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Review on wear mechanism and influence of wheel polygon of rail transit train

WU Dan, DING Wang-cai

School of Mechanical Engineering, Lanzhou Jiaotong University, Lanzhou 730070, Gansu, China

Abstract: The research results of wheel polygon of rail transit trains in China and abroad in recent years were summarized and the main factors and mechanisms leading to the formation of wheel polygon were analyzed. The reasons for the difference in high-order wheel polygons between electric multiple units (EMUs) and metro vehicles were investigated and the main causes of the difference were summarized. The suppression measures for wheel polygon were discussed and the generation and development of vehicle-track coupling dynamics model were summarized. At the same time, the main results of the simulation analysis of vehicle-track coupling dynamics were presented, and a new research direction was proposed, which considered the fatigue damage of vehicle-track system components under the periodic wear of wheel-rail such as wheel polygon. Analysis results show that the initial defect of wheel, self-excitation vibration of wheel-rail friction, stick-slip vibration of wheel-rail, P2 resonance of wheel-rail system, inherent mode vibration of wheelset, wheel diameter, and resonance caused by bogie components can cause wheel polygon. The wheel polygons of metro vehicles are mainly caused by the P2 resonance of the wheel-rail system, while the multiple high-order wheel polygons of high-speed EMUs are generally not directly caused by the P2 resonance. Improving the quality of wheel turning, increasing the abrasive block, enhancing the hardness of wheel tread, strengthening the damping of fastener, and applying variable speed running can restrain the development of wheel polygon. However, according to the formation mechanism of wheel polygon, the initial defect of wheel is the origin, and controlling the initial defect of wheel can fundamentally inhibits the formation and development of wheel polygon. From the perspective of feasibility, installing the abrasive block is the most ideal measure. When the wheel has a high-order polygon, the wheel-rail excitation frequency will increase significantly, and the range distribution will be wider. When the excitation frequencies are close to the inherent vibration frequencies of some parts of vehicle, the resonance is easily triggered, which will lead to a significant increase in its dynamic stress and affect its fatigue life. Therefore, when the fatigue damage of the main bearing parts of vehicle-track system is analyzed, adverse factors such as random track irregularities and periodic wear of wheel-rail should be considered. It can be seen that the existing research results basically reveal the formation mechanism of wheel polygon, and feasible suppression measures are proposed. However, since the train operation environment is uncertain and there are many related factors in the vehicle-track coupling system, the analysis process is inevitably different from the actual situation. Therefore, further in-depth research is still needed. 1 tab, 7 figs, 100 refs. **DOI:** 10.19818/j.cnki.1671-1637.2024.02.005-en

Keywords: vehicle engineering; dynamics performance; wheel polygon; wear mechanism; suppression measure; dynamics model; fatigue damage

0 Introduction

With the increase in the operation mileage of rail transit train, different degrees of wheel polygons have appeared in electric multiple units (EMUs), subways, light rails, locomotives, and vehicles in China and abroad, which has become a persistent problem that puzzles train operation in the railway industry and is also a research hotspot and the primary problem to be solved urgently in the current railway field.

Wheel polygon refers to the periodic harmonic wear formed around the wheel circumference [1], which is divided into low-order wheel polygons and high-order wheel polygons. Low-order wheel polygons have a relatively small impact on vehicle vibration, and wheel polygons with 14th order and above are referred to as high-order wheel polygons, which have a significant impact on vehicle vibration. According to different surface roughness amplitudes, they are divided into four levels: maintaining the status quo, tracking noise, turning within one week, and immediate turning. If the roughness amplitude is less than 10 dB·μm^{-1}, the status quo can be maintained. If the roughness amplitude is 10–18 dB·μm^{-1}, it is necessary to track the noise every 30 000 km and carry out real-time monitoring through the detection of underfloor wheel lathe and the truck performance detection system (TPDS). If the roughness amplitude is 18–23 dB·μm^{-1}, it needs turning within one week. If the roughness amplitude is greater than 23 dB·μm^{-1}, it needs turning immediately. When the roughness amplitude of the high-order wheel polygon exceeds the standard, that is, greater than 18 dB·μm^{-1}, it will cause severe vibration. If the wheel turning is not carried out in time, it is easy to cause some parts of the bogie to crack, loose, or lose.

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Regarding the wear of wheel polygon, scholars in China and abroad have conducted extensive research and achieved important results. This paper briefly introduced the research results and the latest development from four aspects: the formation mechanism of wheel polygons, the suppression of wheel polygons, the vehicle-track coupling dynamics model and dynamics response, and the impact of wheel polygons on fatigue damage, and discussed the challenges faced by subsequent research and the content that needs further research.

1 Formation mechanism of wheel polygons

The formation mechanism of wheel polygons has been discovered and studied abroad as early as the 1980s. Kaper [2] found that as the operation mileage of intercity trains in the Netherlands increased, polygonal wear occurred on the wheels, leading to noise problems, which marked the beginning of research on the wear mechanism of wheel polygons. Kalousek et al. [3] found serious polygonal wear on wheels of the Vancouver subway and conducted relevant research. Morys [4] took the ICE train in Germany as the object, and found after nearly 10 years of research that the formation of wheel polygons was mainly caused by the fact that the third order polygon excitation frequency of the wheel was close to the first order bending modal frequency of the wheelset, which caused abnormal vibration. In other words, the resonance caused by the wheel polygon excitation frequency being close to a certain order of natural modal frequency of the wheelset was one of the factors causing the wheel polygons. Dekker [5] also obtained the same conclusion when studying the wheel polygons of light rail vehicles in the Netherlands. After summarizing the wear characteristics of wheel polygons of Sweden's X2 high-speed train, Johansson et al. [6–7] simulated the evolution law of wheel polygons, and proposed that P2 resonance was the main reason for the occurrence of 5th–7th order polygons by establishing a multi-body system dynamics model of wheel-rail rolling contact. Nielsen et al. [8–9] analyzed the influence of wheel polygons on vehicle components and track systems, and found that the influence of wheel polygons on wheel-rail interaction was significantly greater than that on speed; Barke et al. [10] provided a detailed review of the impact of wheel polygons on vehicle components and track systems.

China's rail transit started late, and various types of domestically produced EMUs were not put into large-scale operation for various reasons before 2004. Wheel polygons mainly appeared in locomotives and general speed passenger and freight vehicles, but due to their low operating speed and the ability to be solved through wheel turning, no in-depth research was conducted on this issue. With the introduction and large-scale operation of CRH series EMUs, wheels of some models have shown varying degrees of wheel polygons, and some models even have excessive high-order wheel polygons, which seriously affects traffic safety and has attracted great attention from railway operation and maintenance departments and scientific researchers. At the same time, wheel polygons of metro vehicles have also been reported. Therefore, studying the formation conditions, causes, and impact on the vehicle-track system of wheel polygons has become one of the most concerned research directions in the field of rail transit.

Scholars in China and abroad have conducted research on the initial defect of wheel, self-excitation vibration of wheel-rail friction, stick-slip vibration of wheel-rail, P2 resonance of wheel-rail system, inherent mode vibration of wheelset, wheel diameter, and resonance caused by bogie components. Research has shown that the above factors can cause wheel polygons.

By tracking the wear characteristics of wheel polygon of China's high-speed trains, Jin et al. [11–12] found that wheel polygon was mainly 2–3 rail corrugations with different wavelengths. When the wheel diameter was an integer multiple of the wavelength, the wavelength was mainly a single wavelength and the rolling contact phase of the wheel-rail was the same, the wear of wheel polygon would increase rapidly; It proposed that the track structure was not the main cause of wheel polygon. The resonance of the internal structure, the roughness of the wheel-rail surface, the wheel eccentricity, the initial out-of-roundness after turning, and the bending resonance of the rail were the main factors for wheel polygon; It believed that adopting variable speed operation and applying abrasive block could effectively reduce the wheel polygon. Li et al. [13] reviewed research in China and abroad from three aspects of the formation mechanism and prediction of wheel polygon, and its impact on the dynamic response of wheel-rail system, summarized six typical factors of wheel polygon formation and two indirect detection methods. They analyzed the noise prediction model and the relationship between wheel polygons and wheel noise and suggested developing a wheel turning plan that was suitable to the situation in China, so as to reduce maintenance costs. Zhu et al. [14] reviewed the influence of wheel polygons on vehicle system dynamics, the formation mechanism of wheel polygons, the static and dynamic monitoring of wheel polygons, and the suppression of wheel polygons. They pointed out that wheel polygons had a significant impact on the dynamic response of vehicle system and the best treatment method was wheel turning. It was recommended to combine dynamic monitoring data with dynamic simulation models to study the formation mechanism and preventive measures of wheel polygons. Tao et al. [15–16] summarized the research results on the formation mechanism, simulation prediction, and control measures of out-of-roundness wear of wheels in China and abroad. They found that wheel polygons were widely present in domestic and foreign rail transit trains, but its manifestations vary. Wheel polygons of foreign rail transit trains were mainly low-order, while wheel polygons of Chinese rail transit trains were mainly high-order. Three major factors that contributed to out-of-roundness wear of wheels were summarized, which were the initial defect of wheel, vehicle-track coupling vibration, and thermoelastic instability during tread braking. It was pointed out that the wheel polygon was often caused by multiple factors. Therefore, even for the formation mechanism of wheel polygons for the same vehicle model, it could be explained from different points of view. The research results of predicting out-of-roundness wear of wheels were summarized, and the widely used methods were summarized, namely, the global parameters of wheel-rail contact were obtained through the simulation of vehicle-track coupling dynamics model, and the global parameters were used as the input of local parameters to calculate out-of-roundness wear of wheels based on the wear model. Finally, the control measures of wheel polygons were summarized, such as improving the quality of wheel turning, installing the abrasive block, and improving the hardness of wheel tread.

