Investigations on formation mechanisms of out-of-round wheel and its influences on the vehicle system

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Abstract. The railway wheels are invariably subjected to the uneven wear owing to the wheel/rail interaction, and always tend to be an out-of-round wheel. Such wear on the wheel circumference can be classified into the local defect and the periodic uneven wear. The local defects, including the wheel flat and wheel shell, have been well documented, while the formation mechanisms of wheel polygonalizations, especially for high-order polygonal wear, have not yet been explained clearly. The formation mechanisms of wheel polygonalizations are thus initially reviewed and discussed in this study, and the metal cutting theory is also employed to explain the formation procedure of wheel polygonalization. A coupled vehicle/track dynamic model integrating with the flexibilities of the wheelset, bogie and car body is subsequently formulated to investigate the influences of wheel polygonalization on the dynamic responses of vehicle system, in terms of wheel/rail normal forces, lateral forces and accelerations of wheelset and bogie frame. A maintenance strategy for wheel polygonalization considering the different peak-to-peak amplitudes and the number of harmonic waves is proposed on the basis of limit values of wheel/rail vertical force.

1. Introduction

With the increase of the vehicle speed, the interaction between wheels and rails is intensifying, leading to increasingly serious wear and tear problems of the wheels, the main manifestations are the lateral concave wear of the wheel tread and the uneven wear of the wheel circumferentially, that is so-called out-of-round wheel [1]. The lateral concave wear of the wheel tread mainly affects the vehicle's dynamic performance, and the out-of-round wheel will intensify the impact between the wheel and rail, which will increase the vibration of the rail, wheelset, arm, frame and body parts. It not only affects the dynamic performance of the vehicle track system, but also seriously threatens the fatigue life of the vehicle and track structure. At present, the study of out-of-round wheel is mainly focused on low-order, and there is still no unified understanding of the mechanism of high-order non-circularity of wheels, therefore, vehicle vibration can only be mitigated by repairing the wheel, causing a sharp increase in costs and uncertainties in safety.

Since the 1990s, German and Swedish researchers have studied the phenomenon of out-of-round wheel through computer simulation and field tests. J C O Nielsen [2-3] statistically classified the out-of-round wheels and summarized the main reasons for the formation of them. The research results show that the out-of-round wheel is mainly related to the elastic vibration between wheelset and track. At the same time, the unbalance of the wheel dynamics and the inhomogeneity of hardness distribution will also aggravate the formation of wheel polygonalization. Due to the problem of wheel-rail noise caused by out-of-round wheel, the wear of out-of-round wheel was initially focused on in Europe. Kaper [4] analyzed the out-of-round brake wheel in New Zealand, the results show that the
thermal-elastic instability of the material during braking is the main cause of out-of-round wear of the wheel on the tread. To reduce the noise caused by out-of-round wear of the wheel, the elastic wheels were applied to the German ICE train, which became the fuse of the German ICE train accident in 1998. The elastic wheels use rubber blocks to connect rim and web, replacing the integral wheels to achieve vibration damping and noise reduction, but the structure also reduces the fatigue strength of the wheels. When the wheel suffers impact caused by polygonal wear, the longevity of this wheel is far less than the integral wheel. Pallgen[5] found that ICE train wheels generally have out-of-round wear by studying the roundness of ICE train wheels, the integral wheel is mainly trigonal, while the elastic wheel is dominated by two-sided wear. Rode et al. [6] studied the wheel repair process and concluded that the wheel’s 3 edge wear was caused by the three-claw disk during the repair process.

In addition to the low-order non-circularity caused by the repair process, uneven wheel material and unbalanced motion can also result in low-order non-circularity of the wheels. Meinke [7] studied the effect of wheel imbalance on the polygonal wear of wheels. Johansson [8-9] tested wheel wear of five different vehicles and found that the initial trigonometry of subway wheels was caused by the three-jaw chuck in the wheel processing. At the same time, a long-term iterative model of out-of-round wear wheel was established based on the coupling dynamic model of the vehicle track and the wheel-rail wear model, he studied the law of initial out-of-round wear and mileage development of wheels 1-20, the results show that the development of the out-of-round harmonics of the wheel above 10th order is faster; the higher the vehicle speed, the easier it is for low-order wheels to be out of round; different types of out-of-round wheel will appear on different wheelsets in the same bogie.

