

Investigation on influencing factors of wheel polygonization of a plateau high-speed EMU train

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Abstract

Purpose – This study aims to investigate the cause of high-order wheel polygonization in a plateau high-speed electric multiple unit (EMU) train.

Design/methodology/approach – A series of field tests were conducted to measure the vibration accelerations of the axle box and bogie when the wheels of the EMU train passed through tracks with normal rail roughness after re-profiling. Additionally, the dynamic characteristics of the track, wheelset and bogie were also measured. These measurements provided insights into the mechanisms that lead to wheel polygonization.

Findings – The results of the field tests indicate that wheel polygonal wear in the EMU train primarily exhibits 14–16 and 25–27 harmonic orders. The passing frequencies of wheel polygonization were approximately 283–323 Hz and 505–545 Hz, which closely match the dominated frequencies of axle box and bogie vibrations. These findings suggest that the fixed-frequency vibrations originate from the natural modes of the wheelset and bogie, which can be excited by wheel/rail irregularities.

Originality/value – The study provides novel insights into the mechanisms of high-order wheel polygonization in plateau high-speed EMU trains. Further, the results indicate that operating the EMU train on mixed lines at variable speeds could potentially mitigate high-order polygonal wear, providing practical value for improving the safety, performance and maintenance efficiency of high-speed EMU trains.

Keywords Wheel polygonization, High-speed EMU train, Modal analysis, Field tests

Paper type Research paper

1. Introduction

Wheel polygonal wear is a type of wave-shaped wear characterized by high and low undulations of the wheel material along the running surface and is common in high-speed trains, locomotives and metro trains (Tao, Wen, Jin, & Yang, 2020). Wheel polygonal wear can cause abnormal vibration and noise of the wheel–rail system (Zhang *et al.*, 2014; Cai *et al.*, 2021) and lead to premature failure of vehicle and rail components (Zhang *et al.*, 2022; Kang, Chen, Zhu, Ren, & Dai, 2022), which directly results in economic losses. In addition, it can also seriously affect the operational efficiency, reduce the riding comfort and even jeopardize the operational safety of the vehicle. Wheel polygonal wear has attracted the attention of engineers and related researchers and has become a research focus in the railway field.

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In recent years, the phenomenon of wheel polygonization has become common in Chinese high-speed trains (Jin, 2014; Zhai, Jin, Wen, & Zhao, 2020). High-order wheel polygonization (with 14–16 and 25–27 harmonic orders) occurred after a plateau high-speed electric multiple unit (EMU) was put into operation for four months, resulting in noise and component failure of the vehicle. The plateau high-speed EMU runs on the Lan-Xin high-speed line, where the operating environment of the high-speed train is different from other types of high-speed trains in China. The line is located in the northwestern area of China and stretches across the three provinces of Xinjiang, Qinghai and Gansu. It starts in Lanzhou city and ends in Urumchi city, as shown in Figure 1. Along the route, there are severe cold, high temperature, strong wind, sand and long distances. There are 150 days a year when the operating weather is winter, with a minimum temperature of about -41.5°C . The high-speed line is about 1,776 km long and covers a large wind and sand area of about 410 km.

Wheel high-order polygonal wear has also been observed in other Chinese high-speed trains. There are three main explanations for the mechanism of wheel polygonal wear on high-speed trains in China: coupling resonance of the bogie system, local bending vibration of the rail between the front and rear wheelsets of the bogie and frictional self-excited vibration of the wheelset-track system. All these three explanations fall into the category of fixed-frequency mechanisms. Wu, Du, Zhang, Wen, and Jin (2017) investigated the mechanism of polygonal wheel wear with 14th and 23rd harmonic orders for a high-speed train operating at a nominal speed of 250 km/h. They found that the excited resonance of the bogie of the train in high-speed operation mainly contributes to the formation of wheel polygonal wear by using the field test. For a type of high-speed vehicle with an operating speed of about 300 km/h, the wheel polygonal wear exhibits the distribution of roughness in the 17th to 19th harmonic order. Their passing frequencies of about 540–600 Hz correspond to the bending modes of the rail (Wu Wu, Rakheja, Wu *et al.*, 2019; Wu, Rakheja, Cai *et al.*, 2019). Through polygonal wear simulation, Cai *et al.* (2019) found that the 20th-order polygon is related to the local third-order bending vibration of the rail at about 650 Hz. They believe that the growth of a certain order polygon depends not only on the wear depth but also on the phase difference between the

