), each harmonic frequency can be solved out. Omitted here...

Finally, according to the Cadzow estimation theory [10], the power spectral of this process can be obtained.

3 Results

The following test scheme is designed to verify the applicability and accuracy of the harmonic frequency identification method in detecting wheel polygonal wear of rail vehicles.

3.1.Vertical axle-box vibration acceleration signal test

The vibration acceleration test is taken on the non-power bogie of a metro vehicle as shown in Figure 2 and 3.

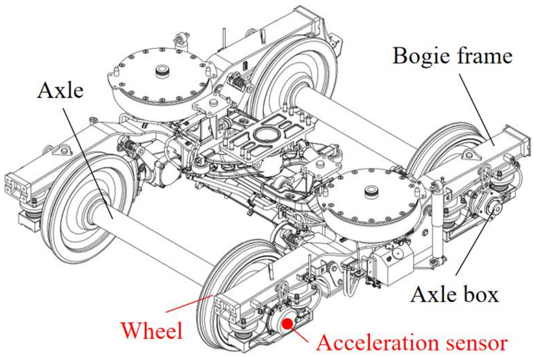


Figure 2: Diagram of the bogie model.

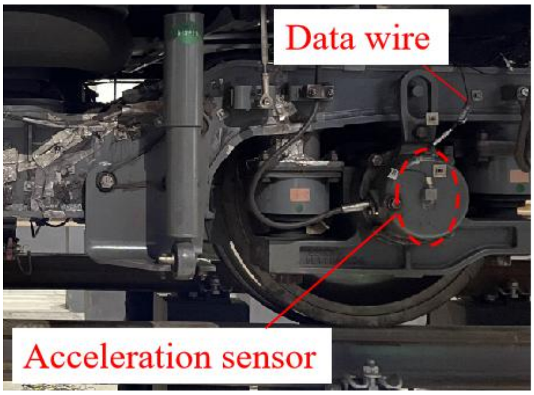


Figure 3: Installation diagram of acceleration sensor.

The processed time-domain signal of axle box vertical acceleration and vehicle real-time running speed are shown in Figure 4.

As shown in Figure 4, the metro vehicle has experienced“traction-idle running-brake”conditions successively. The idle running condition is relatively stable speed conditions. To keep the harmonic vibration frequency generated by the polygon characteristics of the wheel relatively stable, take the signal(b) as a case study here for analysis as shown in Figure 5.

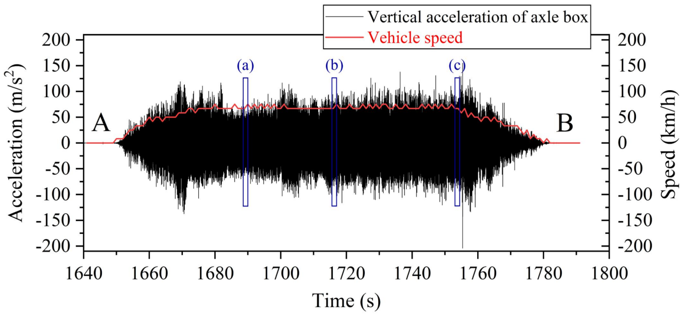


Figure 4: Vertical axle-box vibration acceleration signal and vehicle speed signal.

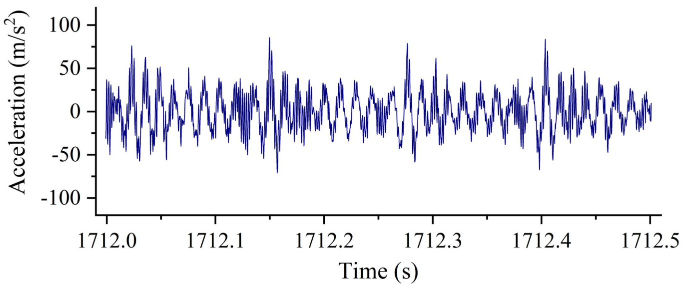


Figure 5: Time-domain signal(b).

Since the signal(b) is pretty short, about 0.5s, it can be considered that the vehicle's speed is relatively stable in such a short time.