This article starts from the fact that the out-of-round wheel on the line and investigates the out-of-round condition of the wheel, then analyzes the main mechanism for forming various types of out-of-round wheel; the effect of out-of-round wear wheel on the vertical and lateral force, wheelset and frame vertical acceleration of the vehicle is studied by using the vehicle-track coupling system dynamics model.

2. Actual Measurement of Out-of-round Wheel

The circumference wear of wheel is mainly measured by out-of-roundness tester which mainly uses contact measurement method showing in Fig.1. Displacement sensor 1 contacts with the wheel in vertical direction for recording the out-of-roundness data of wheel. Rotation sensor 2 is used for measuring circumference data of wheel, which to record phase data of out-of-roundness obtained by sensor 1. The out-of-roundness data of wheel measured by sensors can be expressed by the function of the circumferential length f(x).

![Figure1. Test site photo of wheel out-of-roundness measurement](image)

The roughness of wheel $L^r_k$ is defined as Eq.1, and the unit is dB·mm⁻¹.

$$L^r_k = 10 \times \log_{10} \left( \frac{r^2_k}{r^2_{ref}} \right)$$  \hspace{1cm} (1)

In Eq.1, $r^2_k$ is the quantization of k in the 1/3 octave of roughness of wheel out-of-roundness $r(x)$. $r^2_{ref}$ is the reference value of wheel roughness. In SI, the wavelength of frequent band center is:

$$\lambda_k = 0.01 \times 10^{k+10}, k = -10, -9, \ldots, 14, 15$$  \hspace{1cm} (2)
$r_s^2$ can be acquired by squaring the narrow-band spectral amplitude obtained in each 1/3 octave and summing up, then dividing the calculation point number. In the definition of roughness, the effective amplitude (RMS) of 10μm roughness corresponds with the 20dB roughness class, but the 1μm roughness amplitude corresponds with 0dB roughness class. Final results are mainly expressed by polar chart and wheel order chart, and the polar chart is more visualized which makes wheel spatial irregularity a circle and transforms abscissa into corresponding angle. Wheel order chart can reflect the state of wheel out-of-roundness. Fig.2 shows 3 kinds of states and roughness class of wheel out-of-roundness measured in test cite.

![Figure 2. Typical states of wheel out-of-round measured in test cite](image-url)
In Fig. 2, (1) are wheels in local out-of-round states, in the actual measuring data, wheels with local out-of-round are in a large proportion, which mainly manifest wheel flat and wheel shell, and wheel in this form will make a larger wheel-rail impact. (2) are wheels in low-order out-of-round states, which manifest third-order wheel out-of-round, and Johansson’s [8-9] researches reveal that the initial third-order out-of-round of new wheel is caused by three claw chuck in the manufacture process. (3) are wheels in high-order (20-order) out-of-round.

3. Discussions of Formation Mechanisms of Out-of-round Wheel

The wear of out-of-round wheel consists of local out-of-round and periodic out-of-round. Local out-of-round is mainly presented in the form of wheel flat and wheel shell. Periodic out-of-round is mainly presented in the form of wheel polygonal wear.