In summary, based on the existing research results, the problem of wheel polygons has been effectively controlled and the corresponding suppression measures have been proposed. However, the formation mechanisms have not been fully explored, resulting in the problem of wheel polygons not being fundamentally solved. With the improvement of EMUs dynamic monitoring technology and computer simulation technology, more scholars have conducted in-depth research on the formation mechanism of wheel polygons. In the following, the research results on the wear mechanism of wheel polygons in China and abroad in recent years would be summarized, and the existing differences and the correlation between various causes would be discussed.

1.1 Initial defect of wheel

The initial defect of wheel is often caused by the processing technology during wheel processing or turning. Staśkiewicz et al. [17] confirmed through actual measurements that the formation of wheel polygons was related to the way of fixing the wheel on the lathe. At the early stage of wheelset processing and turning, the three-jaw chuck lathe was mainly used to repair the wheel tread. Due to the elastic deformation of the fixture's action point in the radial direction, tiny initial third-order polygons were formed at the fixture's action point after unloading [18]. With the popularization of underfloor wheelset lathe, due to their advantages of processing of wheel rims and treads and online detection of equivalent taper and polygons under the condition of non-disassembly, wheelset measurement and turning are carried out in underfloor wheelset lathe. Cui et al. [19–20] analyzed the factors that affect the cutting quality during the turning by underfloor wheelset lathe, and pointed out that the multiple occurrence of 1st, 4th–6th and 10th–13th orders was caused by poor machining due to the positioning method of underfloor wheelset lathe. Using driving wheel positioning could easily lead to first-order wheel polygons, and the irregular driving wheel mapping to the wheel could easily form 4th–6th and 10th–13th order wheel polygons. Ren et al. [21] found that the formation of initial wheel polygons was related to the wheel alignment method of underfloor wheelset lathe using two driving wheels as positioning wheels. Su et al. [22] further analyzed the relationship between the driving wheel eccentricity of underfloor wheelset lathe and the initial wheel polygons and found that the driving wheel eccentricity was the main cause of the 4th-order polygon of the newly repaired wheel. Therefore, adopting unreasonable turning techniques and using the driving wheel as the positioning wheel in underfloor wheelset lathe can cause initial defect of wheel.

Meanwhile, research has shown that local defects of wheel tread and the uneven material on the wheel surface can also cause the initial defect of wheel, leading to wheel polygons. Cui et al. [20] calculated the impact of several typical wheel defects on wheel-rail behavior through the combination of actual measurement and simulation. It found that the local defects of wheel tread could cause large wheel-rail impact force, and then cause non-uniform hardening of the wheel circumferential material, so that the wheel polygon developed rapidly. Nielsen et al. [23] analyzed the high-frequency vibration and non-uniform wear mechanism of wheel-rail through numerical simulation and found that the non-uniform material characteristics of wheel surface could cause wheel polygons.

Fig. 1 Increasing lower support of axle box

In summary, the wheels after turning have slight initial wheel irregularities, which gradually develop into wheel polygons as the operation mileage increases. For the underfloor wheelset lathe, a support device can be installed at the lower part of the axle box, as shown in Fig. 1, so as to eliminate the initial defect caused by relying on driving wheel for positioning and avoid the imitation of wheel polygon. In addition, when the arc length formed at the contact point between the wheel and the driving wheel 2 is an integer multiple of the wavelength of a certain high-order wheel polygon, the situation where the high-order wheel polygon still appears after turning. The wheel polygon of this order can be effectively removed through two rounds of turning or by adjusting the distance between the driving wheels. Finally, low-order polygons caused by turning can be suppressed by controlling the eccentricity of the driving wheel of underfloor wheelset lathe.

1.2 Self-excitation vibration of wheel-rail friction

When the wheel-rail contact is in the sliding state, it is easy to generate the self-excitation vibration. Chen et al. [24] established a finite element model (FEM) of a wheel-rail system for elastic vibration of a certain subway train, used the NUCARS software to analyze the contact angle at the wheel-rail contact point and the lateral and vertical forces on the journal when passing through a curve, and realized the finite element discretization of the wheel-rail friction system based on the ABAQUS software. They analyzed the stick-slip vibration modes under two line conditions and obtained the vibration frequency and the real part of characteristic value by the friction dynamics motion analysis. They found that when the real part of characteristic value was positive, the system would appear unstable motion, and the unstable stick-slip vibration caused by the unstable motion would lead to polygonal wear of the wheel. When the friction factor was less than 0.27 and the vertical support stiffness of wheel-rail was not too large or too small, the wheel polygon could be effectively suppressed. Subsequently, this model and research method were further developed to investigate the formation mechanism of wheel polygons of EMUs [25]. In addition, Zhao et al. [26] applied this method to study the formation mechanism of 14th–16th-order wheel polygons in EMUs on the Lanzhou-Xinjiang passenger dedicated line. They found that saturated creep forces of wheel-rail caused by train starting and braking could cause wheel sliding, resulting in unstable motion, and the frequency of unstable vibration was consistent with the measured results, confirming that self-excitation vibration of wheel-rail friction could cause wheel polygons.

In conclusion, when the creep force at the wheel-rail contact point reaches saturation, as the friction factor increases, it is easy to cause stick-slip vibration of wheel-rail system. This alternating motion of stick-slip can lead to corrugated wear on the wheel-rail surface. By controlling the surface roughness of the wheel-rail and reducing the friction factor, wheel polygons can be avoided. At the same time, the electronic anti-slip devices can be optimized to minimize the occurrence of creep force saturation during train operation.

1.3 Stick-slip vibration of wheel-rail

During the operation, the wheel-rail surface contact leads to dry friction behavior in the system. Moreover, due to the existence of lateral clearance between the wheels and rails, and multiple factors such as wheel-rail profile characteristics and contact relationships, and the positioning characteristics of axle box, hunting motion can occur [27]. In addition, under the action of vertical and lateral dynamic loads and vertical bending of wheelsets, lateral friction occurs on the wheel-rail contact surface, and the friction frequency is related to the vibration frequency, resulting in the friction vibration [28]. Kalousek et al. [3] found corrugated wear on the wheel-rail surface of Vancouver subway, and the results showed that it was caused by the stick-slip vibration of wheel-rail system; Zhao et al. [29] found through the complex eigenvalue analysis method that when the creep force between the wheel and rail reached saturation, the low-frequency stick-slip vibration of wheel-rail system could be caused, thereby exacerbating or leading to the polygonal wear of wheels. Wu et al. [30] described the dynamic behavior of wheelset stick-slip vibration by establishing a dry friction-impact vibration dynamic model with symmetric gaps, and derived the connection relationship of adhesion, sliding and collision motion in system motion. The study found that the system exhibited reciprocating switching between large and small oscillations in the low-frequency region, which was a typical periodic flutter motion, and grazing behavior occurred when the system trajectory crossed the interface. The flutter caused significant changes in the stick-slip zone within the wheel-rail contact spot, causing the wheel to slide laterally relative to the rail in the wheel-rail contact area, resulting in periodic changes in the lateral creep force and ultimately inducing wheel polygons.

In summary, the essence of wheel-rail stick-slip vibration is the creep characteristics of wheel-rail. Since all static and dynamic loads of wheel-rail trains need to be transmitted through the wheel-rail contact spot, studying the creep characteristics at the wheel-rail contact spot is fundamental and also the best breakthrough point for analyzing the formation mechanism of wheel polygons.

1.4 P2 resonance of wheel-rail system

In 1974, the Derby Railway Technology Center in the UK proposed the high-frequency force P_1 and low-frequency force P_2 theories for wheel-rail impact when studying wheel passing through rail joints or local defects of wheels [31]. Among them, force P_1 was a high-frequency impact load caused by prominent surface defects such as rail joints and wheel flat scars, with a frequency of 500–1000 Hz, and its action time was extremely short, mainly damaging the surface of wheel-rail. Force P_2 was a low-frequency quasi-static load with a frequency of 20–100 Hz [32], and its action time was relatively long. It could be transmitted upwards to vehicle components and downwards to the track system, and thus posed great harm to the vehicle-track system, and the inevitable track irregularities and wheel circumferential irregularities may cause P2 resonance of the wheel-rail system.

