



Experimental analysis of the mechanism of high-order polygonal wear of wheels of a high-speed train*

Yue WU, Xing DU, He-ji ZHANG, Ze-feng WEN, Xue-song JIN^{†‡}

(State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China)

[†]E-mail: xsjin@home.swjtu.edu.cn

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Abstract: This paper presents a detailed investigation, via field experiment, into the mechanism of high-order polygonal wear of wheels of a new type of high-speed train. The investigation was carried out during the performance acceptance test of the train and its initial commercial operation. The investigation covered the performance acceptance test of 150 000 km and the commercial operation of about 150 000 km. In the performance acceptance test of the first stage of about 70 000 km, at 200–250 km/h with full loading and sometimes overloading by 30%, the serious polygonal wear of 23-order took place on all the wheels of the train, and was measured and analyzed in detail. All the polygonized wheels were re-profiled because the polygonal wear had caused strong vibration and damage to the train parts. After re-profiling, the vibration of the train and track and the wear status of the wheels were measured and analyzed at different test mileages according to the polygonal wear situation of the wheels. The measured vibration of the train includes the accelerations at different positions of a motor car and a trail car. The vibration modes of the key parts of the bogies of the two cars were calculated. Meanwhile, the track resonant frequencies were investigated at the site. The purpose of the above tests and analysis is try to find the frequency of work mode matching the passing frequency of the high-order wheel polygon. The present investigation shows that one of the working models causes the formation and development of the high-order wheel polygonal wear. The growth of this wear was effectively reduced through the frequent changing of the running speed of the train operating on the way back and forth every day.

Key words: High-speed train; Wheel; High-order polygonal wear; Field test; Model analysis; System resonance frequency
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1 Introduction

The polygonal wear of high-speed train wheels is very common in China's high-speed trains (Jin, 2014). The extensive field data measured show that the polygonal wear of wheels includes a main wavelength and several secondary wavelengths. The main wavelength wear means that uneven wear with corresponding wavelength has the greatest wear depth or the greatest contribution to the irregularity wear. The

wavelength of the polygonal wear or the wave number along each wheel circumference is different for different wheel diameters and different operating speeds. The influence of wheel polygonal wear is very similar to that of rail corrugation. It causes fierce vibration of wheel/rail and abnormal noise of trains, thus causing loosening and cracking of train/track parts, and increased noise inside and outside the train. At present, the understanding of these phenomena, including the mechanism of their occurrence and development, is not fully understood. The polygonal wear with only a wavelength around wheel circumference is called the polygonal wear of the first order, which is actually an eccentric wear. That with two equal wavelengths around the circumference is called the second order polygonal wear, or the elliptical

[‡] Corresponding author

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ORCID: Xue-song JIN, <http://orcid.org/0000-0003-3033-758X>

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wear, the three same wavelengths correspond to the third order polygonal wear, and so on.

In research on the noise of intercity trains conducted by Kaper (1988), it was found that the wheel polygonal wear phenomenon is a main cause of train running noise. At that time the wear was called wheel tread corrugation (Kaper, 1988; Feller and Walf, 1991; Kalousek and Johnson, 1992). From the beginning of the 1990s, some scholars and railway engineers started to investigate the mechanism of wheel polygonal wear development. Soua and Pascal (1995) developed a locomotive model to investigate the wear with the first, the second, and the fourth orders, and their conclusion was that the torsional vibration of the wheelset axle and the lateral movement of the wheelset are the main causes of the formation and development of polygonal wear.

In the study carried out by Brommundt (1997), a simple wheel/rail interaction model was established to investigate the development of wheel polygonal wear. The numerical result obtained indicates that the interaction of wheel out of roundness excitation and moment of inertia wheel increases the development of the wear. The higher the train running speed, the faster the wheel low-order polygonal wear.

Morys *et al.* (1995) developed a dynamics model of ICE-1 to investigate the mechanism of polygonal wear development of railway wheels. In their model, the wheels and brake discs of a wheelset were regarded as rigid bodies, the connections of which were replaced by 3D rotational spring-damper units which characterized the bending and torsional properties of the wheelset. The change of the wheel radius, with the shape of a sine wave on the wheel rolling circle, was used to describe the polygonal wear of the wheel. The track modeling adopted the moving supporters under rails and considered the rigid and flexible properties of the track. The FASTSIM (fast algorithm for the simplified theory of rolling contact) model was used to calculate the tangent forces between wheel and rail. A long-term wear model was developed to calculate the radius reduction of the wheel with increasing mileage. The calculated results showed that fluctuating vertical force of wheel/rail excited the bending resonant modes of the wheelset, which led to the situation where the lateral creep force of the wheel/rail varied periodically and the polygonal wear took place on the rolling circle of the wheel. The

passing frequency of the third order polygonal wear is quite close to the frequency of the bending mode of the wheelset. The third order wear developed fastest and the first order wear lowest. The second order wear evolved into the fourth order wear (Morys *et al.*, 1995; Morys and Kuntze, 1997; Morys, 1999).

Meinke and Meinke (1999) proposed a wheelset dynamics model to reproduce the initiation and development of wheel polygonal wear. The wheels and brake discs of the wheelset were also treated as rigid bodies and the axle was modeled using beam elements. This model had 40 degrees of freedom and changed the wheelset dynamics into the rotor-dynamics. It took account of the effect of gravity, rotational inertia, and gyroscopic moment of the wheelset system on the initiation and development of the wear. The numerical results showed that the radius difference of the left and right wheels exceed the limit stipulated in the request after the accumulative wear of a certain mileage even if a new wheelset with no defect was used (Meinke and Meinke, 1999).

Meywerk (1999) thought that the flexible deformations of wheelset and rails due to their interaction caused the initiation and development of wheel polygonal wear. He proposed a coupling dynamics model for elastic wheelset and elastic track to numerically simulate the formation of polygonal wear on the wheel tread. The numerical results showed that the greater was the polygon phase difference of the left and right wheels, the faster was the development of polygonal wear. The first and second bending modes of the wheelset played an important role in the initiation and development of the wear. Moreover, the vehicle sprung mass had an influence (Meywerk, 1999).

Nielsen and Johansson (2000) reviewed the literature on wheel polygonal wear. They systematically described the various forms of wheel defects, and summarized the dynamic models of wheel and rail and long-term wheel wear models. The cause and effect of the first to fifth order polygons were discussed. They proposed control measures for polygonal wear development and the rule for the profiling of polygonized wheels. The rule not only considers the wheel geometry shape in its roundness, but also requires a wheel/rail force limit (Nielsen and Johansson, 2000). Combining field tests with numerical simulations, Johansson and Nielsen (2003) investigated the effect of the wheel polygon on the wheel/rail

vertical force and the track vertical vibration response. The vertical wheel/rail force was measured using the strain gauges on the rim and the axle, and the sensors installed on the track under the condition that wheels had different polygons at different operation speeds. They found that most of the measured results on wheel/rail force from the fields were lower than the limit issued by Swedish Railway. The local defect with long wavelengths on the wheel tread led to the wheel/rail force exceeding its specified limit (Johansson and Nielsen, 2003).

Johansson and Andersson (2005) used the model developed by Morys *et al.* (1995) to calculate the development of the initial polygon measured from the new wheel. Through comparing the calculated developed polygon with its initial status, it was found that the polygonal wear of the 14th to the 20th orders develops fastest. The polygonal wear of the 5th to the 7th orders also increased. They used the fixed wavelength mechanism to explain the development of the initial polygon. The polygonal wear development of the 14th to the 20th orders was caused by the track anti-resonance of 165 Hz in the vertical direction. The formation of polygonal wear of the 5th to the 7th orders was related to the P2 (one of the low frequency impact forces between the wheel and rail) resonance of the vehicle-track system. The calculation assumed that the polygonal wear was caused by the wheel/rail dynamic interaction. Actually, they have the opinion that the polygonal wear formation of wheels was also dependent on other factors, such as plastic deformation, tread brake, traction control, and wheel material inhomogeneity (Johansson and Andersson, 2005).