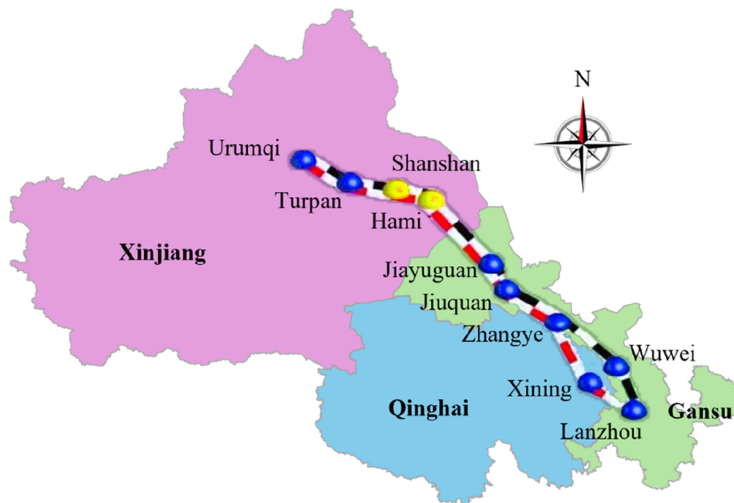


Figure 1.
Map for Lan-Xin high-speed line

Source(s): Authors' own work

wear depth and the initial wheel polygon. If the phase difference is between 90° and 270° , the wear of the order polygon will increase and the closer the phase difference is to 180° , the faster the growth. However, this vibration frequency was not confirmed by actual measured vibration data of the rail. Based on the theory of frictional self-excited vibration, [Zhu, Xie, Zhang, Chen, and Tuo \(2023\)](#) and [Wu *et al.* \(2023\)](#) found that the unstable vibration of the wheelset-track system at around 650 Hz is the cause of the wheel 23rd-order polygonal wear and believed that traction and braking may cause this unstable vibration, but this was not confirmed by measured data. In addition, [Dong and Cao \(2021\)](#) developed a dynamic model of a wheelset-track rotor system and a wheel wear model using principles of rotor dynamics. Their research aimed to simulate the evolution of wheel polygonal wear. They posited that the high-order polygonal wear of the wheel is mainly caused by the second-order bending mode (approximately 585 Hz) of the wheelset, which is excited by the rotation of the wheelset.

Some researchers have also investigated the mechanism of polygonal wear of other types of trains. [Johansson and Andersson \(2005\)](#) investigated the cause for wheel polygonalization of a metro train using a numerical model, which coupled a dynamic train-track interaction with a long-term wear model. The numerical results showed that the wavelength-fixing mechanisms of wheel polygonalization are the vertical track antiresonance and the P2 resonance. [Yang, Tao, Li, and Wen \(2021\)](#) indicated from vehicle vibration tests and polygonal wear simulations that the first-order bending vibration of the wheelset and the P2 resonance when the vehicle passes through the steel spring floating slab and the ladder sleeper track are the causes of 13–16th-order polygonal wear of the wheels of Type A trains with a speed of 80 km/h. However, it is necessary to further clarify which is the dominant factor in the development of wheel polygonal wear. [Jin, Wu, Fang, Zhong, and Ling \(2012\)](#) studied the mechanism of wheel ninth-order polygonal wear for the LIM metro trains through experimental investigation. The experimental results showed that the first bending vibration of the wheelset leads to the formation of the wheel's ninth-order polygonal wear. [Tao, Wang, Wen, Guan, and Jin \(2018\)](#) investigated the mechanism of the wheel polygonal wear of electric locomotives in field tests. The first bending vibration of the wheelset, which is easily excited during the locomotive operation, is the root cause of wheel polygonal wear. [Fröhling, Spangenberg, and Reitmann \(2019\)](#) and [Spangenberg \(2020\)](#) reported the 20th-order polygonal wear problem of locomotive wheels in South Africa. Through theoretical analysis and field experiments, they believed that the coupled vibration of the motor pitch motion and the wheelset torsion was the root cause of the wheel polygonal wear.

According to previous studies, there are different explanations for the mechanism of wheel polygonal wear on high-speed trains in China. The same is that the wheel polygonal wear exhibits a constant frequency, and its wavelength depends on the wheel diameter and a certain speed. However, previous research results have not been able to adequately explain the problem of wheel polygonal wear on EMUs operating on the Lan-Xin high-speed line. In this paper, the formation mechanism of wheel polygonization for the high-speed train is investigated by experimental research.

2. Results of field measurement for wheel polygonization

A type of wheel roughness measurement device was used to measure the out-of-roundness of the wheel tread, represented by the deviation from the mean radius, as shown in [Figure 2](#). The probe of the device was positioned at the nominal contact point 70 mm from the flange side of the wheel. The wheelset was lifted before measurement to allow free rotation of the wheelset. The wheel roughness measurement device has a fixed sampling interval of 0.69 mm. The resolution of the measurement scanner is $0.1 \mu\text{m}$.

After around 170,000 km of operation, high-order polygonal wear is found on the wheelsets of a plateau high-speed EMU train. The type of the EMUs is about CRH5G with the



Figure 2.
Field test photos for a
wheel roughness
measurement device

Source(s): Authors' own work

axle weight of 17 t. The wheelbase and the distance between backs of the wheel flanges of the EMUs are 2.7 m and 1,353 mm, respectively. This type of train consists of five powered coaches and three trailer coaches, as shown in Figure 3. The motor bogie for the powered car consists of an unpowered wheelset with three brake discs and a powered wheelset with a drive gear and two brake discs. The motors are mounted on the car bodies. The nominal diameter of the new wheels is 890 mm. The wheel profile is XP55 and the rail profile is CN60.

2.1 Characteristics of wheel polygonal wear

Field measurements provide information on the characteristics of wheel roughness, which are illustrated in Figures 4 and 5. Figures 4 and 5 show the measured wheel roughness for powered and trailer cars, respectively. It can be seen that the wheel polygonal wear was mainly at 14–16 and 25–27 harmonic orders, whose wavelengths were about 171–183 and 101–110 mm, respectively. The passing frequencies for wheel polygonization are calculated as shown in Table 1. At a nominal vehicle speed of 200 km/h, the passing frequencies of wheel polygonization are about 283–323 Hz and 505–545 Hz, respectively.