Guan et al. [33] found that when a vehicle passed through the welded joint of rail or experienced local unevenness of the rail surface, the unsprung mass of vehicle would produce force P_1 on the track, causing the unsprung mass to produce force P_2 on the track. The wheel-rail vibration caused by force P_2 had the characteristics of simultaneous vibration in the same direction and large participating mass, making the vibration range wide and the vibration energy large.

Therefore, P2 resonance was one of the causes of the initial defects of wheel. Tao et al. [34] found that P2 resonance was the reason for the generation of 5th–8th-order wheel polygons through the actual measurement of wheel polygon, rail corrugation, wheel-rail dynamic interaction, and irregular rail weld joints of a subway vehicle. Liu et al. [35] randomly measured the data of wheel polygon of 172 subway vehicles and found that they are mainly of 6th–7th order. The wheel-rail vibration measurement verifies that P2 resonance was caused by irregular rail weld joints, and P2 resonance was easy to produce low-order wheel polygon.

In summary, the short-wave irregularity caused by the wheel-rail surface defects can cause high-frequency force P_1 and low-frequency force P_2, and the influence wavelength of force P_2 on the wheelset causes the wheel polygon with the size of corresponding wavelength. According to the natural frequency mechanism [36], the excitation frequency of the wheel polygon of subway vehicles under normal speed operation is close to the vibration frequency caused by force P_2. Therefore, the wheel polygon of subway vehicles is mainly caused by the P2 resonance of the wheel-rail system. However, since the operating speed of high-speed EMUs is much higher than that of subway trains, the excitation frequency of high-order wheel polygons under normal speed belongs to medium-high frequency, which is quite different from the P2 resonance frequency. Therefore, the multiple high-order wheel polygons in high-speed EMUs are generally not directly caused by P2 resonance.

1.5 Inherent mode vibration of wheelsets

A large number of studies have found that the low-order bending vibration of wheelsets is related to the formation of wheel polygons. Taking subway vehicles as the research object, Jin et al. [37] found through the combination of actual measurement and simulation that the fundamental cause of the 9th-order wheel polygon dominated by a certain subway vehicle was the first-order bending vibration of the wheelset. Li et al. [38] obtained the frequency response characteristics of a certain subway vehicle wheelset through actual measurement, and found that the two peak frequencies of 72 and 170 Hz were basically consistent with the 1st and 2th-order bending vibration frequencies of the wheelset. Therefore, the excitation resonance wavelength range of the first-order bending of the wheelset was determined, and the development of wheel polygon within one turning cycle was tracked and tested. It was found that the wheel polygon gradually developed from the 4th-order to 9th-order after one month of turning. After increasing the first-order bending vibration frequency of the wheelset through thickening, there was no obvious high-order polygon, confirming that the first-order bending vibration of the wheelset was the main reason for the generation of wheel polygon, indicating that the first-order bending vibration of wheelset excited by the normal operating speed or track excitation could cause polygonal wear of the wheels of subway vehicles.

Similarly, in the study of the wear mechanism of wheel polygon of locomotives, it is also found that the first-order bending vibration of the wheelset has a direct relationship with the formation of the wheel polygon. Tao et al. [39] conducted experimental research on the generation mechanism of wheel polygons of electric locomotives and obtained the growth pattern of wheel polygons. They found that the main reason for the generation of wheel polygons in most electric locomotives was the excitation of the first-order bending vibration of the wheelset, resulting in wheel polygons with a central wavelength of 200 mm in the 1/3 octave band. Liu et al. [40] established a rigid-flexible coupling dynamics model of an electric locomotive considering wheel-rail flexibility and traction behavior, and compared and analyzed the vibration characteristics of axle box and wheel-rail normal forces under typical orders and amplitudes. They found that the passing frequency of the 18th-order wheel polygon at a speed of 70 km·h^{-1}was close to the first-order bending vibration frequency of the wheelset, causing the first-order bending resonance of the wheelset, which led to the formation of more severe wheel polygons.

There are also studies indicating that when the low-order torsional vibration of the wheelset is close to the excitation frequency of the wheel polygon, it is easy to form wheel polygons. Fröhling et al. [41] proved theoretically and experimentally that the torsional vibration of locomotive axles may lead to wheel polygons. Spangenberg [42] analyzed through experiments that the abnormal vibration of locomotives running on heavy-haul lines in South Africa was caused by wheel polygons. It was found that when the locomotive ran at 40 km·h^{-1}, the traction system and wheelset torsion formed a coupling resonance, resulting in the formation of 20th-order wheel polygons.

By establishing a rigid-flexible coupling dynamics model of an EMU, Wu et al. [43] studied the influence of wheel polygons on the vibration acceleration spectrum characteristics of axle box and frame, and revealed its laws. Fig. 2 shows the vibration spectrum characteristics of axle box and frame when the wheel polygon amplitudes is 0.2 mm and the orders are 4, 10, 16, and 22, respectively at speeds of 200 km·h^{-1}. Fig. 2 shows that the main frequencies of vibration responses of the axle box and the frame at orders 4, 10, 16, and 22 are 77.2, 192.4, 307.6, and 422.9 Hz, respectively, which are close to the excitation frequency of wheel polygon at each order. The vibration amplitude of the axle box at 351.6 Hz is the largest, and the reason is that the wheel frequency doubling frequency excites the codirectional umbrella mode of the wheelset, causing resonance of the axle box at this frequency.

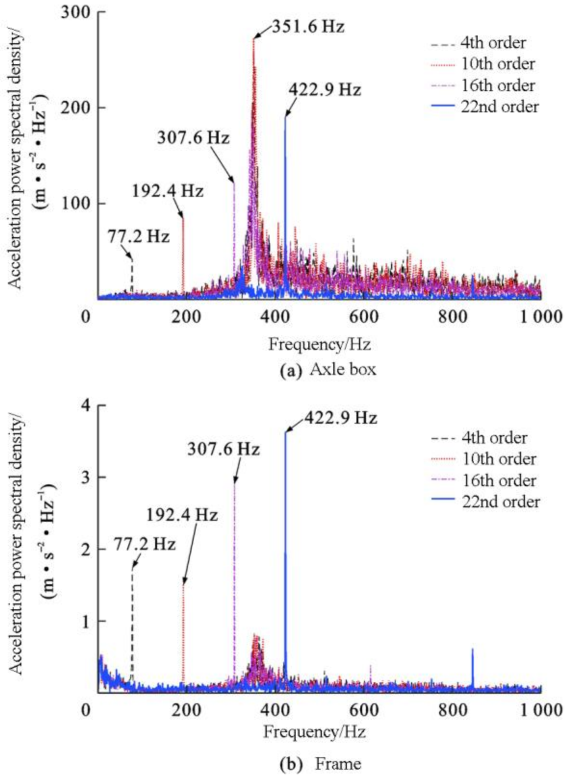

Fig. 2 Vibration spectra of axle box and frame at 200 km·h^{-1}

In summary, although the structure and operation environment of EMUs, subways, and locomotives are different, the natural frequency mechanism of wheel polygons is applicable to all of them, namely, there is a natural frequency vibration excitation between the wheelset and the rail during the operation, and this frequency should be the modal frequency of a certain structure. This is also a highly recognized viewpoint in the current academic community in China and abroad to explain the formation and development mechanism of polygonal wear of wheels [44].

1.6 Diameter of wheel

According to the natural frequency mechanism, the relationship between the wheel diameter and the excitation frequency is:

$$f = \frac{nv}{3.6\pi d}$$

where f is the excitation frequency generated by the wheel polygon; n is the order of the polygon; v is the speed; d is the diameter of the wheel.

By conducting on-site measurements of rail corrugation and wheel polygon of a high-speed railway, Wu et al. [45] speculated that wheel polygons were correlated with the natural frequency of the wheel. The study found that when the diameter of the wheel was an integer multiple of the wavelength of rail corrugation, the wavelength of rail corrugation was a certain value or the changing amplitude of rail corrugation was small, and the wheel was in contact with the rail corrugation at the same position during the wheel-rail rolling contact, the polygonal wear of wheel developed rapidly under the three conditions. Gao et al. [46] analyzed the influence of wheel rim thickness on wheel polygon and found that its influence law conformed to the natural frequency mechanism, namely, as the thickness of the wheel rim decreased, the wheel polygon developed slowly when the wheel perimeter could not completely divide the external excitation wavelength; otherwise, the wheel polygon developed rapidly. Zhao et al. [47] statistically analyzed the relationship between the wheel diameter of EMUs and the order of wheel polygon. It was found that wheel polygons were mainly 18th–20th orders, and the smaller the wheel diameter was, the more likely the polygons were to occur. The correctness of the natural frequency mechanism was verified by establishing the vehicle-track coupling dynamics model and the Archard wear model simulation. Based on actual measurements, it was found that wheel eccentricity, rail corrugation, and abnormal wheel-rail impact were the external excitation factors for the generation of wheel polygons.