Snyder *et al.* (2003) carried out the analysis based on the combination of the datum of the wheel impact load and out-of-roundness of wheels, measured from sites by the American Railway Union and the Transportation Technology Center, USA. The analysis shows that during braking brake shoe locking causes wheel spalling which is an important cause of polygonal wear. Thus, the use of disc braking systems decreases the polygonal wear rate. Another reason for wheel polygon generation is the phenomenon of wheel eccentricity that generates vibrations at high frequencies, and this influences the useful life of bearing boxes, wheelsets, and track parts. When the wheel operation time is over a specified maintenance period, polygonal wear develops quickly. Thus, the

maintenance of polygonized wheels should be carried out in a timely manner (Snyder *et al.*, 2003).

Mazilu *et al.* (2011) developed the coupling model of an elastic wheelset and a ballasted track to calculate the development of a 3-order polygon of wheel and some of the influencing factors. Using different models and test data, Barke and Chiu (2005) made a contrasting analysis on the effect of wheel/rail impact vibration caused by wheel polygon on the fatigue life of parts of railway vehicle and track. The optimal re-profiling criterion of polygonized wheels was proposed according to the fatigue limit of the parts (Mazilu *et al.*, 2011).

Jin *et al.* (2012) studied the mechanism of the 9th order polygonal wear of wheels of linear motor (LIM) trains operating on metro line 4 of Guangzhou, China. The investigation included the dynamical behavior measurement of train and track, model identification tests of parts of the train and track, and the model calculation of some parts. Through the detailed investigation it was found that the resonant frequency of the first wheelset bending matched the passing frequency of the 9th order wear. The resonance occurring in the first wheelset bending caused the period change of the lateral creepage and the forces between wheels/rails, and this was the root cause of the 9th order polygonal wear. The investigation showed that the depth of the polygonal wear increased as the mileage increased after wheel re-profiling. Meanwhile, it was found that the polygon of the 4th order caused by machine re-profiling disappeared with mileage increase after the re-profiling. It is proved that the initial polygon can be eliminated through the natural wear of wheel/rail in running if the passing frequency of the initial polygon is different from the excited resonant frequency of the wheel/rail (Jin *et al.*, 2012).

This paper conducts a detailed field investigation into the mechanism of high-order polygonal wear of wheels of a new type of high-speed train. The investigation covered a performance acceptance test distance of 150000 km and a commercial operation distance of about 150000 km. In the performance acceptance first stage test of more than 70000 km at 250 km/h with full loading and sometime overloading by 30%, it was found that the serious polygonal wear of 23-order took place on all the wheels of the train. The polygonal wear status of all the wheels was measured and analyzed in detail. All the polygonized

wheels were re-profiled because the polygonal wear was causing strong vibration and damage to the train parts. After re-profiling, the vibration of the train and track and the wear status of the wheels were measured and analyzed at different test mileages according to the polygonal wear situation of the wheels. The measured vibration of the train includes the accelerations at different positions of a motor car and a trail car. The resonant modes of the key parts of the bogies of the two cars were calculated. The track resonance modes were also tested at sites. The results of the tests and the analysis show the characteristics, and the growth rate of the polygonal wear of wheels is very much related to the train operation speed, the changing radii of the wheels, and some resonance excited in the bogies. The wheel eccentricity and the irregularities of the track can increase the growth rate of the wheel high-order polygonal wear, but are not the root causes of polygonal wear initiation. In the commercial operation range, quite often changing train speed or the fact that in operation trains have pit stops, can effectively suppress the development of the high-order wear.

2 Description of high-order out-of-roundness of wheels

Railway wheels will be out-of-round due to irregular accumulative wear or deformation along their circumferences. Wheel out-of-roundness includes many patterns, such as flats, eccentricities, polygons, and random irregularity. This study emphasizes the polygonal wear of wheels of high-speed trains which are very common in China now. The polygonal wear includes eccentric, elliptic, the polygonal wear of the n th order, and so on. Figs. 1a, 1b, and 1c show the polygonal wear of the first order, the sixth order, and the 23rd order, respectively.

Actually, the polygonal wear is quite often a combination of the polygonal wear of different orders. The radius wear of a worn wheel is defined as the difference between the minimum radius of the worn wheel and the radius at measuring point θ on the wheel tread, where θ is the arc coordinate of the wheel. The radius wear reads

$$Z_0(t) = \sum_{i=1}^N A_i \sin\left(i \frac{v}{R} t + \varphi_i\right), \quad (1)$$

where t is time, A_i is the amplitude of the polygonal wear of the i th order, v is the operating speed, R is the radius of the wheel, φ_i is its phase angle, N is the total number of polygons included in $Z_0(\theta)$ (irregularity between the wheel and the rail), and the subscript i indicates the polygon of the i th order.

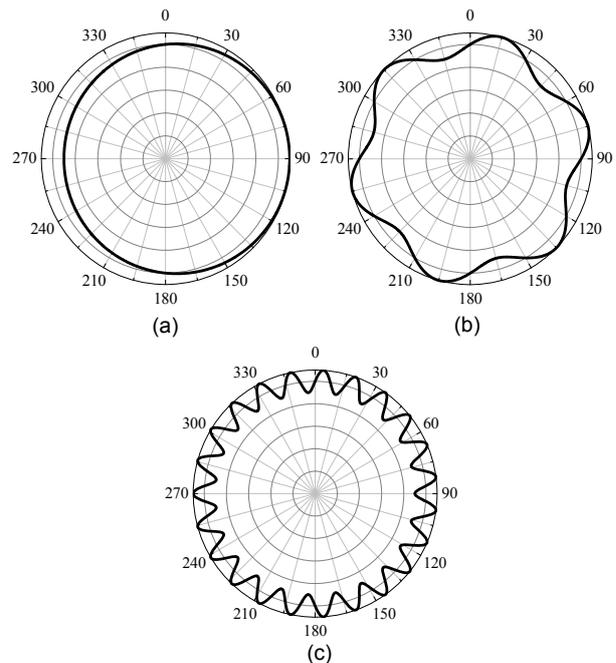


Fig. 1 Definition of wheel polygons described in polar coordinates: (a) the first order; (b) the sixth order; (c) the 23rd order (unit: $^{\circ}$)

Fig. 2 shows the test photo of the wheel roughness measurement. Fig. 3 shows the measured results of two wheelsets of the new type of high-speed train with test mileage of more than 70000 km. The maximum operation speed is 250 km/h. The diameter of new wheels is 860 mm. The test track is the slab track. The tested high-speed train consists of eight coaches, four trailer coaches, and four powered coaches. Figs. 3a and 3b indicate the results of a wheelset of a trailer car, and Figs. 3c and 3d indicate those of a powered car. Figs. 3a and 3c indicate the out-of-roundness of the wheels described in polar coordinates, and Figs. 3b and 3d show their irregularity spectra with different orders. The measured irregularities described in polar coordinates denote clearly the out-of-roundness of wheels, and the irregularity spectra vs. different orders indicate clearly the amplitudes of the polygonal wear of different orders. Those results show that the left and right

wheels of the same wheelset have differences in amplitudes and phases of polygonal wear, namely, the polygonal wear of the left and right wheels of the same axle are unsymmetrical. The polygonal wear occurring on the wheels of both trailer and powered cars indicates that wear is not related to the power system of the coaches, such as electrical motors and gear boxes.