In order to investigate the development of wheel polygonization, the wheel roughness was measured for the same train type with different mileages after January 2016. Figure 6 shows the measured wheel roughness for trains with different mileage on the Lan-Xin high-speed line. Figure 7 shows the average wheel roughness for trains with different mileage. It can be seen that the high-order polygonal wear of order 25–27 developed most rapidly in the range of 150–200 thousand kilometers of service. At a mileage of less than 150 thousand kilometers,

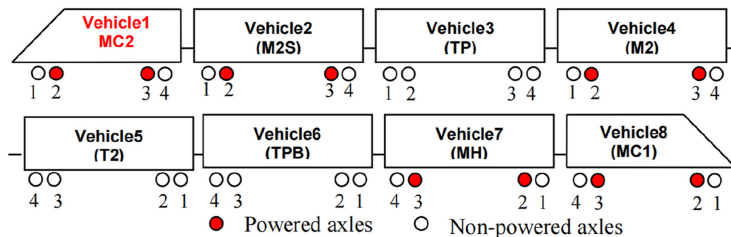


Figure 3.
Information about
the train

Note(s): 1,2,3,4 represent the number of axles for each vehicle

Source(s): Authors' own work

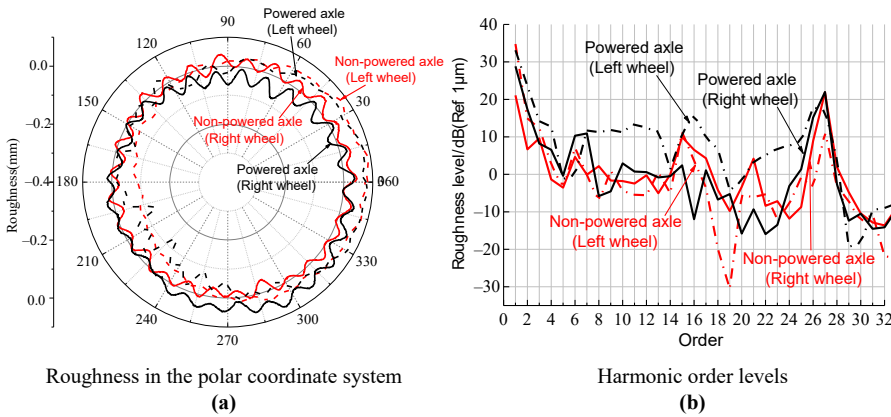


Figure 4. Measured results of wheel roughness for powered cars

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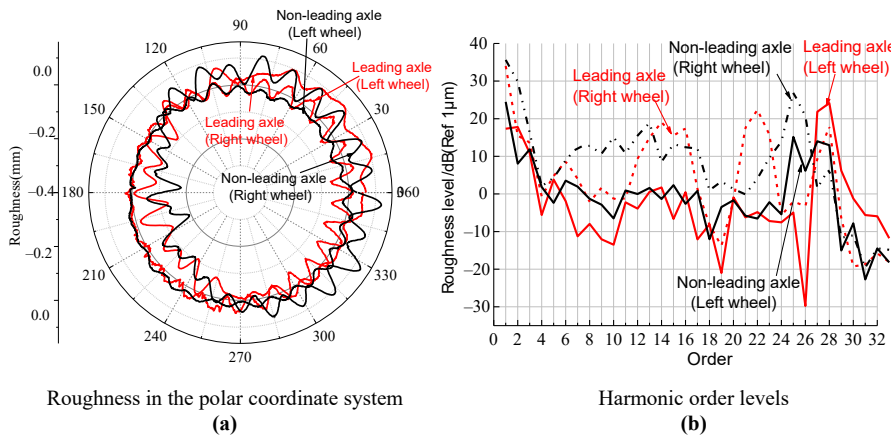


Figure 5. Measured results of wheel roughness for trailer cars

Source(s): Authors' own work

Order	Wavelength (mm)	Passing frequency (Hz)
14–16	171–183	283–323
20–23	120–137	404–465
25–27	101–110	505–545

Table 1. Harmonic orders, wavelengths and passing frequencies for wheel polygonal wear at an operating speed of 200 km/h

Source(s): Authors' own work

the polygonal wear of order 25–27 was not obvious, but the polygonal wear of orders 14–16 and 25–27 already occurred at a mileage of more than 50 thousand kilometers, as shown in Figures 6 and 7.