To sum up, although the external excitation (wheel-rail surface defects and track irregularities, etc.) that vehicles experience during the actual operation is random, the periodic wear of the wheel after a period of operation follows the natural frequency mechanism. When the wheel diameter meets the natural frequency, it will also cause the development and aggravation of polygonal wear of the wheel.

1.7 Resonance caused by bogie components

Research has found that when the vibration frequency of certain components in the bogie is close to the excitation frequency of the wheel polygon, it is easy to form polygonal wear of wheels. Wu et al. [48] analyzed the influence of wheel polygon of high-speed trains on the wheel-rail interaction force based on the vehicle-track coupling dynamics model. The study found that the wheel-rail interaction force increased with the increase of wheel polygon amplitude and speed, and there was a phase difference between the maximum wheel-rail force distribution and the wheel polygon amplitude, but it corresponded to the first derivative of wheel polygon amplitude with respect to angle. Furthermore, it proposed that the coupling vibration of frame and wheelset may be the reason why the excitation frequency of the wheel polygon of high-speed trains often occurred at 580 Hz. Ma et al. [49] analyzed the reasons for the occurrence of 9th-order wheel polygons in subway vehicles and proposed that multiple-periodic vibration caused by wheel rolling contact was the main reason for the formation of wheel polygons. Based on the linear motor subway vehicle-track coupling dynamics model, it found that the linear motor vibration could cause the formation of wheel polygons, especially when the operating speed was 72–80 km·h^{-1}, namely, when the frequency was between 39.08–43.84 Hz, it was easy to form 9th-order wheel polygons. Gao et al. [50] tracked and tested the wheel polygon of the operating trains on the Lanzhou-Xinjiang passenger dedicated line. During the complete operating cycle (1.2 million km), it was found that the wheels mainly exhibited 14th–16th, 20th–23th, and 25th–27th-order polygon during the 3rd–7th single turning cycle, with 14th–16th order dominating. Through experimental analysis, it was found that the resonance frequencies generated by the frame and wheelset at 320 and 540 Hz were the periodic excitation for the polygonal wear of wheels.

Wu et al. [51] conducted modal analysis on the bogie frame of a certain type of EMU, removed the rigid body modes of the first six orders and extracted the 7th–60th-order free modes of the frame in finite element analysis software. They found that the overall torsion, bending, and shear modal frequencies of the frame were all below 230 Hz, only with locally modal frequencies around 580 Hz. However, since the local mode of the frame was not related to the wheelbase, there was no causal relationship between the excitation frequency of around 580 Hz and the frame, and whether there was a causal relationship with the bogie as a whole needed to be further explored. Due to space limitations, the overall and local modes of the frame are selected, and their modal frequencies and vibration modes are shown in Table 1 and Fig. 3.

Table 1 Frame modal analysis results

Mode	Order	Frequency/Hz	Vibration mode
Global mode	7	32.95	Vertical torsion of side frame around horizontal axis
	11	77.58	Simultaneous shear of both side frames in the horizontal plane
	12	84.28	First-order bending of both side frames in vertical direction
	20	224.88	Second-order bending of side frame and horizontal frame
Local mode	21	237.35	Deformation of axle box spring sleeve
	34	428.85	Deformation of axle box spring sleeve and rocker arm
	51	567.19	Deformation of axle box spring sleeve and rocker arm
	52	596.50	Deformation of axle box spring sleeve and rocker arm

In summary, the formation of wheel polygons is a long-term and complex process. Due to the limitations of existing experimental conditions and the incompleteness of numerical simulations, the formation mechanism needs to be further improved. But with the upgrading of experimental conditions, the development of dynamic monitoring technology, the application of big data technology, and the improvement of dynamics model of vehicle-track coupling systems, the factors affecting the polygonal wear of wheels of various types of vehicles such as EMUs, subways, locomotives, and normal speed passenger and freight vehicles may be identified, thus providing a deeper understanding of its formation and development.

2 Suppression of wheel polygons

Regarding the formation mechanism of wheel polygons, although domestic and foreign researchers have achieved fruitful research results and put forward some representative views, the underlying mechanism has not been fully explored. Therefore, in the face of wheel polygon problems during actual operation, it is urgent to propose specific, feasible and effective wheel polygon suppression measures, so as to ensure the safety and stability of train operation and reduce the cost of train operation and maintenance.

Due to the fact that the suppression measures for wheel polygons can be verified through experiments, theoretical and experimental research on wheel polygon suppression measures has good identifiability. Up to now, the representative views include improving the quality of wheel turning, increasing the abrasive block, enhancing the hardness of wheel tread, strengthening the damping of fastener, applying variable speed running, changing the inherent vibration frequency of wheelset, avoiding the inherent vibration frequency of the system, and controlling the irregularity of lines.

2.1 Improving the quality of wheel turning

Since the structure of the existing vehicle components and track lines do not need to be changed, improving the quality of wheel turning is currently the easiest control measure to achieve. The relevant research results have been detailed in Section 1.1. Additionally, Zhang et al. [52] compared the surface roughness of the wheel before and after the improvement of the turning process and confirmed that controlling the radial runout of the driving wheel, the two-tool turning process, and adopting the axle box support turning could significantly improve the turning quality of the wheel polygon.

2.2 Increasing abrasive block

The abrasive block is also known as tread trimmer. It was found that the development of wheel polygon could be suppressed by installing the abrasive block on the wheel tread to repair the irregularity of the wheel tread. Qiao et al. [53] found that the abrasive block could significantly suppress the wheel polygon by building an abrasive block test platform, and analyzed the influence of wheel-rail sliding and adhesion on the development of wheel polygon by establishing a finite element model of self-excitation vibration of non-power wheelset friction. The results showed that under wheel-rail sliding state, the most easily excited frequency of the friction self-excitation vibration was close to the actual vibration frequency of wheel polygon, while under wheel-rail adhesion state, the self-excitation vibration would not occur in the wheel-rail system, so the abrasive block could effectively suppress the development of wheel polygon. Through a tracing test, Wu et al. [54] analyzed the effect of the abrasive block on suppressing the wheel polygon under two conditions of constant speed drag and brake drag, and found that the effect of the abrasive block on suppressing the wheel polygon under constant speed drag was significantly better than that under brake drag. At the same time, the tracking test found that the abrasive block would not affect the equivalent taper of the tread and could effectively suppress the high-order wheel polygon.

In summary, the installation of abrasive block can effectively suppress the development of wheel polygon, and abrasive block has been installed in the newly built Fuxing EMUs (CR300AF/BF, CR400AF/BF). According to the investigation, it is found that the wheel tread shape of the Fuxing EMUs using the abrasive block is in good working condition, and there is no abnormal wear of wheel polygon [53]. Installing the abrasive block in existing rail transit trains is a local improvement with high operability. Therefore, this method is currently the most ideal suppression measure.

2.3 Improving the hardness of wheel tread

The hardness of wheels is divided into wheel tread hardness and wheel rim section hardness, and the wheel tread hardness is higher than the wheel rim section hardness. The rim section hardness of the radial wheel shows a stepwise decrease distribution. Chang et al. [55] conducted wear tests under nine working conditions for the combination of three commonly used wheel materials of EMUs and three rail materials on the Amsler wear testing machine and found that the degree of polygonal wear of wheels varied under different wheel-rail hardness ratios. When the hardness ratio of wheel-rail matching material was less than 1.05, polygonal wear of wheel was prone to occur. When the hardness ratio was greater than 1.36, there was almost no wheel polygon, and when the hardness ratio was between 0.80 and 1.05, the radial jump value of the wheel polygon decreased with the increase of the hardness ratio. Shen et al. [56] found through actual measurement of 22 794 wheel polygon data that the proportion of polygonal wear of wheels increased as the wheel diameter decreased. They proposed using a hydraulic device of the underfloor wheelset lathe to roll the wheels, so as to improve the hardness of the wheel tread, which could effectively alleviate the polygonal wear of wheels. Moreover, rolling would not cause damage to the surface condition and contact fatigue of wheels.

In conclusion, by appropriately increasing the hardness of the wheel tread, wheel wear could be reduced. However, as a pair of rolling contact pairs, the hardness ratio of the contact surface of the wheel and rail determines the degree of wear of the wheel and rail. If the wheel tread is hard, the rail will wear quickly and is prone to rail corrugation. If the rail surface is hard, the wheels will wear out quickly and easily form wheel polygons. Therefore, it is not possible to reduce wheel wear solely by increasing the hardness of the wheel tread, but to study the causal relationship between the wheel polygon and the rail corrugation, optimize the wheel-rail contact hardness, and achieve the best matching relationship.