Fig. 2 Test photo of wheel roughness measurement

Fig. 4 shows the measured spectra of out-of-roundness roughness of all wheels of the train before and after re-profiling. There are very similar characteristics in the polygonal wear of all wheels of the same high-speed train, the left and right wheels, and the wheels of the powered cars and trailer cars. Fig. 4 shows three main peaks at the first order, the 14th order, and the 23rd order, which are denoted by A, B, and C, respectively. The polygonal wear of this high-speed train in the present prescribed operation conditions mainly contains an eccentricity and two polygons of the 14th order and the 23rd order. The statistics of the measured results of all wheels of the whole train show that, with the amplitudes larger than 20 dB, 55% of the wheels have the first order polygonal wear, 30% have the 14th order polygonal wear, and near 100% have the 23rd order polygonal wear. When the speed is 250 km/h and the wheel diameter is 860 mm, the passing frequencies of the three polygons are about 26, 260, and 591 Hz, respectively. The amplitudes of the 23rd order polygon of most of the wheels are larger than those of the polygons of the first order and the 14th order. The re-profiling can effectively eliminate the high-order polygons, but the first order polygon or the eccentric wear remains, as

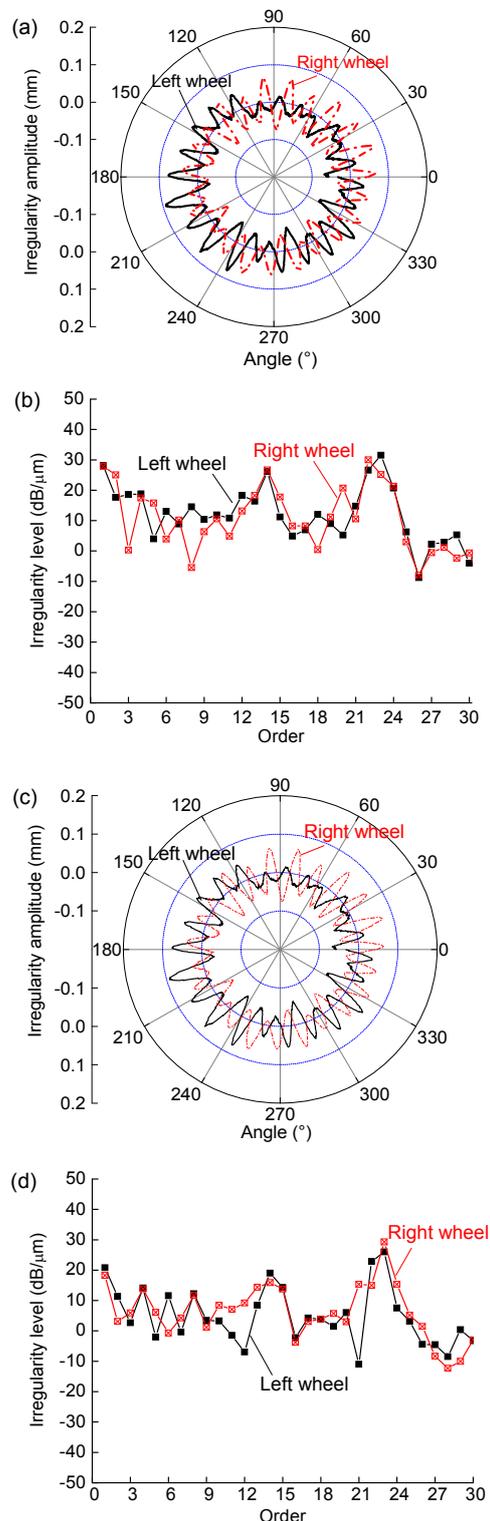


Fig. 3 Measured results of out-of-roundness of wheelsets of trailer and powered cars

(a) & (b) Out-of-roundness of the wheels of axle 2 of a trailer car described in polar coordinates and in irregularity spectra with different orders; (c) & (d) Out-of-roundness of the wheels of axle 3 of a powered car

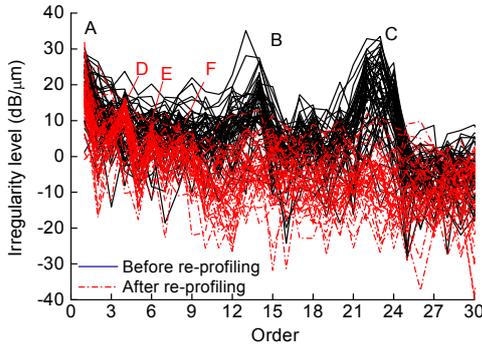


Fig. 4 Measured results of out-of-roundness of all the measured wheels of the same high-speed train

indicated by the dash-dotted lines at point A in Fig. 4. Moreover, the re-profiling makes the initial polygons of the 4th, 6th, and 8th orders, as indicated by D, E, and F in Fig. 4, respectively.

3 Analysis on development of high-order wheel out-of-roundness and its mechanism

3.1 Development of high-order wheel out-of-roundness

In the first stage operation test of more than 70000 km, the serious polygonal wear damaged some key parts of the train, and caused strong vibration and noise of the train and the track. All the worn wheels were re-profiled, and the spectra of their roundness after re-profiling are indicated by the dash-dotted lines in Fig. 4. After re-profiling the operational test continued, in which the vibration was measured of a power car and a trailer car, from the bearing boxes to the coach floors. The wear status of all the wheels was traced through site measurements. The test speed is 250 km/h.

Fig. 5 shows the results of out-of-roundness of the first wheelset of another trailer car before re-profiling and in the test period of 29000 km after re-profiling. Figs. 5a and 5b show the results for the left wheel, and Figs. 5c and 5d for the right wheel. The black line indicates the measured results of wheel out-of-roundness before re-profiling. The red, green, blue, and purple lines indicate the results with test mileages of 0, 11000, 20000, and 29000 km, respectively, after re-profiling. It is clear that the polygonal wear of eccentricity, the 14th order, and the 23rd order increases with test mileage after

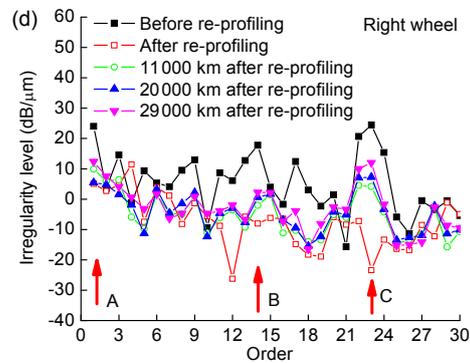
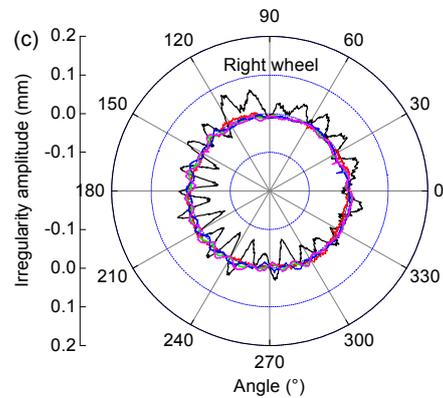
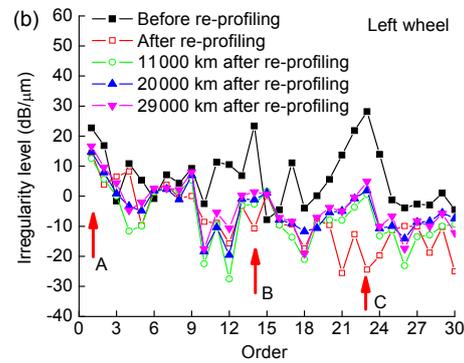
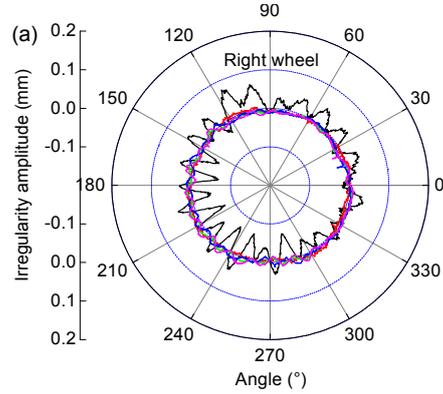


Fig. 5 Measured results of the first wheelset of another trailer car: (a) & (b) left wheel; (c) & (d) right wheel

re-profiling at 250 km/h, as indicated by arrows A, B, and C (Fig. 5). Every day, the train had two round trip tests with mileage of 4×270 km, and no stop in each round trip. Almost the same results were obtained for the wheels of the power cars, so the results are not shown.