There are still many controversies in the formation mechanisms of out-of-round wheel. According to the wear theory, the wear between wheel and rail is mainly determined by normal force of wheel-rail, relative slippage of wheel-rail, hardness of material and wear coefficient. There is periodic wear in wheel circumference, which is caused by periodic fluctuation determining wear variable, thus it can be attributed to fixed wavelength mechanism, fixed frequency mechanism and uneven distribution of initial hardness. The starting point of fixed wavelength mechanism lies in cross impact. The line test reveals that cross impact will lead to periodic fluctuation of axle boxes acceleration, and the cross impact in some lines can reach to 5g in winter. This periodic fluctuation may influence the circumference wear of wheel. Take a wheel as an example. Its diameter of nominal rolling circle is 0.92m and its gauge is 0.6m. There is 4.81 times cross impact in one rolling circle, and 5 circles is a period. According to this hypothesis, the wheel will form 24-edge polygon. The uneven distribution of initial hardness in wheel circumference may be caused by cooling process in the wheel manufacture process or work hardening between wheel and rail. After wheel polygonalization, its circumferential hardness will also reveal polygonalization. This uneven distribution may occur under tread in several millimeters, and it cannot be eliminated by wheel turning, so newly turning wheel may become polygonalization wheel. Fixed frequency mechanism means that it is caused by a fixed excitation frequency in the operation process and can also be attribute to structure resonance. The typical fixed frequency is from rail. According to the analysis, it can be known that lateral Pin-Pin frequency from rail is close to pass frequency of polygonalization wheel in 300km/h operation which shows in Eq. 3. Constructing the rail structure finite element model and computing its mode, it can be found that rail lateral Pin-Pin frequency occur in 559.4Hz~601.8Hz, which shows in Fig. 3.

$$f_{pp} = \frac{\pi}{2l^2} \sqrt{\frac{EI}{m}}$$

In Eq.3, $l$ is discrete support distance of rail, $EI$ is bending rigidity, $m$ is rail mass of unit length.

![Figure 3. Lateral mode of rail structure](image)

Therefore, many scholars think that high-order out-of-round wheel is caused by wheel defects motivating the natural frequency of rail system. This formation process is similar to cut marks.
formation mechanism in cutting vibration. In metal cutting process, because of the vibration of the cutting knife tool, there will be some cutting marks on the surface of metal workpiece[10]. In each circumference, the number of cutting marks on the surface of workpiece can be express as:

\[ N = \frac{60f}{n} = \frac{f_z}{f_w} \]  

(4)

In Eq.4, \( f \) is relative frequency between knife tool and workpiece, \( n \) is rotation rate of workpiece, \( f_z \) is self-excitation frequency of the system, \( f_w \) is rotation frequency of workpiece.

When Eq.4 cannot be divided exactly, there will be remainders, so the Eq.4 can be rewritten as:

\[ N_0 + \varepsilon = \frac{60f}{n} = \frac{f_z}{f_w} \]  

(5)

In Eq.5, \( N_0 \) is integer part of relative vibration between knife tool and workpiece in each circumference, \( \varepsilon \) is remainder part, so \(-1<\varepsilon<1\). According to the research conducted by DAI Depei[11], the number of cutting marks on work piece is:

\[ N = m\left(N_0 + \varepsilon\right) = mN_0 - 1 \]  

(6)

In Eq.6, \( m \) is times of cutting marks between front and after knife, corresponding with remainder \( \varepsilon \).

Take high-speed railway as an example. The operation speed is \( v = 300km/h \). The radius of nominal rolling circle is \( R=0.43m \). The rotation frequency of wheel \( f_w \) is:

\[ f_w = \frac{v}{2\pi R} = 30.8Hz \]  

(7)

When there is only one circle leading to 20-edge polygon, according to Eq.4, it can be known that the self-excitation frequency is \( f_z=616Hz \). When there are \( m \) circles needed to form 20-order out-of-round wheel, according to Eq.5 and Eq.6, it can be known that \( m=3 \) or \( m=7 \). The corresponding self-excitation frequency of system is \( f_z=205.3Hz \) or \( f_z=88Hz \).

4. The Establishment of a Simulation Model

In order to study the influence of wheel polygon abrasion on vehicle and track system, a detailed dynamic model of vehicle track coupling system is established in this paper.

4.1. Vehicle Model

The degree of freedom considered in the vehicle multi-body system dynamic model is shown in Table 1. In order to ensure the accuracy of the simulation, the vehicle body hanging equipment such as the sewage tank, air conditioning equipment, etc. are taken into consideration in the model; the suspension system of the vehicle adopts the arm-axle positioning method with a vertical damper And steel springs; secondary suspension system considering the air spring model, anti-snake shock absorbers, two vertical shock absorbers and lateral shock absorbers, nonlinear lateral stop and anti-rolling torsion bar. At the same time, consider the body, frame, and wheelset as flexible structures, as shown in Fig.4.