2.4 Strengthening the damping of fastener

Whether it is ballastless track or ballast track, the fastener system is a key component connecting the rail and the foundation under the track, and its stiffness and damping play an important role in the vibration and impact between the wheel and rail. Chen et al. [25] analyzed the influence of fastener stiffness, damping, and wheel-rail friction factor on wheel polygon. The study showed that reducing friction factor and appropriately increasing the damping of fastener could suppress wheel polygon, while the influence of fastener stiffness on wheel polygon was small. Zhao et al. [57] used the negative eigenvalue analysis method to study the formation mechanism of wheel polygon and evaluated the occurrence trend of self-excitation vibration of friction based on the equivalent damping ratio of the system. When the equivalent damping ratio was negative and the absolute value was larger, the self-excitation vibration of friction was more likely to occur. It was calculated that the frequency of self-excitation vibration of wheel-rail friction when a high-speed train brakes was 495.01 Hz, and the corresponding equivalent damping ratio was less than 0. When the stiffness of fastener was increased, there were still points with equivalent damping ratios less than 0 at two unstable vibration frequencies of 495.20 and 495.21 Hz in the system, and the numerical changes were slight. However, as the damping of fastener increased, there was no situation where the equivalent damping ratio was less than 0 in the system. Therefore, the stiffness of fastener had a relatively small impact on the wheel polygon, but increasing the damping of fastener appropriately could effectively suppress the polygonal wear of wheels. Wu et al. [58] found that higher fastener stiffness accelerated wheel wear and was more likely to lead to low-order wheel polygon, and strengthening the damping of fastener appropriately could effectively reduce the growth rate of high-order wheel polygon. Tao et al. [34] compared the effects of two types of subway track fasteners on the vertical acceleration of axle box through on-site experiments. The study found that the wheel-rail contact force on the track using soft stiffness fasteners was low, and the development of polygonal wear of wheel could be slowed down by reducing the stiffness of fastener.

In summary, appropriately strengthening the damping of fastener can effectively suppress the development of wheel polygon, which has been widely recognized by scholars. However, there are different opinions on the impact of changes in fastener stiffness on wheel polygons. Some believed that increasing the fastener stiffness could suppress the generation and development of high-order wheel polygon [44]; some believed that the influence of fastener stiffness on wheel polygon was relatively small [25, 57]; some believed that increasing the fastener stiffness could lead to the generation of low-order polygon [58]; and some believed that reducing the fastener stiffness was an effective measure to reduce the formation of polygonal wear [34]. Therefore, the influence of fastener stiffness on wheel polygon needs to be further verified through experiments.

2.5 Applying variable speed running

By changing the running speed of the train, the vibration excitation of the natural frequency is avoided to prevent it from matching with the excitation frequency caused by the polygonal wear of wheel. Wu et al. [59] studied the formation factors of polygonal wear of wheel through tracking investigation and on-site experiments and found that the wheel was affected by periodic external excitations, which made the bogie system resonate within 550–600 Hz, resulting in the generation of wheel polygon. After tracking and testing the vibration characteristics of vehicle, it was found that frequently changing the running speed of train during round trips could effectively reduce the growth of the polygon wear of wheel. Wang [60] analyzed the cause of abnormal vibration in the brake disc of a certain EMU on the Lanzhou-Xinjiang passenger dedicated line through actual measurement, which was caused by that the excitation frequency of wheel polygon and the excitation frequency of rail corrugation were close to the natural modal frequency of the brake disc, resulting in resonance. He proposed applying variable speed running and changing the modal frequency of the brake disc structure to alleviate the high-frequency vibration. Liu et al. [61] analyzed the influence of wheel polygon on the vertical wheel-rail force based on the rigid-flexible coupling dynamics model under elastomer wheelset and proposed that the running speed corresponding to the excitation frequency generated under the dominant order of wheel should be avoided as far as possible.

The resonance frequency can be prevented by frequently changing the running speed of trains traveling between certain routes, but in the actual operation process, it is bound to bring more inconvenience to the scheduling work. Obviously, the feasibility of this measure remains to be discussed.

In addition, the natural frequency can be avoided by changing the inherent vibration characteristics of the wheelset. Li et al. [38] improved the first-order bending resonance frequency of the wheelset by thickening and found that there was no obvious high-order polygon. Active vibration control can also be used to avoid the inherent vibration of system and then the development of wheel polygon can be suppressed. Hung et al. [62] established a vehicle-bridge coupling dynamics model and analyzed that the low-frequency excitation induced by long-wavelength irregularity may be close to the natural frequency of the vehicle suspension system, causing severe vibration of the vehicle body. They proposed installing damping plates under the rail pad to avoid resonance of the vehicle suspension. However, it is difficult to implement these two suppression measures in existing vehicles, but they can be considered in new vehicles.

Of course, controlling the irregularities of track is the fundamental way to suppress wheel wear, so high-speed railway lines all use seamless rails. However, there are welded joints in seamless rail, so it is necessary to control the irregularities of the welded joints [34]. In addition, rail corrugation [45] and uneven under-rail support and turnouts [59] can also generate periodic external excitations. After running for a period of time, the wheel will experience periodic wear, and when the periodic wear conforms to the natural frequency mechanism, wheel polygon will be generated and will develop rapidly.

In summary, through a series of theoretical explorations, on-site experiments, and engineering practices, the wheel polygon problem of rail transit train can be basically controlled, but the underlying mechanisms have not been fully explored.

3 Dynamics model and dynamics response of vehicle-track coupling

The formation mechanism of wheel polygon involves multiple factors, many of which are difficult to be analyzed through on-site experiments. Therefore, it is necessary to carry out research with the help of basic theories and dynamic numerical simulation. The most fundamental of numerical simulation is the dynamics model, and the accuracy of the model is particularly important to the calculation results. At the same time, studying the influence of wheel polygon on the dynamic response of vehicle system often uses a dynamics model for simulation analysis. Of course, the conclusions obtained from on-site or laboratory tests under the same working condition are the most convincing. Therefore, the most ideal way to conduct research on vehicle-track coupling dynamics is to combine testing and simulation.

3.1 Vehicle-track coupling dynamics model

The establishment of a dynamics model for rail transit can be traced back to 1867, when Czech engineer Winkler proposed an elastic foundation model when calculating railway track [63]. After continuous improvement, Clark et al. [64] proposed a continuous track model with discrete elastic supports in 1982, indicating the mature construction of the track model. The construction of vehicle dynamics model has gone through the development of single wheelset model, bogie model, and vehicle dynamics model. The theoretical model of wheel-rail rolling contact has experienced the development of the Carter's theory, Vermeulen-Johnson's theory, Kalker's linear theory, and Kalker's simplified theory. It is worth pointing out that although the above three classical dynamics models can meet the calculation requirements at that time, with the high-speed and heavy loading of railway transportation, the problem of wheel-rail dynamic interaction has become increasingly prominent. In this context, Zhai [65] first proposed the theoretical system of vehicle-track coupling dynamics, established a vehicle-track unified model (i.e., Zhai's model), and proposed the design principle and method of optimal matching between vehicle and track.

Based on this model, scholars in China and abroad have established different types of dynamics models through local improvements. Baeza et al. [66] established a vehicle-track rigid-flexible coupling dynamics model considering flexible rotating wheelsets. Zhang et al. [67] added the motor and gear transmission system on the basis of the above model. Ling et al. [68] considered the influence of car-body flexibility based on this model. Han et al. [69] established a vehicle-track rigid-flexible coupling dynamics model of rotating flexible wheelsets, and considered the influence of wheelset flexibility and rotation effects in the calculation of wheel-rail rolling contact. Wu et al. [43] established a vehicle-track rigid-flexible coupling dynamics model based on the above model. Due to the significant increase in computational complexity caused by the addition of flexible bodies in the dynamics model, the calculation time is significantly increased. Therefore, when making components flexible, the focus should be on the analysis object and components with higher modal frequencies. The vibration frequency of each component of the vehicle-track coupling system and the research object should be comprehensively considered, and the calculation time and accuracy should be taken into account. The wheelset can be mainly processed flexibly, and the modeling process is shown in Fig. 4.

In summary, the above models do not consider longitudinal direction but belong to the vehicle-track vertical and lateral spatial coupling models.

Under the influence of the longitudinal impact of long grouping heavy-haul trains, the construction of vehicle-track coupling dynamics model has gradually developed from the vertical-lateral coupling model to the vertical-lateral-longitudinal three-dimensional coupling model [70]. Liu et al. [71] established a three-dimensional dynamic model for heavy-haul train-track coupled system, calculated the action force between wheel and rail under two operating conditions of running and braking, and verified the accuracy of the model through experiments.

With further research on the vehicle-track coupling dynamics model, it is clearly not enough to only consider the track line as a roadbed structure, for in actual lines, there are bridges and tunnels in addition to the roadbed structure. Zhao et al. [72] established a vehicle-track-bridge dynamics model and verified the accuracy of the model through experiments. Xu et al. [73] established a vehicle-track-tunnel coupling dynamics model and analyzed in detail the vibration characteristics of vehicles inside the tunnel.