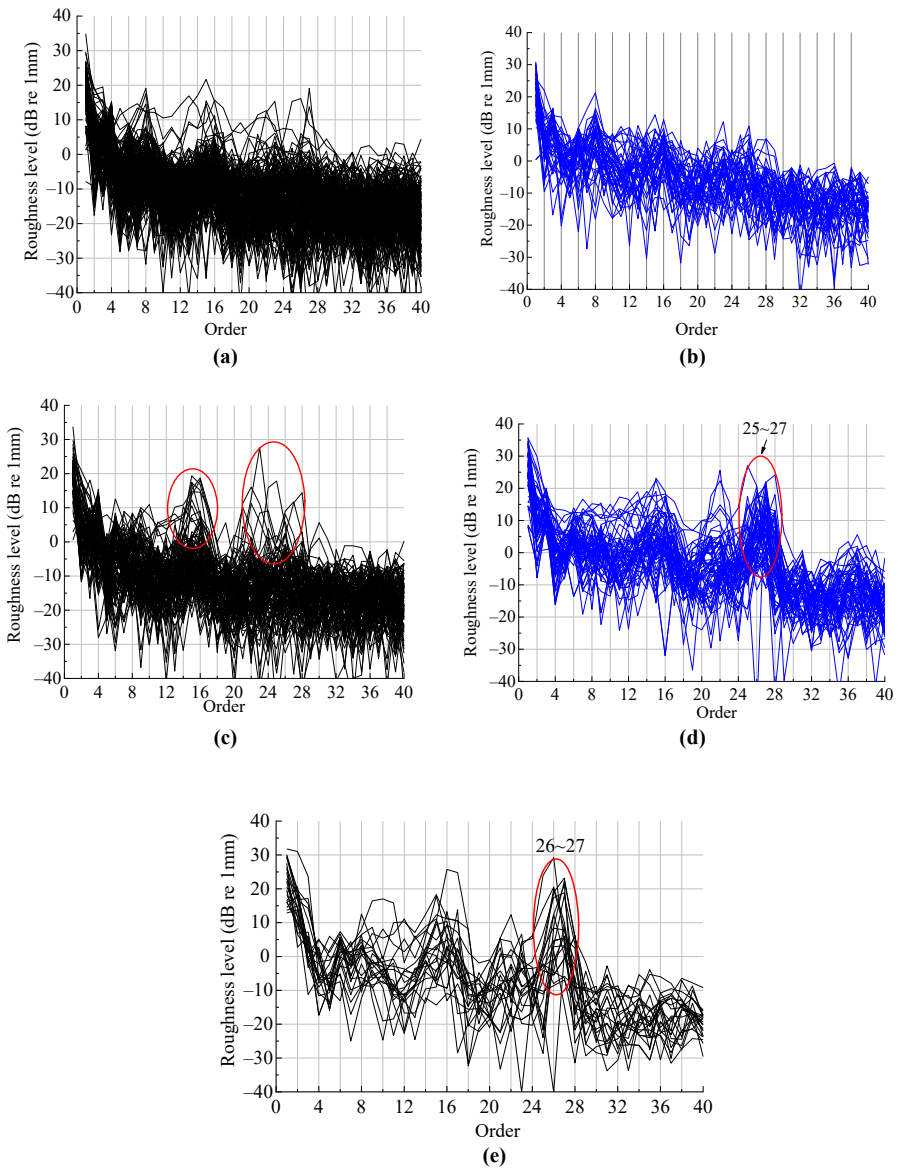
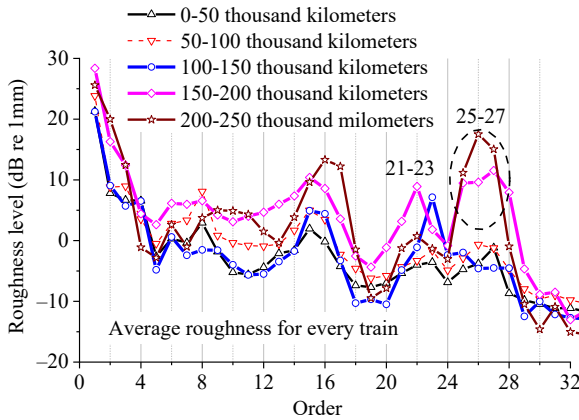


Figure 6. Wheel roughness for trains with different operation mileages: (a) 99 wheelsets below 50 thousand kilometers; (b) 23 wheelsets between 50 and 100 thousand kilometers; (c) 58 wheelsets between 100 and 150 thousand kilometers; (d) 30 wheelsets between 150 and 200 thousand kilometers and (e) 11 wheelsets between 200 and 250 thousand kilometers

Source(s): Authors' own work

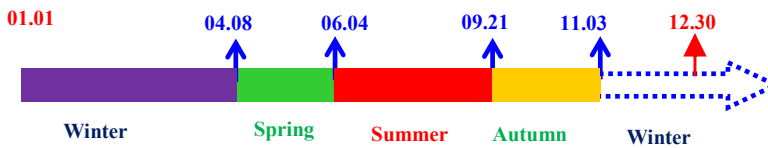
2.2 Factors influencing wheel polygonization

2.2.1 Seasonal influence on the development of wheel polygonal wear. Trains on the Lan-Xin high-speed line run at temperatures below -22°C in the winter season and at average temperatures above 39°C in the summer season. In the spring and autumn seasons with strong wind and sand, the average maximum wind speed is 37.6 m/s. The time zone for different seasons is shown in [Figure 8](#).



Source(s): Authors' own work

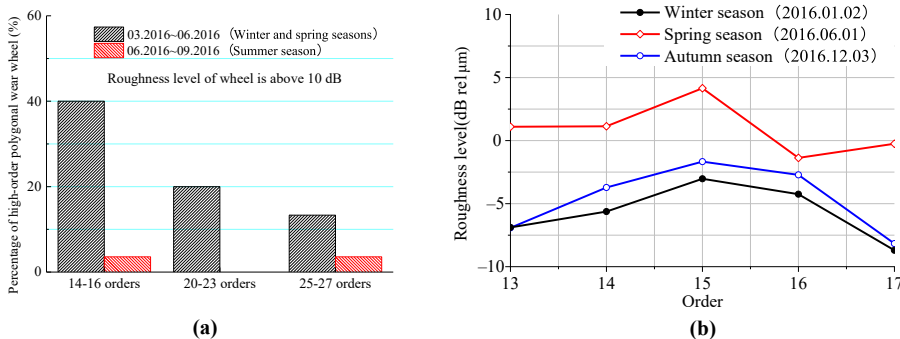
Figure 7. Average wheel roughness for trains with different operation mileages



Source(s): Authors' own work

Figure 8. Time zone for different seasons in the Lan-Xin high-speed line

The development of the polygonal wear of the wheels of a test train in the different seasons was monitored. The influences of the different seasons, the vehicle speed and the wheel re-profiling cycles on the development of wheel polygonal wear were investigated. The monthly mileage of the train is about 50 thousand kilometers. Figure 9(a) shows the percentage of high-order



Note(s): (a) Percentage of highorder polygonal wear wheel with more than 10 dB with the vehicle operating mileage of about 150 thousand kilometers. (b) Average roughness levels of 14–16 orders with different seasons after reprofiling operation mileage of about 100 thousandkilometers

Source(s): Authors' own work

Figure 9. Roughness levels for high-order polygonal wear wheels when the test vehicle operates in different seasons.

polygonal wear of the wheels with a roughness level of more than 10 dB when the test train had a mileage of about 150 thousand kilometers. Figure 9(b) represents the average roughness levels of the wheels when the test train had a mileage of 100 thousand kilometers for different seasons after wheel re-profiling. It can be found that the high-order polygonal wear of the wheels developed faster in spring than in the other seasons. This could be due to the fact that the weather with strong wind and sand mainly occurs in spring. The sand between the wheel and the rail leads to an increase in the adhesion coefficient, which can increase wheel wear.