3.2 Vibration and dynamic characteristics of vehicles

Fig. 6 shows the measured vertical accelerations at the bearing box, the bogie frame above the first primary suspension, and the outside and the inside of the carriage floor of the measured trailer car, in the test operation of 250 km/h after re-profiling. They are denoted by the black lines a, the red lines b, the blue lines c, and the green lines d, respectively. The results at every measuring point include the two sets of data sampled from two different sites at 250 km/h, on the same high-speed test track. Every group of lines of the same color has a good repeatability, which reflects the stability of the trailer structure behavior in the test. The variation of the curves in the red dashed line rectangular box shows some interesting things which are discussed as follows. (a) The accelerations of the bearing box and the bogie frame above the first primary suspension are quite close, as indicated by the black and red lines. This is similar for the lateral acceleration and on the power cars. Some of these results are not shown in this paper due to limitations of space. Results indicate that the first primary suspension is poor in its vibration isolation performance or the connection between the bogie and the bearing box has high coupling stiffness, such as a bad performance of damper and linker. (b) At about 590 Hz, the peaks of the accelerations stand out, which should not be related to the 23th polygon of wheel that was pared in re-profiling. It should be attributed to the resonance occurring in the bogie or the track or the wheel/rail system in the frequency range in the red dashed line box. The present work will carry out an investigation into the resonance at about 590 Hz from the bogie or the track system or their coupling system. (c) Near the red box, the curves present many spikes with nearly equal separation distance. These peaks are very marked from 500 Hz to 1000 Hz. The distance between neighboring peaks is about 26 Hz. It is just the passing frequency of the wheel eccentricity or the first order polygon at 250 km/h.

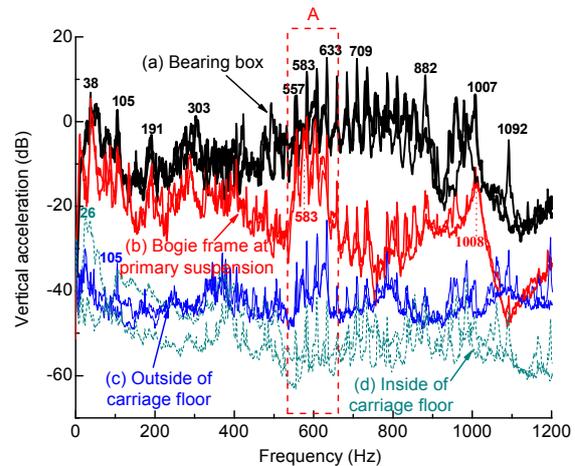


Fig. 6 Measured accelerations of the tested trailer car

An eccentric wheel rolling over a rail causes wheel/rail contact vibration, as described in Fig. 6. In such a situation, the normal force or the vertical force between wheel and rail fluctuates periodically. Its fluctuation period is 26 Hz, as indicated by the dashed curve in Fig. 7. The eccentric wheel rolling is an important excitation source to the train/track coupling system. The excitation of the eccentric wheel can cause the harmonic frequency vibration of the vehicle structure or the bogie system in the high frequency range, as indicated in Fig. 7. This can be explained clearly using the relevant vibration theory, which is omitted here. The harmonic frequency vibration includes the vibration components of modulation frequencies which are $N \times 26$ Hz, $N=1, 2, 3, \dots$. Namely, the passing frequency of the first order polygon of the wheel or the rotational frequency of the wheel is modulated. The harmonic frequency vibration contains the components of wide frequencies and so easily excites the resonances of the vehicle structure or the bogie system in an extensive frequency range. For example, the resonance of about 590 Hz is excited, which is related to the excitation of the eccentric wheel.

Fig. 8 shows the spectra of the measured vertical accelerations of the bearing box at mileages of 0, 20000, and 29000 km after re-profiling. The solid, dashed, and dotted curves indicate the results at 0, 20000, and 29000 km, respectively. It is clear that the peaks near 350 Hz and 590 Hz increase faster than those in other frequency ranges with the mileage increase. The polygonal wear of the 13th and 14th orders and the 23rd order increases with the mileage, as shown in Fig. 4.

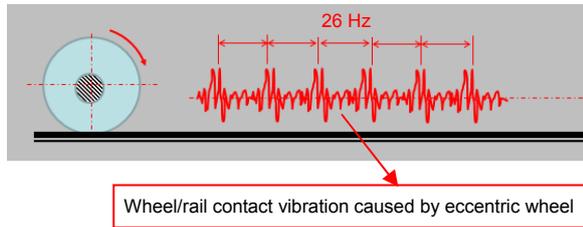


Fig. 7 Wheel/rail contact vibration caused by eccentric wheel

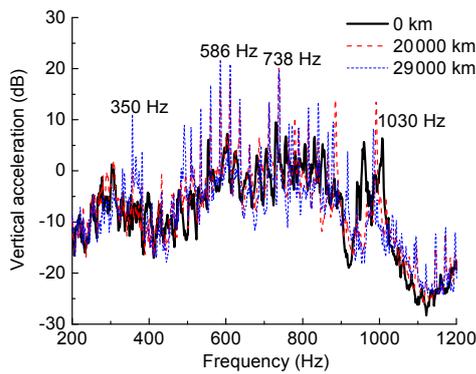
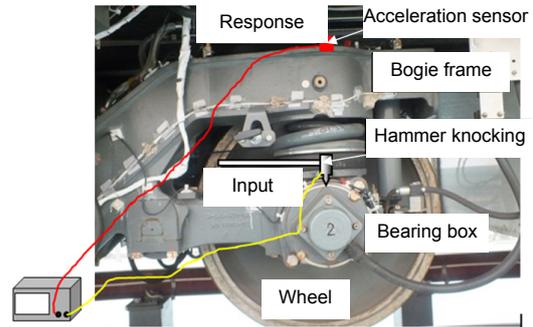
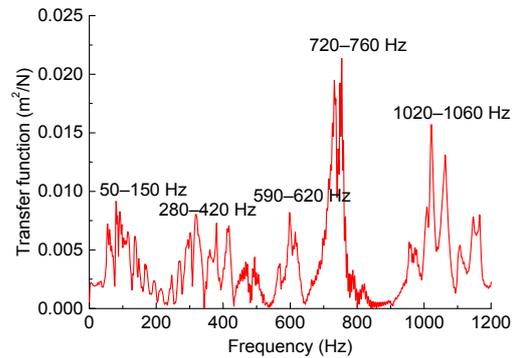


Fig. 8 Spectra of the measured accelerations of the bearing box at different mileages after re-profiling