In summary, based on the original "Zhai's model", the vehicle-track coupling dynamics model gradually extends from the vertical model to the three-dimensional coupling model considering lateral and longitudinal directions. At the same time, the track model becomes more comprehensive, providing an efficient computational model for studying wheel-rail contact dynamics. Since the pantograph-catenary contact will affect the stability of train under high-speed operation, the vehicle-track coupling dynamics model considering the pantograph-catenary system can be established in the future.

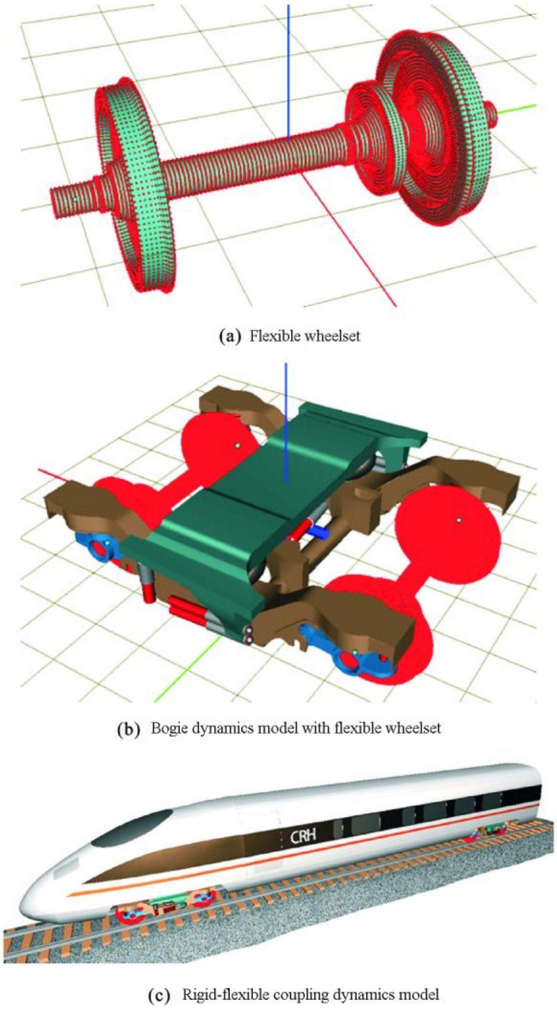

Fig. 4 Vehicle-track rigid-flexible coupling dynamics model

3.2 Simulation analysis of vehicle vibration response

Based on the vehicle-track coupling dynamics model, the influence of wheel polygon on vehicle vibration response is studied by combining simulation and measurement, and then the formation mechanism of wheel polygon is analyzed. Liu et al. [74] studied the influence of wheel polygon on the wheel-rail dynamic interaction based on the vertical coupling dynamics model of vehicle-ballast track. The study found that wheel polygon would cause large fluctuations in the wheel-rail interaction force, and the short wavelength component of the wheel polygon would excite the high-frequency vibration of the rail and sleeper. By establishing the vertical coupling dynamics model of vehicle-slab track, Chen et al. [75] analyzed the effects of two working conditions of the wheel polygon and the combination of wheel polygon and rail weld irregularity on the wheel-rail dynamic characteristics. The study found that when the maximum change rate of wheel polygon irregularity coincided with the maximum irregularity point of the rail weld zone, the wheel-rail vertical force was maximum. The vertical dynamic responses caused by the combination of wheel polygon irregularity and weld irregularity were significantly higher than various indicators under single wheel polygon. Song et al. [76] established a wheelset-slab track coupling dynamics model and studied the influence of the order and amplitude of wheel polygon on the transient dynamic behavior (displacement, acceleration, and Mises equivalent stress, etc.) of wheel-rail contact. The results showed that the displacement and Mises equivalent stress were directly proportional to the order, amplitude, and velocity of the wheel polygon. Yin et al. [77] analyzed the influence of speed, order, and amplitude of wheel polygon on the wheel-rail vertical force based on the vehicle-track dynamics model by measuring the vibration acceleration of wheel polygon and axle box. The study found that the vertical force increased with the increase of amplitude and speed, and the order of polygon also showed this pattern. However, the excitation frequency of wheel polygon under some orders was close to the natural frequency of the track, causing resonance and large jumps. Gan et al. [78] analyzed the influence of 20th-order wheel polygon on equivalent conicity and hunting movement and found that the wheel polygon had no significant effect on equivalent conicity and hunting movement wavelength, but had a significant impact on the wheelset longitudinal velocity, contact radius, yaw angle rate, and lateral acceleration. Peng et al. [79] found through the actual measurement of the vibration acceleration of the wheel polygon, the axle box and vertical block that the vibration peak frequency of the axle box and vertical block was close to the excitation frequency of the prominent wheel polygon. Through the finite element analysis of the vertical block under the constraint condition, it was found that its modal frequency was close to the excitation frequency of the 27th-order wheel polygon, causing resonance and fatigue fracture of vertical block. Yang et al. [80] analyzed the influence of wheel polygon on the vibration response of wheel-rail and axle box through a combination of measurement and simulation, and analyzed the influence of wheel polygon on the lateral vibration of brake disc when considering braking force. They found that when the excitation frequency of wheel polygon was close to the natural modal frequency of some components of vehicle-track system, its vibration intensified. When braking force was applied, the vibration acceleration of the brake disc was much smaller than that without braking, and the 4th-order bending modal frequency of the wheelset disappeared due to the application of braking. By establishing a vehicle-track coupling dynamics model that considers the flexibility of wheelsets, axle boxes, and tracks, Wu et al. [81] obtained the polygonal wear of wheel and the vibration acceleration of axle box through testing and verified the accuracy of the model. The study found that high-order wheel polygon would cause high-frequency vibration between wheel and rail, and excite the inherent mode shapes of wheelset and axle box, resulting in large vibration acceleration and dynamic stress of axle box.

Wu et al. [82] tracked and tested the wheel polygons of some models of EMUs before and after turning, and the testing site was shown in Fig.5. A statistical analysis was conducted on the relationship between the vibration frequency of wheel polygon and the wheel diameter, speed, and wheelbase. Based on the dominant order and different amplitudes, the wheel-rail vibration response was analyzed with the combination of wheel polygon and three types of track excitation being wheel-rail periodic wear working condition. Among them, working condition 1 only considered the wheel polygon, working condition 2 was the combination of wheel polygon and residual corrugations, and working condition 3 was the combination of wheel polygon and rail corrugations. The research found that the excitation frequency generated by the wheel polygon of EMUs was 550–600 Hz. When the natural modal frequency of the vehicle or track components was close to this frequency, resonance was prone to occur, which increased the wheel-rail vertical force and further aggravated the wheel polygon, as shown in Fig. 6.

Fig. 5 Measurement of wheel polygon

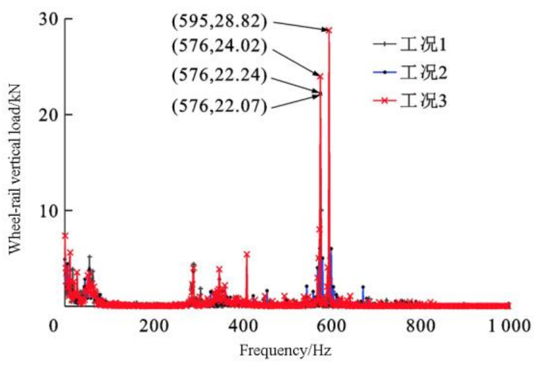

Fig. 6 Frequency domains of wheel-rail vertical force at 300 km·h-1

3.3 Analysis of measured data of vehicle vibration response

Through on-site measurement of the vibration response of bogie components, the influence law of wheel polygon on vehicle vibration response is analyzed in the frequency domains, and then the formation mechanism of wheel polygon is analyzed. As for the vibration response caused by the wheel polygon of EMUs, Shi et al. [83] tracked and tested the wheel wear evolution and vehicle dynamic performance of EMUs for 2 million km and found that the wear rate increased with the increase of operating distance, and the wear of wheel tread led to the softening of the surface and then wheel polygon. The equivalent conicity of the wheel increased approximately linearly with the wear of the wheel, and the increase of the equivalent conicity intensified the vehicle vibration. Luo [84] conducted field tests on the wheel polygon of EMUs, compared and analyzed the vibration characteristics of axle box before and after turning, and found that there was no high-frequency vibration in the vibration spectrum after turning. At the same time, the vibration spectrum law of the axle box, frame, and motor before turning was obtained through actual measurement, and it was found that the vibration of the component was significantly enhanced under the wheel polygon, and there was high-frequency vibration.