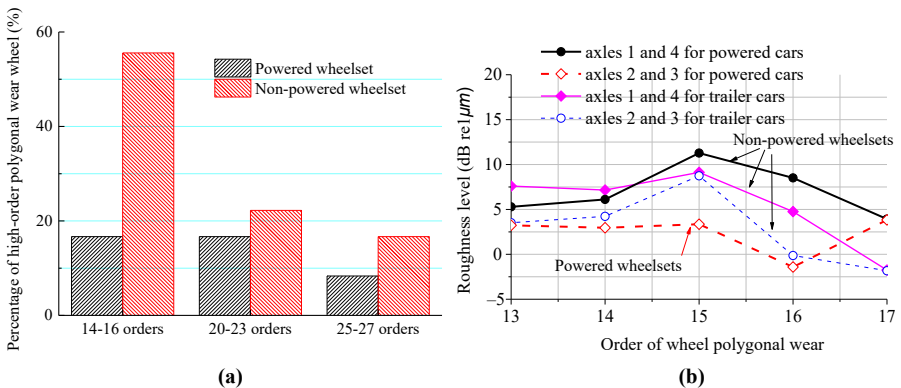
2.2.2 *Influence of powered axle on the development of wheel polygonal wear.* In the investigated trains, the bogie for the powered car includes a non-powered wheelset and a powered wheelset, while the bogie for the non-powered car includes only non-powered wheelsets, as shown in Figure 3. Figure 10(a) gives the percentage of wheels with high-order polygonal wear for powered and non-powered wheelsets with a roughness level above 10 dB when the test vehicle runs about 150 thousand kilometers. Figure 10(b) represents the average roughness levels of the wheels for different axles at a mileage of about 150 thousand kilometers. It can be found that the high-order polygonal wear of the wheels for non-powered wheelsets is greater than for powered wheelsets. It may be because wheel wear on the powered wheelsets may be influenced by traction torque compared to the non-powered wheelsets. In addition, the bending vibration modes of the power wheelsets are relatively difficult to be excited due to the constraints of the gearbox.

2.2.3 *Influence of operating lines on the development of wheel polygonal wear.* For a vehicle running mainly on the Lan-Jiayuguan line, which is a part of the Lan-Xin high-speed line, as shown in Figure 1, severe wheel high-order polygonal wear occurred when the mileage of the vehicle reached about 170 thousand kilometers. However, for another vehicle with a mileage of 150 thousand kilometers, the polygonal wear of the wheels is relatively low, as shown in Figure 11. This vehicle operated not only on the Lan-Jiayuguan line but also on the Lan-Xin line and the airport lines. The proportion of the vehicle's mileage on the Lan-Jiayuguan line, Lan-Xin line and airport line is 40.9, 30.4 and 28.7%, respectively, as shown in Figure 12. On the airport line, the speed of the test vehicle is about 80 and 150 km/h. For the Lan-Xin and Lan-Jiayuguan lines, the speed of the test vehicle is about 200 km/h. It can be found that the wheel high-order polygonal wear can be suppressed by operating on mixed lines.

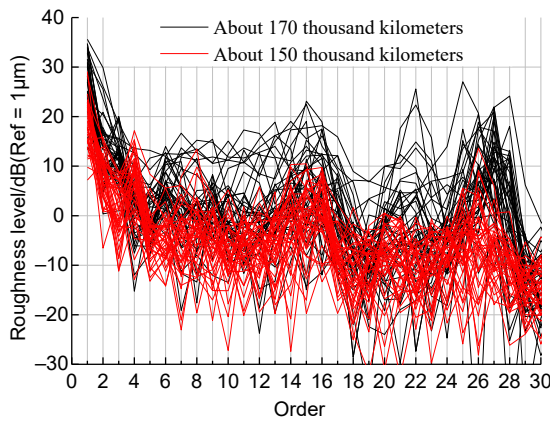
2.3 *Vibration of the tested vehicle component*

To find the source of the constant frequencies for wheel polygonization, the vibration accelerations of the axle box and the bogie were measured when the wheel after re-profiling

Figure 10. Roughness levels for high-order polygonal wear wheels for powered and non-powered wheelsets with operation mileage of about 150 thousand kilometers. (a) The percentage of wheels with a roughness level above 10 dB (b) Average roughness levels for wheels of different axles

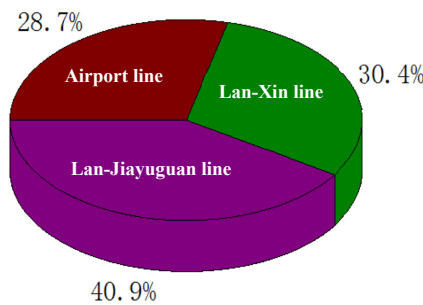


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Figure 11. Wheel roughness levels for two vehicles



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Figure 12. Proportion for vehicle operation mileage on different lines

traveled on tracks with normal rail roughness on the Lan-Xin high-speed line. The wheel and rail roughness for the tested vehicle and track are shown in Figures 13 and 14. It can be found that the roughness of the re-profiled wheels and the rail was normal. The frequencies of the vibration accelerations of the axle box and the bogie at different track sections are analyzed and compared with the passing frequencies of wheel polygonization.