In order to establish the dynamic characteristics of the bogie, a test of the transmission characteristics of the first-suspension was carried out. The acceleration sensor was installed on the bogie frame over the bearing box to measure the vertical acceleration of the frame, and the force hammer was used to knock the bearing box in the vertical direction, as indicated in Fig. 9a. Fig. 9b illustrates the transfer function of the suspension system in the vertical direction. Fig. 9b shows the high amplitudes of the transfer function in the frequency ranges of 50–150 Hz, 280–420 Hz, 590–620 Hz, 720–760 Hz, and 1020–1060 Hz within the range of 0–1200 Hz. The passing frequency of the 23rd order polygon drops into the range of 590–620 Hz which is the range of interest in this paper. The bogie system has dense resonance frequencies in the analyzed frequency range. Fig. 10 shows the mode shapes of the bogie frame and the wheelset of the trailer car. Fig. 10a indicates the modal shape of the bogie frame corresponding to 589 Hz. The modal shape characterizes the large local deformations at the four corner ends of the frame, which are serious distortions. Fig. 10b indicates the modal shape of the wheelset corresponding to 601 Hz. The resonant frequencies of the two key parts of the bogie system

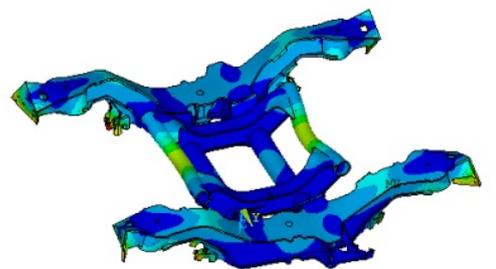


(a)

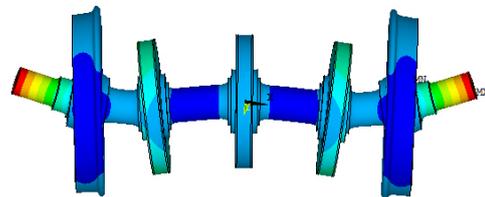


(b)

Fig. 9 Test of transfer function of the first suspension of the trailer car (a) and the transfer function measured (b)



(a)



(b)

Fig. 10 Modal shapes of the bogie frame (a) and the wheelset (b) of the trailer car

shown in Fig. 10 or their neighboring resonant frequencies match the passing frequency of the 23rd order polygon. Moreover, their contributions to the dynamical responses of the bogie frame and the

bearing box are significant when the train is running, as shown in Figs. 6 and 8.

3.3 Dynamic characteristics and response of track

The roughness of the track has a great influence on the dynamical response of the train and track and the wheel wear including polygonal wear. The rail corrugation equipment was used to measure the roughness of the rails on which the dynamical tests were carried out. Fig. 11a is a photo showing the roughness of the rail soon after the grinding of a new rail and indicates the measured roughness spectra of the low and high rails and the roughness level of ISO3095. Fig. 11b shows that the roughness level exceeds the level of ISO3095 in three ranges, i.e., wavelength larger than 350 mm, wavelength less than 35 mm, and wavelength between 63 mm and 80 mm. Especially in between 63 mm and 80 mm, a peak in the roughness spectra indicates the initial corrugation caused by grinding. The average passing frequencies of the initial corrugation wavelength are 788 Hz and 985 Hz at 200 km/h and 250 km/h, respectively. These frequencies of the roughness excitation do not

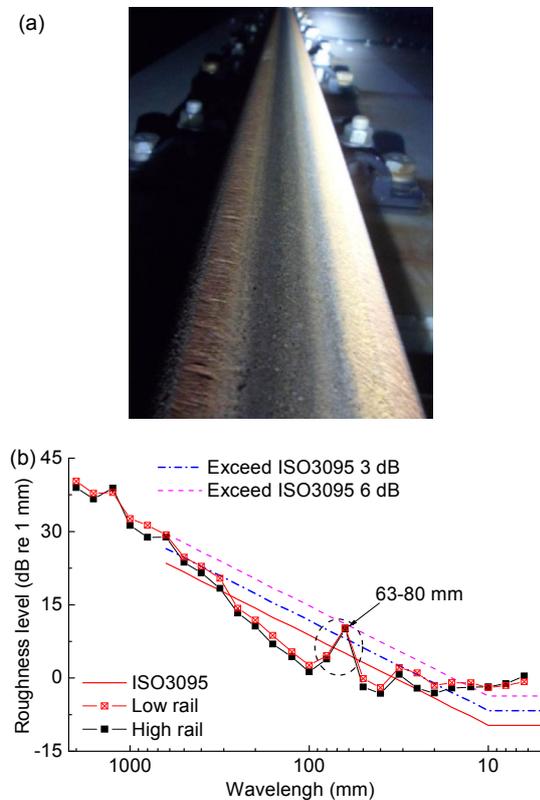


Fig. 11 Rail roughness photo (a) and the measured roughness spectra (b)

match the passing frequency of the 23rd order polygon at 250 km/h. Thus, the generation of the 23rd order polygon is not related to the initial corrugation directly. However, the corrugation with high passing frequencies or roughness at a high level can excite the resonances of the bogie and the track, even exciting the resonance with the same frequency as the passing frequency of the polygonal wear.

The high-speed operation of the train can also excite the resonance of the train and the track, and therefore can easily lead to polygonal wear on wheels. Therefore, it is very important to know well the resonant frequencies of the track. Fig. 12 shows the measurement of the track frequency response function, the results, and the calculated mode shapes of a rail coupling with slabs. The force hammer was used to knock the rail in different directions, and the acceleration sensors were used to measure the

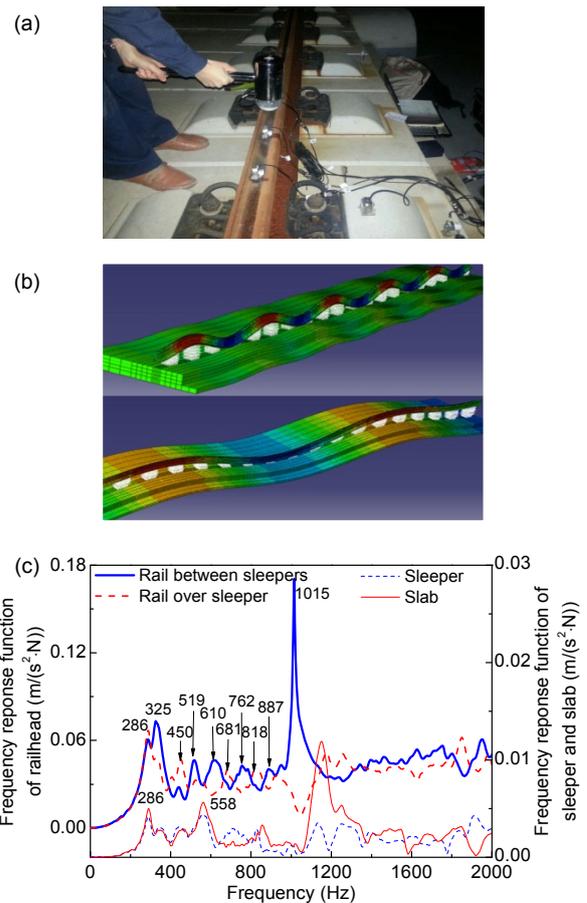


Fig. 12 Photo of the measurement of the track frequency response function (a), the calculated mode shapes of a rail coupling with slabs (b), and the frequency response functions of the railhead, sleeper, and slab (c)

accelerations at different points of the rail, sleeper, and the slab in different directions. Fig. 12a is the photo of the site measurement. Fig. 12b indicates the calculated mode shapes of a rail coupling with slabs. For the two modal shapes, the picture indicates that the rail vibrates at relatively high frequencies with respect to the slabs and the low one denotes that the rail and the slab vibrate together at relatively low frequencies. Fig. 12c indicates the frequency response functions of the railhead, sleeper, and slab. In Fig. 12c, the peak at 1015 Hz is the pin-pin resonant peak of the track, the peaks near 300 Hz denote that the rail and the slab vibrate together at relatively low frequencies, and peaks in the range of 400–800 Hz illustrate the rail vibrating at relatively high frequencies with respect to the slab. The peaks near 590 Hz are non-significant. The results for the track do not show the characteristics of the track having an influence on the generation of high-order polygons of train wheels.