At the same time, to study the effect of the longitudinal impact of heavy-duty freight transportation on wheel wear, Wang et al. [85] obtained through actual measurement that the main frequency of longitudinal vibration of the locomotive body with severe vibration was 20.6 Hz, and the main frequencies of longitudinal vibration of wheelset were 19.2 and 20.6 Hz. The reason for vehicle body vibration was the longitudinal vibration of wheelset. The experiment verified that installing a series of longitudinal shock absorbers could effectively suppress longitudinal vibration of 17–19 Hz, thereby reducing the damage of wheel tread.

To quantitatively analyze the wear degree of wheel polygons of subway vehicles, Chi et al. [86] obtained all wheel polygon data of a subway train in Qingdao Metro Line 2, and found that the wheel polygons were mainly of the first 5 orders and 7–9 orders. Based on the measured data, they provided the fitting empirical formula of wheel polygon.

To sum up, analysis of measured data has the advantage of high accuracy in the study of vehicle vibration response, but it has limitations in the analysis of the generation mechanism and wear prediction. Therefore, scholars generally use the combination of measurement and simulation to study the generation mechanism and influencing factors of wheel polygon.

4 Influence of wheel polygon on fatigue damage

Wheel polygon can exacerbate wheel-rail vibration, and research in China and abroad shows that the damage of some components of vehicle structures and track systems is almost entirely related to wheel polygon.

4.1 Influence of wheel polygon on fatigue damage of vehicle components

As for research on fatigue damage of vehicle structural components caused by wheel polygons in China and abroad, the existing achievements mainly involve bogie frame, gear box, wheel, and axle. Fu et al. [87] analyzed the causes of fatigue cracks in the bogie frame of subway vehicles and pointed out that the low-frequency wheel-rail impact caused by rail joints and the wheel polygon excited the inherent mode of frame, resulting in high-frequency resonance. Wang et al. [88] analyzed the main factors causing fatigue damage to the bogie frame of subway vehicles through actual measurement, and analyzed the influence of wheel polygon, rail corrugation and rail joints on the fatigue damage of the frame. The research found that rail corrugation accompanied by wheel polygon was the main factor causing fatigue damage of the bogie frame. Wang et al. [89] analyzed the influence of common wheel-rail defects on the fatigue damage of subway vehicle bogie frame by establishing a fatigue reliability model of the frame. The study found that the rail welds in straight sections had little effect on the fatigue damage of the frame, and the rail corrugation, wheel polygon and velocity related excitation would cause high-amplitude and high-frequency dynamic stress, thus aggravating the fatigue damage of the frame. Therefore, the high-frequency vibration caused by the wheel-rail periodic excitation formed by the combination of wheel polygon and rail excitation (rail corrugation and rail welded joints) was the main cause of fatigue damage of bogie frame.

Wu et al. [90] established a three-dimensional multi-body vehicle system dynamics model that considered the flexibility of the gear box and wheelset and the nonlinear wheel-rail contact. The measured dominant order of the wheel polygon of the operating EMUs was the 20th order, which was used as the wheel-rail excitation input to calculate the dynamic stress of the gear box under different amplitudes of the wheel polygon. Based on the kernel density estimation method, the dynamic stress on the gear box was extrapolated to evaluate its fatigue damage, and the fatigue damage of the gear box without polygonal wear was compared and analyzed. The results showed that the impact of the 20th-order wheel polygon on the fatigue damage of the gear box was increased by 63% compared to that without the polygon. Hu et al. [91] conducted a study on fatigue cracks of the EMUs gearbox casing and found that the combination of wheel polygon and track irregularities excited the inherent modes of the gear box at 571 and 602 Hz, causing resonance and leading to fatigue cracks. Therefore, whether it is high-speed trains or subway vehicles, wheel polygon is the cause of fatigue damage of bogie gearbox casing.

By establishing the vehicle-track coupling dynamics model of CRH2 EMUs, Xiao et al. [92] calculated the longitudinal and lateral creep force/rates of wheel-rail under different orders and amplitudes, and used them as input parameters of the stability diagram and damage function to analyze the fatigue characteristics of wheels with polygonal wear. The study found that the rolling contact fatigue of wheel deepened with the increase of order and amplitude and was more sensitive to the change of wave depth. Zhang et al. [93] analyzed the influence of wheel polygon on tread fatigue damage under high and low wheel-rail adhesion contact conditions by establishing a vehicle-track coupling dynamics model and a wheel tread fatigue damage prediction model. The study found that under high adhesion conditions, severe wheel polygons would aggravate tread fatigue damage, and under low adhesion conditions, wheel polygon would aggravate tread wear. Yan et al. [94] revealed the influence of wheel polygon on the life of cracked wheels by testing the crack propagation rate of wheels at different angles. The study found that as the order of wheel polygon increased, the crack propagation life of wheels significantly decreased.

Wu et al. [51] analyzed the effect of wheel polygon on the fatigue damage of high-speed EMUs axles based on the vehicle-track coupling dynamics model. According to the theory of cumulative fatigue damage, the Brown-Miller method was used to calculate the fatigue life of axles considering polygonal wear of wheel, and the cloud diagram of logarithmic mileage fatigue life was shown in Fig. 7. The results showed that the fatigue life of back axle after considering the wheel polygon was less than the design life of 20 years specified in the Operation and Maintenance Regulations of Railway EMUs (TG/CL127-2013). Since the life was based on the fatigue life of high-order wheel polygon before wheel turning, it could not be concluded that the axle did not meet the design requirements. However, sufficient attention should be paid to high-order wheel polygon, and if wheel turning was not carried out in time, it would seriously affect the service life of the axle.

Fig. 7 Distribution of axle fatigue life

4.2 Influence of wheel polygon on fatigue damage of track components

When the vibration generated by wheel polygon is transmitted downwards, it affects the fatigue life of track components. Kang et al. [95] conducted dynamic simulation analysis of fastener spring bar based on the rigid-flexible coupling dynamics model of wheel-rail system. Based on the Miner criterion, the influence of polygonal amplitude on the fatigue life of the spring bar was analyzed. The results showed that when the wheelset run on the track at a speed of 237 km·h^{-1}, the external load of the 24th-order wheel polygon had no significant effect on the Mises equivalent stress of the spring bar. When the amplitude of the 24th-order wheel polygon reached 0.225 mm and above, the excitation frequency of about 1172 Hz was transmitted from the wheel-rail system to the fastener system, thereby reducing the fatigue life of the spring bar. Zhang et al. [96] established a fatigue crack propagation model of wheel-rail rolling contact in the presence of wheel polygon to analyze the influence of wheel polygon on the fatigue crack propagation behavior of rails. The study found that wheel polygon could cause significant periodic fluctuations in normal and tangential wheel-rail forces, and with the increase of polygonal amplitude and order, the fatigue crack propagation of rails would be significantly accelerated.

In conclusion, when the vehicle runs on the track with good wheel-rail contact, it is mainly affected by low-frequency excitation from track irregularities [97]. The dynamic interaction force between the wheel and rail does not fluctuate much, and the interaction force is transmitted upwards through the attenuation of the first and second series suspension, and downwards through the attenuation of the fastener system and the rail slab, so that the vehicle and track components meet the design life requirements. However, when there are high-order wheel polygons, the wheel-rail excitation frequency will increase and the range will be wider. When the excitation frequency is close to the inherent vibration frequency of some components of the vehicle, it is easy to cause resonance, which leads to the significant increase of the dynamic stress and thus affects its fatigue life. However, there are relatively few studies on the fatigue life of structures under wheel-rail periodic wear such as wheel polygon or rail corrugation. Therefore, it is a new direction to analyze the fatigue damage of vehicle structures and track system components under wheel-rail periodic wear such as wheel polygon.

5 Conclusions

(1) Wheel polygon is a kind of abnormal wheel wear that is commonly present but has not been completely solved in rail transit trains. When there is initial defect of wheel, every impact with the track will produce wear at the defect position, and the wear extends in a wavy shape along the tread circumference. When the wavy wear is connected at the head and tail, the initial wheel polygon is formed [98]. The initial wheel polygon further aggravates the wheel-rail vibration, which gradually forms a vibration excitation with a natural frequency during the vehicle operation. When the vibration excitation frequency is close to the inherent modal frequency of some parts of vehicle and track, it is easy to cause resonance, thus forming more serious wheel polygon [99].

(2) The suppression of wheel polygon has achieved good results after a series of theoretical explorations, on-site

experiments, and engineering practices. From the formation mechanism of wheel polygon, it can be seen that the initial defect of the wheel is the origin. Therefore, controlling the initial defect of the wheel is the fundamental way to suppress the formation and development of wheel polygon. From the perspective of feasibility, installing the abrasive block of tread on operating vehicles is undoubtedly the most ideal measure. On this basis, further optimizing the material of abrasive block, improving the matching relationship between tread and abrasive block, and increasing the conformality of the two [100], so that the suppression effect of the abrasive block becomes more ideal.