4.2. Track Model

The track is simplified to an infinite Euler beam, which is considered as a continuous elastic discrete support point. The track is considered as a flexible structure while considering the transverse, vertical and torsional elastic vibrations of the track. The rails and rails are connected by damping and linear
springs in the vertical and horizontal directions, and the vertical, lateral, and torsional vibrations of the rails are considered. See Fig.5.

| Table 1. The degree of freedom in the vehicle system model |
|----------------------------------------------------------|
| the degree of freedom of vehicle system vibration        |
| Telescopic | Traverse | Floating | Roll | shake | nod |
| Car body | $X_o$ | $Y_o$ | $Z_o$ | $\varphi_o$ | $\psi_o$ | $\beta_o$ |
| Frame ($i = 1, 2$) | $X_{ni}$ | $Y_{ni}$ | $Z_{ni}$ | $\varphi_{ni}$ | $\psi_{ni}$ | $\beta_{ni}$ |
| Wheel set ($i = 1 \sim 4$) | $X_{ai}$ | $Y_{ai}$ | $Z_{ai}$ | $\varphi_{ai}$ | $\psi_{ai}$ | $\beta_{ai}$ |

4.3. Out-of-round Wheel Model

The non-circularity of the wheel is described by the harmonic function, and the wheel misalignment under different conditions can be simulated by changing the wheel Out-of-round order, amplitude, initial phase angle and wheel rotation angular velocity. The harmonic function is expressed as:

\[
\Delta R = A \cdot \sin(n \cdot \theta + \theta_0)
\]

\[
R(\theta) = R - \Delta R
\]

\[
\theta(t) = \theta(t-1) + \omega \Delta t
\]

In Eq8, $\Delta R$ denotes the wheel diameter difference of the non-circular wheel, $A$ denotes the non-circular wheel amplitude, $n$ denotes the order of the polygon, $\theta$ denotes the rotation angle of the wheel, $\theta_0$ denotes the initial phase angle, $R(\theta)$ denotes the wheel diameter, and $\omega$ denotes the wheel rotation angular speed.

5. The Impact of Wheel Misalignment on Vehicle Performance

Although there is disagreement about the mechanism of wheel non-round wear, there is a common understanding of the effects of wheel non-round wear. Wheel and rail impacts caused by out-of-round wheel wear can cause vehicle component failures, such as axle box bolt breakage and rim cracking, etc., as well as failure of lower rail components such as rail fatigue, fastener breakage, and rail foundation failure. This part analyzes the influence of wheel non-circular wave depth and wheel non-circular order on vehicle dynamic performance from the perspective of dynamics. It mainly includes wheel-rail vertical force, lateral force, wheel pair vertical acceleration and frame vertical acceleration.
5.1. Effect on Wheel-rail Vertical Force
(1) Effect of wheel non-circular order on wheel-rail vertical force

Set the vehicle wheel non-circular wave depth to 0.1mm. Fig.5 shows the regularity of the wheel-rail vertical force of wheel non-circular order (from 1 to 25).

![Figure 5. Effect of wheel non-circular order on vertical force of wheel-rail](image)

It can be seen from Fig.6 that when the wheel non-circular order is less than 5, the vertical force on the wheel rail is less affected, and when the order of wheels non-circular is between 6-9, the vertical force of the wheel rail increases steadily. When the wheel non-circular order is larger than 10, the vertical force of wheel and rail increases rapidly. From the perspective of vehicle operating speed, under the condition that the wheel non-circular order is the same, the higher the running speed of the vehicle, the greater the vertical force of the wheel and rail. When the operating speed is 200~350km/h, the vertical forces of the wheel and rail meet or exceed the upper limit of the vertical force of the wheel/rail in the 22nd, 18th, 15th, and 13th order respectively; in this case The wheels should be repaired in time to ensure the safety of the train.