According to the fixed wavelength mechanism [2], when the vehicle runs at a stable speed, the difference between the axle box vibration frequencies generated by the $(n+1)^{\text{th}}$ and n^{th} order polygonal wear features should be a constant:

$$\Delta f_n = f_{n+1} - f_n = \frac{(n+1)v}{3.6\pi d} - \frac{nv}{3.6\pi d} = \frac{v}{3.6\pi d} \tag{11}$$

Where:n(1,2,...) is the order of wheel polygonal wear; v is the running speed of vehicle(km/h); d is the wheel diameter(m).

The speed corresponding to signal(b) is 68.79km/h. The wheel diameter is d=0.74m. Then the theoretical values of axle box vibration frequency interval Δf_n generated by two adjacent orders of the polygonal wheel within the time range of (b) shall be 8.22Hz.

3.2.Detection of wheel polygonal wear based on modern power spectral estimation

Based on the theories and methods in section-2, the power spectral density estimation of (b) is shown in Figure 9. And the identified harmonic frequency is shown in Table 1.

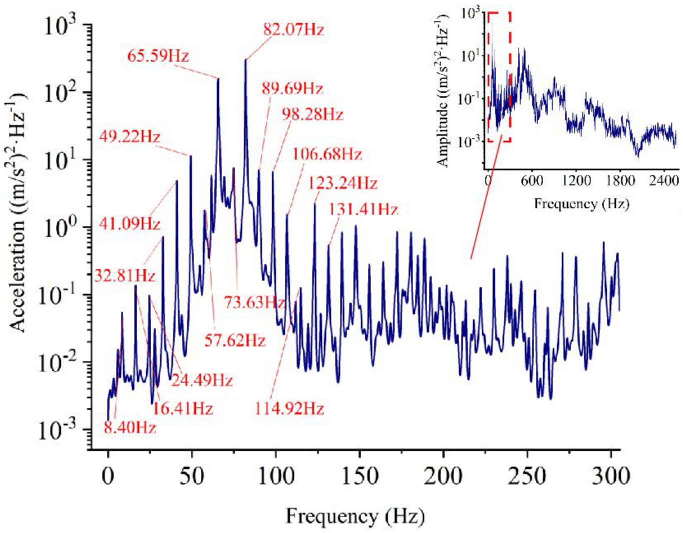


Figure 6: Power spectral density estimation of time-domain signals (b).

Observing the power spectrum of axle box acceleration shown in Figure 6, it can be seen that signal(b) have approximately equally spaced single frequency spikes. It can be inferred that there are several prominent wheel polygonal wear excitation characteristic frequencies in the signal. To verify the correctness of the above speculation, the frequency intervals generated by two adjacent wheel polygon characteristics in the signal(b) are calculated and averaged in Table 1.It is concluded that the errors between the test value and the theoretical value is 0.23%. It is fully confirmed that the wheel has polygonal wear. In addition, by observing the vibration amplitude, it can be found that the 10th, 8th, 9th orders of polygonal wheel contribute greatly.

Order	(b)	
	Frequency f (Hz)	Interval Δf (Hz)
1^{st}	8.40	8.02
2^{nd}	16.41	8.08
3^{rd}	24.49	8.32
4^{th}	32.81	8.28
5^{th}	41.09	8.13
6^{th}	49.22	8.4
7^{th}	57.62	7.97
8^{th}	65.59	8.04
9^{th}	73.63	8.44
10^{th}	82.07	7.62
11^{th}	89.69	8.59
12^{th}	98.28	8.4
13^{th}	106.68	8.24
14^{th}	114.92	8.32

15th	123.24	8.17
16th	131.41	-
Frequency Interval Δf (Hz)	Mean value (Hz)	8.20
	Theoretical value (Hz)	8.22
	Error (°)	0.23

Table 1: Identification results of axle box vertical acceleration vibration frequency generated by wheel polygon feature.

4 Conclusions and Contributions

4.1. Comparative analysis

Compare the modern power spectral estimation results with the periodogram method's, as shown in Figure 7. The periodogram method is a traditional frequency domain analysis method based on the Fourier transform.