Figures 15 and 16 show the vertical accelerations of the axle box and the bogie in the frequency domain. It can be found that the vibration response of the axle box and the bogie was in the range of 280–330 Hz and 500–550 Hz, which was similar to the passing frequencies of wheel polygonal wear. Based on the tested wheel and rail roughness, it could be found that the vibrations in these frequency ranges of the axle box did not originate from the excitation of the wheel-rail interface but either from the track system or from the bogie system.

The modals of the wheelset and bogie are simulated numerically in order to compare them with the main frequencies of the measured vibration accelerations (see Figures 17 and 18). The results show that the dominant passing frequencies of wheel polygonal wear are similar to the frequencies of axle boxes and bogies vibration, which could be due to the natural modal frequencies of the wheelset and bogies.

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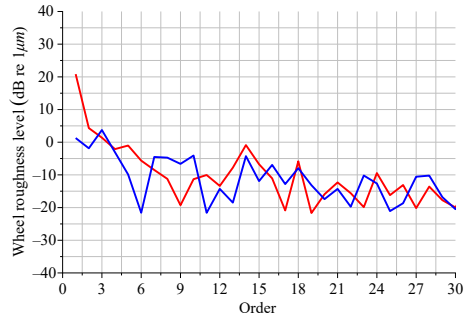
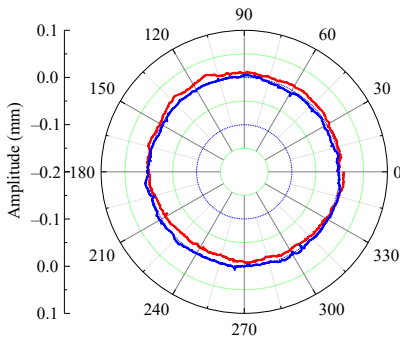


Figure 13.
Wheel roughness for
tested vehicle

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Figure 14.
Rail roughness for
tested track

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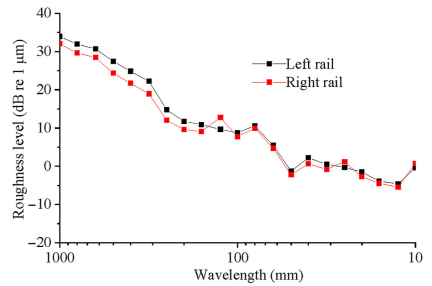
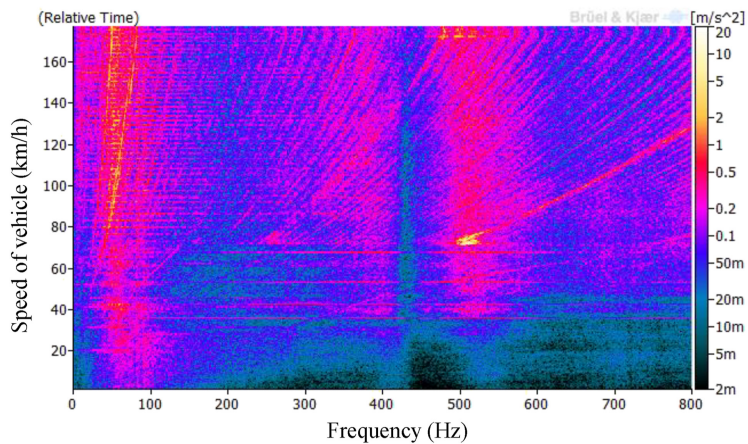
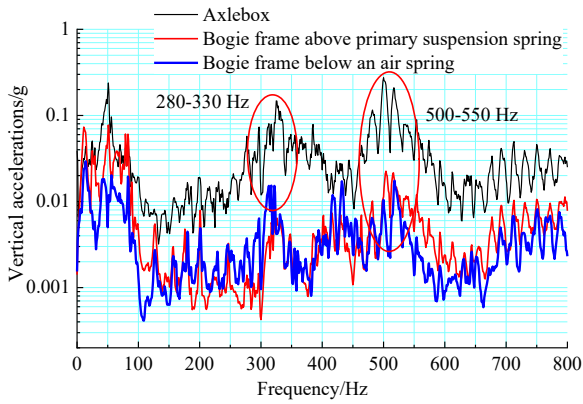


Figure 15.
Vertical acceleration of
axle box in the
frequency domain
when vehicle passing
through track in the
acceleration process
from 0 to 200 km/h
(after wheel re-
profiling)