![Figure 6. Effect of wheel non-circular wave depth on vertical force of wheel-rail](image)
It can be seen from Fig. 6 that the low-order non-circular wheel has a small influence on the vertical force of the wheel and rail, so this section only studies that the wheel with more than tenth non-circular order at a running speed of 300km/h, and the influence of wave depth to wheel rail vertical force. The effect of force is shown in Fig. 6.

It can be seen from Fig. 6 that when the vehicle speed is 300km/h, the train is safe when the wave depth is 0.01~0.04mm; but when the wave depth reaches 0.05mm and 0.06mm, the non-circular order corresponding to the 25th and the 23rd, the wheel rail force exceeds the 170kN limit. Comparing Fig. 5 with Fig. 6, it can be seen that when the vehicle runs at a low speed, the wheel has a darker wave, and the higher the order, the higher the wheel-rail force exceeds the standard. In order to give an early warning of the wheel's non-circular wheel wave depth, it is necessary to stipulate the wheel non-circle wave depth limit under different speed levels and different orders.

Table 2 shows the wave depth limits corresponding to the high-order non-circularity wheels at the four speed levels of the wheel.

| Operating speed (km/h) | Wheel non-circular order N |
|------------------------|-----------------------------|
|                        | 10  | 15  | 20  | 25  |
| 200                    | 0.5 | 0.25| 0.1 | 0.075|
| 250                    | 0.3 | 0.18| 0.075| 0.05 |
| 300                    | 0.22 | 0.09 | 0.05 | 0.032 |
| 350                    | 0.16 | 0.07 | 0.04 | 0.025 |

5.2. Impact on Wheel-rail Lateral Force

Set the vehicle operating speed to 300km/h, analyze the influence of different wave depths 0.1mm–0.6mm and the wheel non-circular order on the wheel-rail lateral force, see Fig. 7.

![Figure 7. The effect of wheel non-circular wave depth on the wheel rail lateral force](image)

It can be seen from Fig. 7 that as the depth of wave increases, the lateral force of the wheel and rail increases. When the wheel non-circular order is not less than 10, the wheel rail lateral force increases slowly. When the wheel non-circular order is not more than 10, the wheel rail lateral force increases rapidly.

5.3. Impact on Wheelset and Frame Vibration Acceleration

Set the non-circular wave depth of the wheel to 0.1mm, analyze the effect on the vertical acceleration
of the wheelset and the frame under the conditions of 150km/h and 300km/h of the 1st, 3rd, 11th, and 20th non-circular wear. See Fig.8 and Fig.9.

![Figure 8. Effect of wheel non-circular order on vertical acceleration of wheelset](image1)

![Figure 9. Effect of wheel non-circular order on the vertical acceleration of the frame](image2)

As can be seen from Fig.8, with the increase of the order of wheel non-circularity, the vertical acceleration of the wheelset gradually increases; for the wheel of the same order, the higher the speed, the greater the acceleration of the vertical vibration of the wheelset; Under the condition of the same speed level, the wheel non-circular wave depth is deeper and the vertical wheel vibration acceleration is greater. A similar pattern can be seen in Fig.9. However, in the same speed class, with the same wheel non-circular wave depth condition, the vertical vibration acceleration of the frame caused by the 11th non-circular order wheel is greater than that caused by 20th non-circular order wheel. The reason for the analysis is that the vibration frequency generated due to the 11th order non-circle stimulates the modality of the frame.

6. Conclusion
(1) This paper discusses the formation mechanism of polygonal wear of wheel from the reasons of constant wavelength mechanism, constant frequency mechanism and uneven initial hardness distribution; Judging from the phenomenon of out-of-round wear wheels of the multiple unit, the initial defects of the wheels or rails excite the natural modes of the wheel-rail system, causing high-frequency vibration, which is the main cause of wheel polygonalization.

(2) Establishing a full three-dimensional vehicle-rail coupled system dynamics model and fully considering the correction of wheel-rail normal force caused by wheelset elasticity; Using a simple harmonics to simulate the wheel polygon model, the analysis found that out-of-round wheel has a
greater effect not only in vertical and lateral wheel-rail forces, but also in vibration acceleration of wheelset and frame, the change law is more and more significant with the increase in the order and depth of the out-of-round wheel.

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