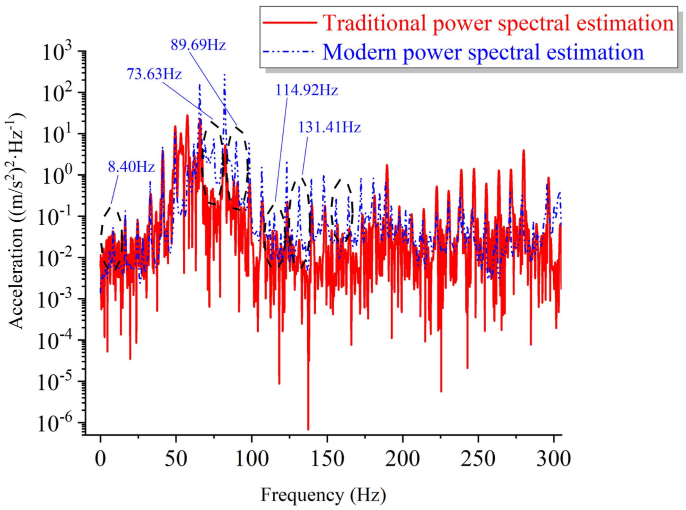


Figure 7: Power spectral estimation based on modern and traditional methods.

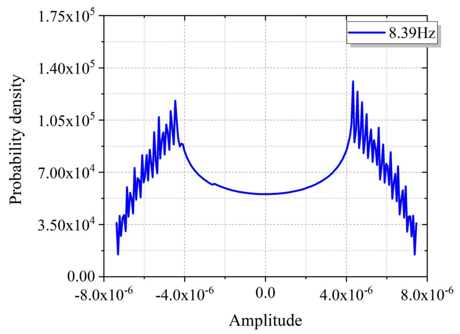
Both the modern and traditional spectral estimation methods can identify most of these harmonic frequencies. However, there are serious energy leakage and errors in the power spectrum estimation results based on the traditional method, which directly causes the low detection accuracy for harmonic frequencies.

In this case, the 1st (8.59Hz), 9th (73.63Hz), 11th (89.69Hz), 14th (114.92Hz), and 16th (131.41Hz) orders of wheel polygonal wear feature even can not be identified because these orders of wheel polygonal wear are not very serious yet. The inherent defects of traditional methods, such as: low-frequency resolution ratio, fence effect, window function effect, make the traditional method low recognition efficiency. But the power spectrum estimation results based on the modern method are apparent and identifiable because it is a modeling and analysis method based on parameterization. It is highly advantageous to realize the high-resolution frequency domain analysis based on very short time-series data, and detect the initial polygonal wear of the railway wheel.

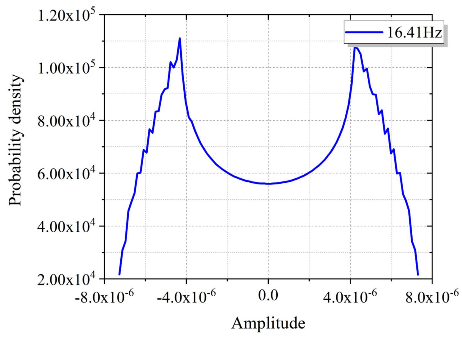
4.2. Verification analysis

To verify the accuracy of identification results, the probability density analysis method is taken for the first 8 characteristic frequency bands of the signal(b). According to the theory of statistics, the probability density function curve of the periodic signal and Gaussian random signal should look like U-shaped and bell-shaped. The probability density function curve should look like a saddle-shaped for the mixed-signal of periodic signal and Gaussian random signal.