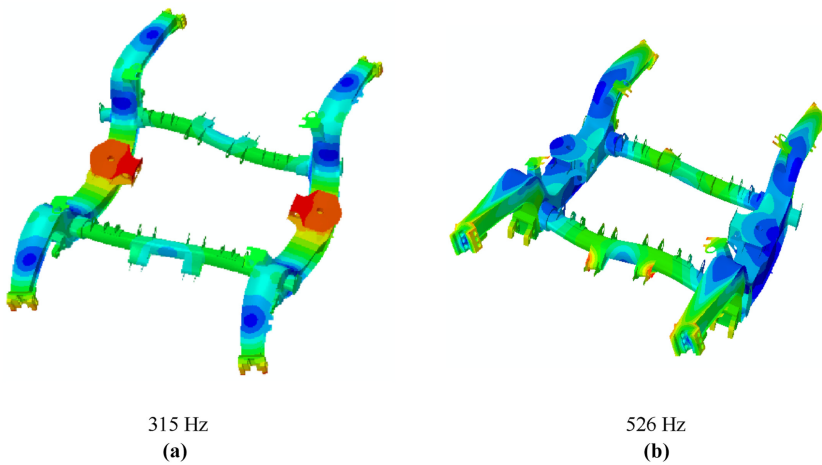


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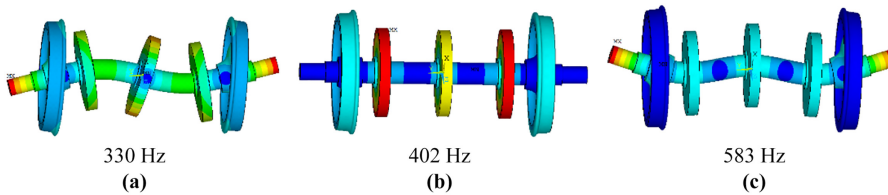
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Figure 16. Vertical acceleration of axle and bogie in the frequency domain when vehicle passing through track in the uniform velocity of about 200 km/h (after wheel re-profiling)



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Figure 17. Modal analysis of bogie



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Figure 18. Modal analysis of wheelset

2.4 Dynamic behavior of the track

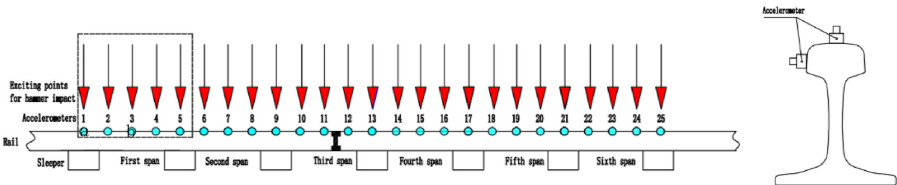
CRTS-I double-block sleeper ballastless track with Vossloh fasteners is used on the Lan-Xin high-speed line. The fastener spacing of the track is 0.65 m. The receptance and modal of track were measured using the hammer impact method. The dynamic characteristics of the track are also used to explain possible track resonances during the passage of the vehicle. The sleeper space of the track is about 0.65 m. An impact excitation test was conducted on the unloaded tracks using an impact hammer with an aluminum tip, as shown in Figures 19 and 20. The frequency bandwidth and the force range of the excitation are 0–4.5 kHz and 500–10,000 N, respectively. For the modal identification in the field test, acceleration sensors were installed in the span in the railhead, the railhead above the sleeper in the vertical and lateral position (see Figures 19 and 20), the rails were arranged in a total of 25 sensors, between the two rail spans to evenly select five points as the force hammer excitation point, a total of 25 excitation points, each excitation point position vertical and lateral were struck three times, the collection of the span in the head of the rail, above the head of the rail sleeper, the sleeper, the position of the spring bar measuring point vertical and lateral response. Test method for mobile force hammer, multi-point excitation and multi-point response method.



Figure 19. Measurement for receptance of track by using the hammer impact method in the field

Source(s): Authors' own work

Figure 20. A field impact excitation test of the track at midspan and above a sleeper by exciting at different points (a) excitation points (1, 2, 3, 4 and 5) and response points (a and b)



Source(s): Authors' own work

Figure 21(a) and (b) show the vertical and lateral frequency response functions (FRFs) for service tracks without a loaded vehicle, respectively. To obtain the FRFs, the input was recorded with a force sensor, and the response was recorded with accelerometers placed at the railhead above a sleeper (point a) and at a mid-span (point b), as shown in Figure 20. The result at each measurement point was determined by averaging the results of three impacts. Figures 22 and 23 represent the measured vertical and lateral bending modes of the rail using the modal identification, respectively. It can be found that the response peaks of the vertical rail acceleration occur at the frequencies of 160 and 935 Hz, which represent the vertical bending of the rail, as shown in Figure 22. The response peaks of the lateral rail acceleration occur at the frequencies of 81, 438, 701–878 and 1,059 Hz, which represent the lateral bending of the rail, as shown in Figure 23. Therefore, it can be speculated that the obvious vibrations of the axle box and the bogie at 280–330 Hz and 500–550 Hz were not caused by the vibration of tracks.