Fig. 13 shows the dynamical responses of the track when the train operates at 200 km/h after re-profiling of the wheels. Fig. 13a indicates the time

history of acceleration response of the rail midpoint between neighboring sleepers. The acceleration amplitude caused by the first powered car passing is the largest. Fig. 13b is the spectrum of the acceleration shown in Fig. 13a. The highest peak at 750 Hz is caused by the initial rail corrugation. There are no prominent peaks near 590 Hz that is the passing frequency of the 23rd order polygon at 250 km/h. Therefore, there is not sufficient evidence to say that the resonance occurring on the track at or near the passing frequency of the 23rd order polygon causes the initiation and development of the 23rd order polygon. It is very interesting that the acceleration spectrum vs. frequency is very similar to the frequency response function of the track shown in Fig. 12, namely, the track has a sensitive response to the excitation at frequencies larger than 260 Hz at the wheel/rail contact point. Due to the limitation of site test conditions, the results at 250 km/h were not measured. However, the measured results at 200 km/h show that the track does not have a sensitive resonance frequency of about 590 Hz that can cause initiation of the 23rd order polygonal wear on wheels.

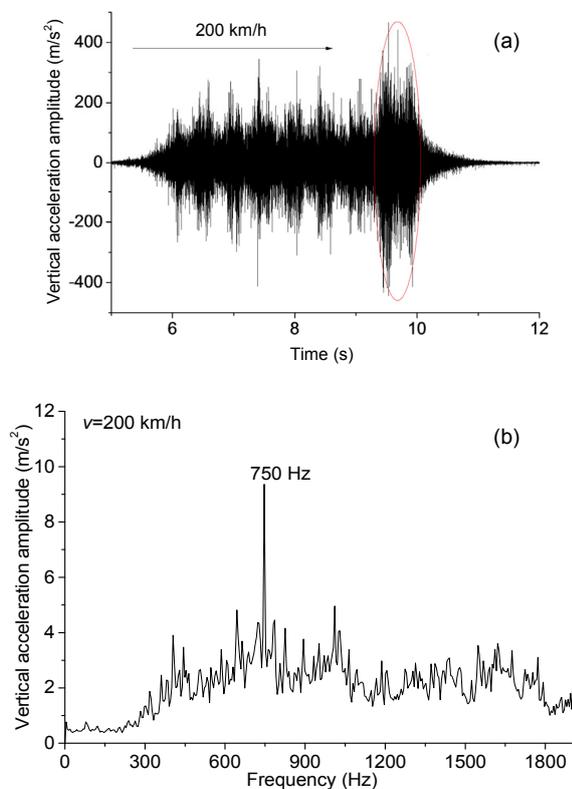


Fig. 13 Dynamical responses of the track when the train is operating at 200 km/h after re-profiling of the wheels

4 Discussion on necessary conditions for polygonal wear generation of wheels

An approach using an adaptive design method to study the tolerance fluctuation problem in the machining of precision parts has been developed and is presented. The status and trends of tolerance fluctuations of parts are calculated by the HMM (a doubly stochastic process on the basis of the Markov chain) based on the monitoring data of the press equipment. There are some meaningful observations in this study which are presented as follows.

The necessary conditions for wheel/rail “wear-type” corrugation generation are a combination of factors (Jin, 2014): (1) periodically fluctuating normal (or tangent) load of wheel/rail and the existing creepage (or slip), (2) the existing load of wheel/rail and periodically fluctuating creepage (or slip), and (3) periodically fluctuating of both. The resonance of the coupling system of train and track can cause the load and creepage of wheel/rail to fluctuate periodically. The basic condition for wheel out-of-roundness (OOR) generation is more rigorous than that for rail corrugation formation, because the rail is infinitely

long and the corrugation on it in development can extend infinitely along with its track. However, the perimeter of the wheel rolling circle is finite. The referenced start point of the uneven wear on the wheel running surface in each cycle during the wheel rolling has a different phase if the perimeter cannot be divided exactly by the wavelength of the uneven wear. If so, the uneven wear or called wheel corrugation or wheel OOR develops very slowly. In another case, the wheel OOR can develop very quickly. This case indicates that the perimeter of a wheel can be divided exactly or approximately by such a wavelength λ . λ is obtained by

$$\lambda = v/f, \quad (2)$$

where f is the excited resonant frequency of the bogie, as described in Fig. 14. If the excited resonances contain several frequencies, f_i ($i=1, 2, \dots, N$), and they satisfy the condition that the perimeter of the rolling circle can be divided by using $\lambda_i = v/f_i$, the polygonal wear of the wheel contains several polygons.

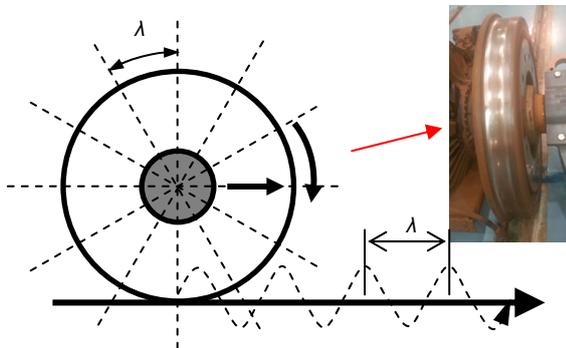


Fig. 14 Description of basic condition for wheel OOR generation

According to the field test analysis, the following situation can cause strong vibration and noise of the high-speed train/track coupling system in operation. This situation indicates that such polygonal wear of the wheel contains a single wavelength of a high-order (similar to a short wavelength) or several wavelengths, one of which with high-order dominates in the uneven wear depth, as shown in Figs. 3 and 4. So it is very important that the development rate of such wear should be kept under strict control. The key to doing so is to suppress the growth of that polygon of high-order which has a dominant wave depth. Figs. 3 and 4 show that such a polygon has 23 orders,

wavelength of 118 mm, and wave depth of 30 dB/mm (0.03 mm). The frequency of wheel/rail excitation caused by such a polygon is about 590 Hz at 250 km/h. This frequency is just the resonant frequency of the bogie frame, as discussed before. Thus, it is necessary to break the condition for initiation and quick development of the 23rd order wheel polygon to control wheel polygonal wear. To break the condition means to change the operation speed v , or the excited resonant frequency f , or change the wheel perimeter, according to Eq. (1). However, it is not easy to change the resonance frequencies of the bogie causing the generation of wheel polygons, because changing them would require a change in the structural geometry parameters of the bogie, and this can cause other problems, such as instability, noise, lack of strength, and fatigue of bogie. Moreover, the resonant frequencies of the bogie are very thickly dotted and the frequencies excited are different at different operational conditions. To change the frequencies by changing the bogie structure parameters is impracticable. The perimeter or diameter of the wheel decreases with its operating mileage increase. This is due to wear and re-profiling. The limitation of its perimeter or diameter is also strictly controlled according to the technical specification of wheel use. It is not infeasible by changing the perimeter or diameter of wheel to suppress its polygon increase. Frequently changing the operating speed v is probably the best choice to suppress the growth of the wheel polygon, and this has been verified in practice.