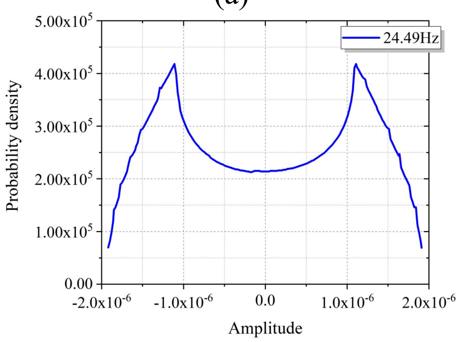
As shown in Figure 8, it can be seen that the probability density curves of signal(b) near the frequency bands of 8.40Hz~65.59Hz all show the saddle-shaped, indicating that the vibration at these frequencies obviously includes the periodic vibration, which are generated by the polygon features of this wheel. It verifies the accuracy of the dynamic detection method of polygonal wear of railway wheel based on modern power spectral estimation.



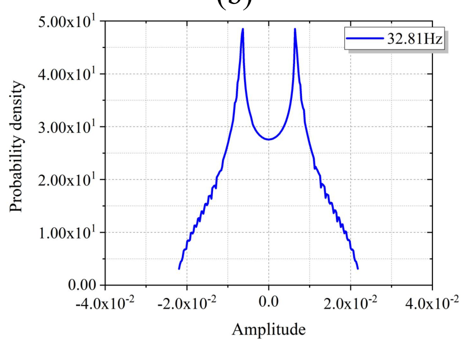
(a)



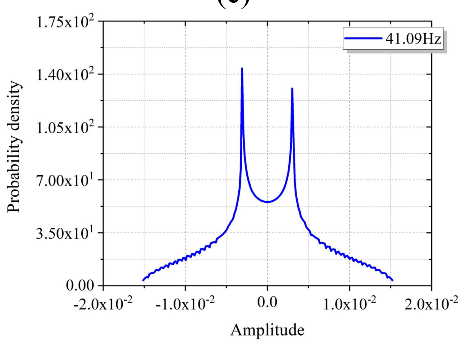
(b)



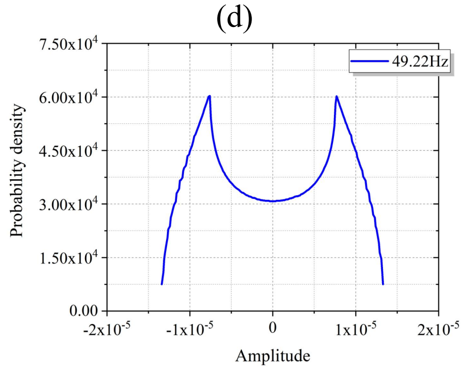
(c)



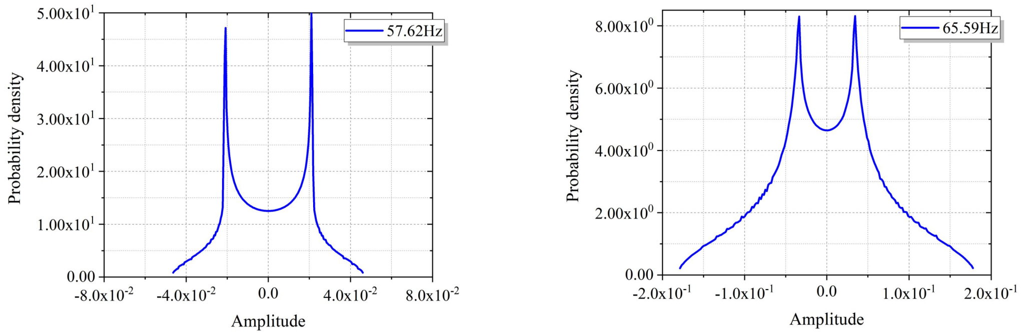
(d)



(e)



(f)



(g) (h)

Figure 8: Probability density analysis of polygonal vibration characteristics of wheels.

4.2. Conclusion

In this work, a dynamic detection method of wheel polygonal wear based on modern power spectral estimation is proposed for the first time. The results show that the method is highly advantageous to realize the high-resolution frequency domain analysis based on very short time-series data and detect the initial polygonal wear of the railway wheel.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 51805373). And thanks the China Scholarship Council for supporting Wang Qiushi to study at school of Mechanical and Aerospace Engineering in Nanyang Technological University, Singapore, the support Number is 202106260138.

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