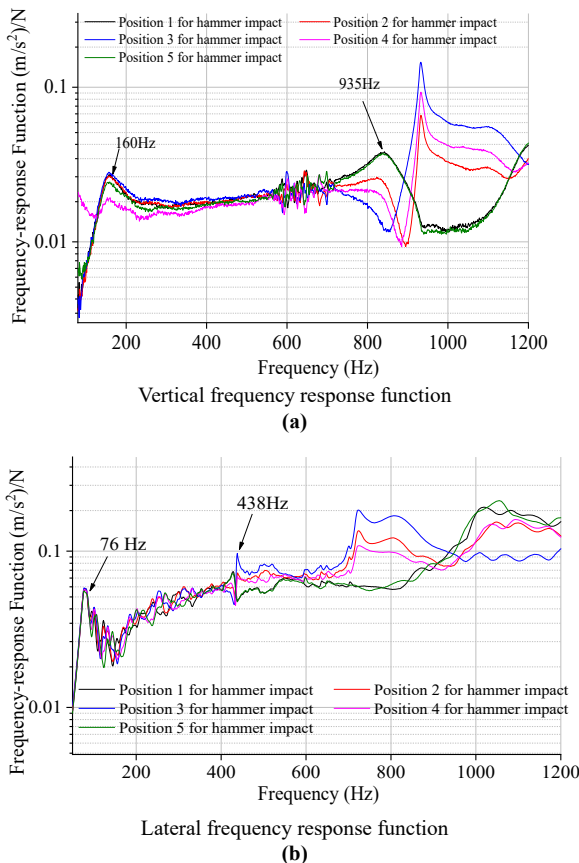
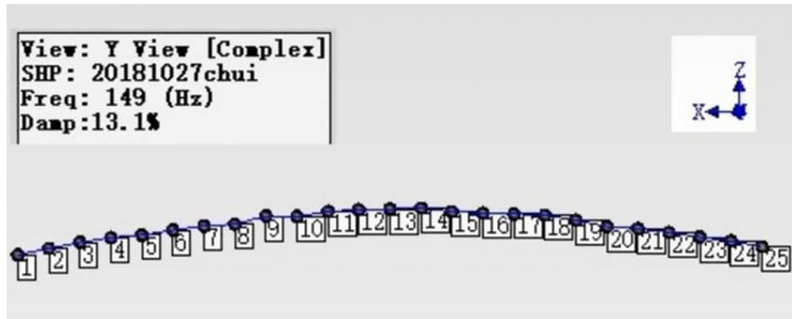
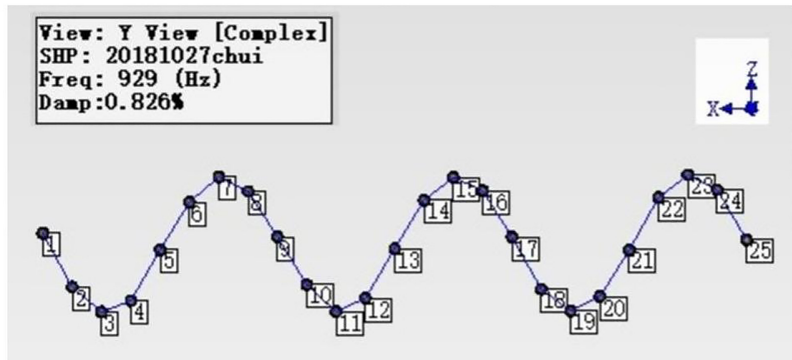


Figure 21. Frequency response characteristic for service tracks

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149 Hz
(a)



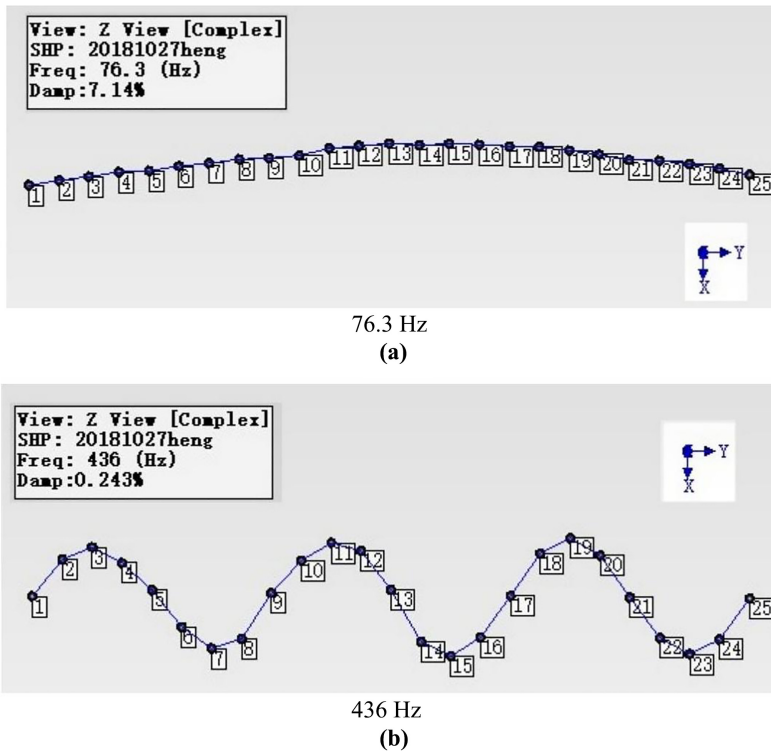
929 Hz
(b)

Figure 22.
Vertical bending shape
of rail

Source(s): Authors' own work

3. Conclusion

After four months of operation, the phenomenon of high-order wheel polygonal wear was observed in a plateau high-speed EMU train. Field experiments were conducted to investigate the reason for wheel polygonization. To explain the fixed-frequency mechanism of wheel polygonization, the vibration accelerations of the axle box and bogie were measured when the newly profiled wheels traveled on a high-speed line with normal rail roughness. The dynamic characteristics of the tracks were also measured. Modal analyses of the wheelset and bogie were employed to analyze the main frequencies of the measured vibration accelerations. In addition, the influences of the different seasons, the vehicle speed and the wheel re-profiling cycles on the development of wheel polygonal wear were investigated. The experiment results indicate that the wheel polygonal wear mainly exhibits the harmonic orders 14–16 and 25–27. The passing frequencies of wheel polygonization are about 283–323 Hz and 505–545 Hz, which are similar to the vibration frequencies of the axle boxes and bogies. The fixed-frequency vibrations are attributed to the natural modes of the wheelset (the corresponding frequencies are 330 and 583 Hz) and bogie (the corresponding frequencies are 315 and 526 Hz), which can be excited by wheel/



Source(s): Authors' own work

Figure 23.
Lateral bending shape
of rail

rail irregularities and are independent of the natural vibrations of the track. The study reveals that the wheel high-order polygonal wear develops faster in spring than in the other seasons, which is due to the weather conditions with strong wind and sand. Furthermore, the wheel high-order polygonal wear for non-powered wheelsets is more severe than for powered wheelsets. The wheel high-order polygonal wear could be mitigated by operating on mixed lines with variable speeds.

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