5 Effect of operating speed on generation of wheel OOR

After the performance acceptance test of the first stage of more than 70 000 km at 250 km/h, this train was moved to another high-speed line to continue its performance acceptance test. The test mileage increased from 34 000 km to 71 000 km. The test line section is part of a high-speed line from Harbin to Dalian in China. The test journey to and fro is 600 km. There is no stop in the round trip. The test speed is 200 km/h. The train has a full loading. Fig. 15 indicates the results of out-of-roundness of the left wheel of axle 2 of trailer 2. Fig. 15a illustrates the results described in polar coordinates, and Fig. 15b the spectra of the results that are shown in Fig. 15a. It is

clear that the 23rd order and the 14th order polygons developed in the mileage of 29 000 km after re-profiling. However, at the mileages of 46 000 km and 64 000 km after re-profiling, or after the test mileage of 34 000 km (no measured results here), the increase of the polygons of the 14th order and the 23rd order stopped, as indicated by points A and B in Fig. 15b, respectively. The results of the other wheels are similar and not shown.

Fig. 16 indicates the spectra of the accelerations of the bearing box and the bogie frame above the bearing box at 200 km/h and mileage of 46 000 km after re-profiling. The black lines denote the accelerations at the bearing box of axle 2 of trailer 2, and the red lines illustrate the results of the bogie frame above the bearing box. Every measuring point has two sample data which are measured at different times. The results of each measuring point have good repeatability. Carefully comparing the results to the corresponding results in Figs. 6 and 8, it is found that the acceleration peaks near 590 Hz go down but the peaks in the range of 440–470 Hz go up. The peaks in the range of 440–470 Hz are just caused by the 23rd order polygon (23rd OOR) excitation at 200 km/h, already generated in the test from the re-profiling to the mileage of 34 000 km at 250 km/h, as shown in Fig. 5. At 200 km/h the passing frequency of the 23th order polygon is about 470 Hz. The peak at 281 Hz is clearly caused by the 14th polygon (14th OOR) excitation. The 14th polygon was also generated in the test of 34 000 km mileage after re-profiling (Fig. 5). The peaks near 590 Hz and 700 Hz are just the resonant peaks of the bogie in operation at 200 km/h, as discussed before. According to the basic condition for the polygonal wear generation, the excited resonance at about 590 Hz can lead to generation of the 29th or 30th order polygon under the condition of 200 km/h operating speed and 860 mm diameter wheel. Actually, in the test of 34 000–71 000 km at 200 km/h, the 29th or 30th order polygon is generated, as shown in Fig. 15b, but its amplitude is quite small, about 10 dB (0.003 mm). Its wavelength is about 91 mm.

Thus, changing the test speed from 250 km/h to 200 km/h effectively stopped the development of the severe 23rd order polygon. The polygonal wear could be eliminated with the operational mileage increase. Changing speed can change the characteristics (wavelength and depth) and the growth rate of the polygonal wear of wheel.

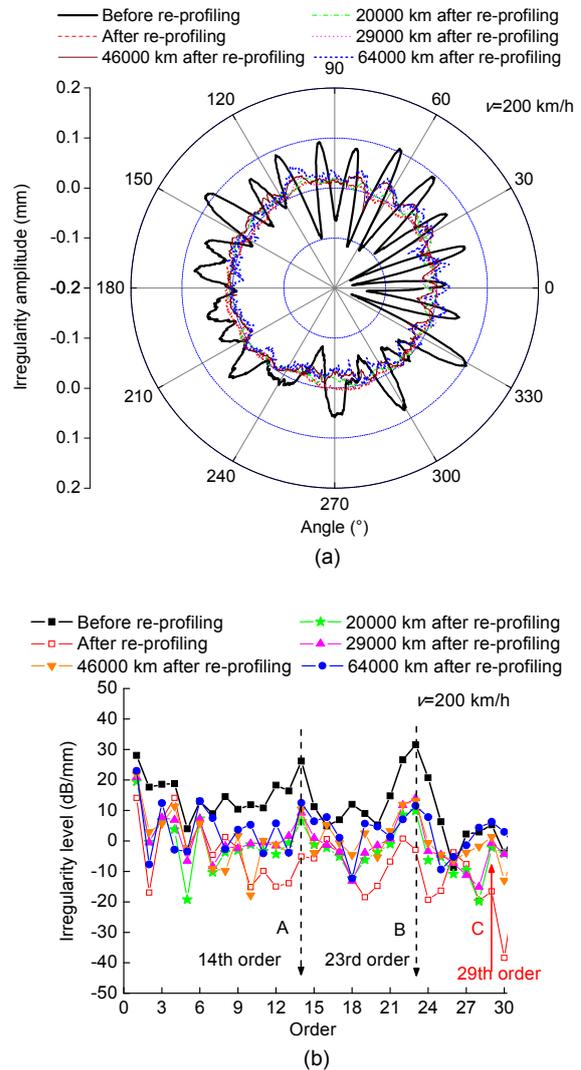


Fig. 15 Out-of-roundness of the left wheel of axle 2 of trailer 2: (a) results described in polar coordinates; (b) spectra of the results

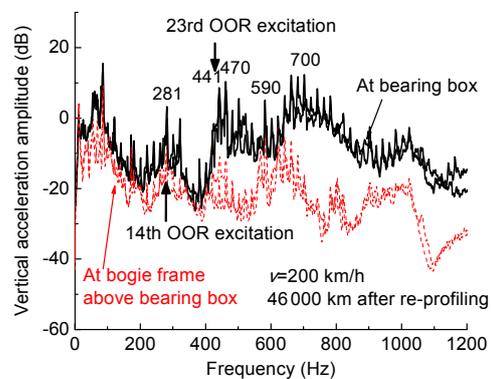


Fig. 16 Spectra of the accelerations of the bearing box and the bogie frame above the bearing box of axle 2 of trailer 2

The following is another successful example in suppressing the polygonal wear development by changing operating speed. After the test of 71 000 km at 200–250 km/h, this new type of high-speed train was put into commercial operation. The distance from the origin station to the terminal station is 207 km. There are three stops between the two terminals. The maximum operating speed is 250 km/h. The average speed of the journey there and back is about 170 km/h. All wheels were profiled again before this test. Fig. 17 indicates the distribution of train operating speed in the journey there and back. This will also be a normal operating speed profile in the future. It is different from the test speed distributions discussed above. The test speeds are invariable in the journeys there and back.

Fig. 18 illustrates the measured irregularity levels of all the wheels of the train vs. their orders. Compared to the results shown in Fig. 3, these results do not present prominent peaks at the 14th order and the 23rd order. This situation is very normal wear, which is just as expected. Thus, quite often changing operating speed of high-speed trains can effectively suppress the polygonal wear of their wheels, and is to the benefit of the even wear formation along the rolling circles of the wheels.

6 Conclusions

The polygonal wear of high-speed wheels is very common in China's high-speed train operation. The high-order polygons in the uneven wear develop very quickly in certain size ranges of wheel diameter. In high-speed operation, the high-order polygons cause strong vibration and noise of the train/track coupling system and the fracture of some key parts, and are a potential threat to operational safety. This paper conducted a detailed investigation into the mechanism of high-order polygonal wear of wheels of a high-speed train through field tests and analysis. The field tests were carried out in the performance acceptance test of a high-speed train and the initial phase of its commercial operation. The conclusions are as follows:

1. The mechanism of polygonal wear of wheels of a high-speed train can be attributed to the excited resonance of the train/track coupling system in operation, and its root cause is the excited resonance of the

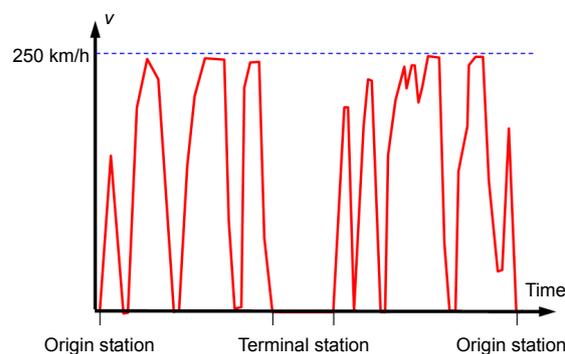


Fig. 17 Distribution of train operation speed in the journey there and back

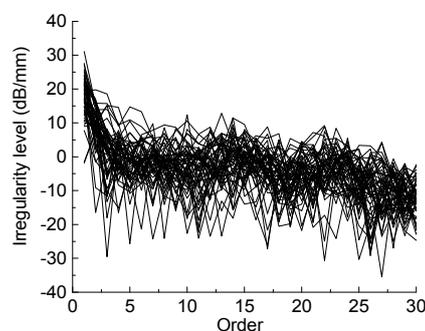


Fig. 18 Out-of-roundness of all wheels of the same high-speed train

bogie of the train in high-speed operation and under the extensive excitation of wheel/rail, such as rail welding, normal irregularities of the track, initial rail corrugation caused by initial grinding of new rails, and initial defects caused by wheel processing (eccentricities of mass and roundness).

2. The basic condition for the polygon generation of wheels depends on the operating speed, the excited resonant frequency, and the current perimeter or diameter of wheel. If the perimeter of wheel can be approximately divided by the wavelength corresponding to the excited resonant frequency of the bogie, the polygonal wear easily generates and develops quickly. The wavelength is obtained by dividing the operation speed by the frequency of the excited resonance.

3. Changing the operating speed can easily break the basic condition for polygon generation of wheels and effectively suppress the growth of polygonal wear. However, it is not easy to change the resonant frequencies by changing the structural parameters of the bogie or the diameters of the wheels due to the

decrease of the diameters with the mileage increase. Moreover, the diameters of the wheels are strictly under control during the operation and maintenance of trains.

References

- Barke, D.W., Chiu, W.K., 2005. A review of the effects of out-of-round wheels on track and vehicle components. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **219**(3): 151-175.
<http://dx.doi.org/10.1243/095440905X8853>
- Brommundt, E., 1997. A simple mechanism for the polygonalization of railway wheels by wear. *Mechanics Research Communications*, **24**(4):435-442.
[http://dx.doi.org/10.1016/S0093-6413\(97\)00047-5](http://dx.doi.org/10.1016/S0093-6413(97)00047-5)
- Feller, H.G., Walf, K., 1991. Surface analysis of corrugated wheel treads. *Wear*, **144**(1-2):153-161.
[http://dx.doi.org/10.1016/0043-1648\(91\)90012-J](http://dx.doi.org/10.1016/0043-1648(91)90012-J)
- Jin, X.S., 2014. Some key problems faced in high-speed train operation. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, **15**(12):936-945.
<http://dx.doi.org/10.1631/jzus.A1400338>
- Jin, X.S., Wu, L., Fang, J.Y., et al., 2012. An investigation into the mechanism of the polygonal wear of metro train wheels and its effect on the dynamic behaviour of a wheel/rail system. *Vehicle System Dynamics*, **50**(12): 1817-1834.
<http://dx.doi.org/10.1080/00423114.2012.695022>
- Johansson, A., Nielsen, J.C.O., 2003. Out-of-round railway wheels—wheel-rail contact forces and track response derived from field tests and numerical simulations. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **217**(2):135-146.
<http://dx.doi.org/10.1243/095440903765762878>
- Johansson, A., Andersson, C., 2005. Out-of-round railway wheels—a study of wheel polygonalization through simulation of three-dimensional wheel-rail interaction and wear. *Vehicle System Dynamics*, **43**(8):539-559.
<http://dx.doi.org/10.1080/00423110500184649>
- Kalousek, J., Johnson, K.L., 1992. An investigation of short pitch wheel and rail corrugations on the Vancouver mass transit system. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **206**(2):127-135.
http://dx.doi.org/10.1243/pime_proc_1992_206_226_02
- Kaper, H.P., 1988. Wheel corrugation on Netherlands railway (NS): origin and effects of 'polygonization' in particular. *Journal of Sound and Vibration*, **120**(2):267-274.
[http://dx.doi.org/10.1016/0022-460X\(88\)90434-8](http://dx.doi.org/10.1016/0022-460X(88)90434-8)
- Mazilu, T., Dumitriu, M., Tudorache, C., et al., 2011. Wheel/rail interaction due to the polygonal wheel. *UPB Scientific Bulletin Series D: Mechanical Engineering*, **73**(3):95-108.
- Meinke, P., Meinke, S., 1999. Polygonalization of wheel treads caused by static and dynamic imbalances. *Journal of Sound and Vibration*, **227**(5):979-986.

- <http://dx.doi.org/10.1006/jsvi.1999.2590>
- Meywerk, M., 1999. Polygonalization of railway wheels. *Archive of Applied Mechanics*, **69**(2):105-120.
<http://dx.doi.org/10.1007/s004190050208>
- Morys, B., 1999. Enlargement of out-of-round wheel profiles on high speed trains. *Journal of Sound and Vibration*, **227**(5):965-978.
<http://dx.doi.org/10.1006/jsvi.1999.2055>
- Morys, B., Kuntze, H.B., 1997. Simulation analysis and active compensation of the out-of-round phenomena at wheels of high speed trains. *Proceedings of World Congress on Railway Research*, p.95-105.
- Morys, B., Kuntze, H.B., Hirsch, U., 1995. Investigation of origin and enlargement of out-of-round phenomena in high speed ICE-wheels. *Proceedings of the 10th European ADAMS Users' Conference*.
- Nielsen, J.C.O., Johansson, A., 2000. Out-of-round railway wheels—a literature survey. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **214**(2):79-91.
<http://dx.doi.org/10.1243/0954409001531351>
- Snyder, T., Stone, D.H., Kristan, J., 2003. Wheel flat and out-of-round formation and growth. *Proceedings of the IEEE/ASME Joint Rail Conference*, p.143-148.
<http://dx.doi.org/10.1109/RRCON.2003.1204660>
- Soua, B., Pascal, J.P., 1995. Computation of the 3D Wear of the Wheels in a High Speed Bogie. Report INRETS-LIN, Arcueil, France.

中文概要

题目: 高速列车高阶车轮多边形磨耗机理的试验研究

目的: 通过试验研究, 对高速列车车轮多边形磨耗机理进行初步探究。

创新点: 以试验方法为基础, 跟踪调查车轮多边形磨耗的发展规律, 然后分别对轨道系统和车辆系统开展现场试验, 对导致车轮发生多边形磨耗的因素进行排查, 探明了车轮多边形磨耗的机理。

方法: 1. 进行车轮多边形磨耗跟踪测试; 2. 进行轨道结构模态特性测试、钢轨波磨测试和轨道振动响应测试; 3. 进行转向架模态特性仿真研究、悬挂系统隔振特性测试以及车辆振动特性跟踪测试。

结论: 1. 列车运行时, 车轮受到周期性激励作用会发生多边形磨耗, 且当激励波长整分车轮周长时, 多边形磨耗发展迅速; 2. 作为主要激励源, 轮轨接触表面出现的车轮偏心、钢轨表面不平顺、轨下支承不均匀、钢轨接头和道岔等激发了转向架系统在 550~600 Hz 频段内的模态耦合共振, 从而导致了车轮多边形磨耗的产生; 3. 变速运行可以有效地控制车轮多边形磨耗的产生与发展。

关键词: 高速列车; 车轮多边形磨耗; 机理; 试验研究; 模态分析; 系统共振频率