(3) Avoiding wheel-rail coupling resonance is still the most fundamental method to suppress wheel polygon, and the wavelength of uneven wear on the wheel circumference can be changed repeatedly by changing the speed or the intersection operating mode, so as to suppress the growth of a single short wavelength.

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轨道交通列车车轮多边形磨耗机理及其影响综述

吴　丹,丁旺才
(兰州交通大学 机电工程学院,甘肃 兰州　730070)

摘　要:总结了近几年国内外轨道交通列车车轮多边形的研究成果,分析了导致车轮形成多边形的主要因素与发生机理以及动车组与地铁车辆多发的高阶车轮多边形不同的原因,探讨了车轮多边形的抑制措施,概括了车辆-轨道耦合动力学模型的产生与发展,总结了车辆-轨道耦合动力学仿真分析的主要成果,提出了考虑车轮多边形等轮轨周期性磨耗下的车辆-轨道系统零部件的疲劳损伤这一新研究方向。分析结果表明:车轮初始缺陷、轮轨摩擦自激振动、轮轨黏滑振动、轮轨系统 P2 共振、轮对固有模态振动、车轮直径与转向架组成部件引起的共振等会造成车轮多边形的发生;地铁车辆发生的车轮多边形主要是由轮轨系统 P2 共振所致,而高速动车组多发的高阶车轮多边形一般不是由 P2 共振直接引起的;提高车轮镟修质量、增加研磨子、提高车轮踏面硬度、增大扣件阻尼、变速运行等措施可以抑制车轮多边形的发展,但从车轮多边形的形成机理可知,车轮初始缺陷是起源,控制车轮初始缺陷是抑制车轮多边形形成与发展的根本,从可行性角度而言,增加研磨子是最理想的措施;当车轮存在高阶多边形后,轮轨激励频率会显著增大且范围分布更广,当激励频率与车辆某些部件的固有振动频率接近时,易引发共振,导致其动应力显著增大,影响其疲劳寿命,故分析车辆-轨道系统主要承载部件的疲劳损伤时,应考虑随机轨道不平顺以及轮轨周期性磨耗等不利因素。可见,现有研究成果基本揭示了车轮多边形的形成机理,并提出了可行的抑制措施,但考虑到列车运行环境的不确定性以及车辆-轨道耦合系统关联因素众多,分析过程难免与实际有差异,故仍需进一步深入研究。

关键词:车辆工程;动力学性能;车轮多边形;磨耗机理;抑制措施;动力学模型;疲劳损伤
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Review on wear mechanism and influence of wheel polygon of rail transit train

WU Dan, DING Wang-cai
(School of Mechanical Engineering, Lanzhou Jiaotong University, Lanzhou 730070, Gansu, China)

Abstract: The research results of wheel polygon of rail transit trains in China and abroad in recent years were summarized, the main factors and mechanisms leading to the formation of wheel polygon were analyzed, the reasons for the difference in high-order wheel polygons between electric multiple units (EMUs) and metro vehicles were investigated, the main causes of the difference were summarized. The suppression measures for wheel polygon were discussed, and

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作者简介:吴　丹(1986-),男,甘肃庄浪人,兰州交通大学副教授,工学博士,从事车辆系统动力学与疲劳强度理论研究。
通信作者:丁旺才(1964-),男,甘肃天水人,兰州交通大学教授,工学博士。
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the generation and development of vehicle-track coupling dynamics model were summarized. At the same time, the main results of the simulation analysis of vehicle-track coupling dynamics were presented, and a new research direction was proposed, which considered the fatigue damage of vehicle-track system components under the periodic wear of wheel-rail such as wheel polygon. Analysis results show that the initial defect of wheel, self-excitation vibration of wheel-rail friction, stick-slip vibration of wheel-rail, P2 resonance of wheel-rail system, inherent mode vibration of wheelset, wheel diameter, and resonance caused by bogie components can cause wheel polygon. The wheel polygons of metro vehicles are mainly caused by the P2 resonance of the wheel-rail system, while the multiple high-order wheel polygons of high-speed EMUs are generally not directly caused by the P2 resonance. Improving the quality of wheel turning, increasing the abrasive block, enhancing the hardness of wheel tread, strengthening the damping of fastener, and applying variable speed running can restrain the development of wheel polygon. However, according to the formation mechanism of wheel polygon, the initial defect of wheel is the origin, and controlling the initial defect of wheel can fundamentally inhibits the formation and development of wheel polygon. From the perspective of feasibility, installing the abrasive block is the most ideal measure. When the wheel has a high-order polygon, the wheel-rail excitation frequency will increase significantly, and the range distribution is wider. When the excitation frequencies are close to the inherent vibration frequencies of some parts of vehicle, the resonance is easily triggered, which will lead to a significant increase in its dynamic stress and affect its fatigue life. Therefore, when the fatigue damage of the main bearing parts of vehicle-track system is analyzed, adverse factors such as random track irregularities and periodic wear of wheel-rail should be considered. It can be seen that the existing research results basically reveal the formation mechanism of wheel polygon, and feasible suppression measures are proposed. However, since the train operation environment is uncertain, there are many related factors in the vehicle-track coupling system, and the analysis process is inevitably different from the actual situation. Therefore, further in-depth research is still needed. 1 tab, 7 figs, 100 refs.

Key words: vehicle engineering; dynamics performance; wheel polygon; wear mechanism; suppression measure; dynamics model; fatigue damage

Author resumes: WU Dan(1986-), male, associate professor, PhD, wudan@mail.lzjtu.cn; DING Wang-cai(1964-), male, professor, PhD, dingwc@mail.lzjtu.cn.

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0 引 言

随着轨道交通列车运营里程的增加，国内外动车组、地铁、轻轨以及机车和车辆均出现了不同程度的车轮多边形，成为了铁路行业困扰列车运营的顽疾，也是目前铁路领域的研究热点和亟待攻克的首要问题。

车轮多边形是指沿车轮圆周形成的周期性波状磨损[1]，分为低阶车轮多边形和高阶车轮多边形。低阶车轮多边形对车辆振动影响较小，14 阶及以上称为高阶车轮多边形，对车辆振动影响较大，根据不同的表面粗糙度幅值分为 4 个等级，即维持现状、跟踪噪声、1 周内镟修与立即镟修。如果粗糙度幅值小于 10 dB · μm^{-1}，维持现状即可；如果粗糙度幅值在 10～18 dB · μm^{-1}，需每 3 万公里跟踪噪声，并通过不落轮机床检测和车辆运行品质轨边动态监测系统实时监控；如果粗糙度幅值在 18～23 dB · μm^{-1}，需 1 周内进行镟修；如果粗糙度幅值大于 23 dB · μm^{-1}，需立即镟修。当高阶车轮多边形的粗糙度幅值超标时，即大于 18 dB · μm^{-1}，则会引起车辆剧烈振动，如果不及时进行车轮镟修，容易导致转向架某些部件出现裂纹或松动丢失。

关于车轮多边形磨耗,国内外学者做了大量研究并取得了重要成果。本文主要从车轮多边形的形成机理、车轮多边形的抑制、车辆-轨道耦合动力学模型与动力学响应、车轮多边形对疲劳损伤的影响四方面概要介绍过去的研究成果及其最新发展,探讨后续研究所面临的挑战及有待进一步研究的内容。

1　车轮多边形的形成机理

关于车轮多边形的形成机理,国外早在 20 世纪 80 年代就已经发现并开展了相关研究。Kaper[2] 发现随着荷兰城际列车运行里程的增加,车轮出现了多边形磨耗,导致噪声问题出现,随即拉开了车轮多边形磨耗机理研究的序幕;Kalousek 等[3] 在温哥华地铁上发现车轮存在严重的多边形磨耗,并开展了相关研究;Morys[4] 以德国 ICE 列车为对象,经过近 10 年的研究,发现车轮多边形的形成主要是由于车轮的 3 阶多边形激励频率与轮对的 1 阶弯曲模态频率接近,引起异常振动所致,也就是说,车轮多边形激励频率与轮对某阶固有模态频率接近而引发的共振是造成车轮多边形的因素之一;Dekker[5] 对荷兰轻轨车辆出现的车轮多边形进行研究时,也得到了相同的研究结论;Johansson 等[6-7] 在总结了瑞典 X2 高速列车车轮多边形的磨耗特征后,通过建立轮轨滚动接触多体系统动力学模型,仿真分析了车轮多边形的演变规律,提出 P2 共振是导致车轮发生 5～7 阶多边形的主要原因;Nielsen 等[8-9] 分析了车轮多边形对车辆部件和轨道系统的影响,研究发现车轮多边形对轮轨相互作用的影响明显大于速度的影响;Barke 等[10] 详细综述了车轮多边形对车辆部件和轨道系统的影响。

中国轨道交通起步晚,2004 年以前国产各型动车组因种种原因未能投入大规模运营,车轮多边形主要出现在机车和普速客货车上,但因其运行速度低且通过车轮镟修可以解决,故未对该问题进行深入研究。随着 CRH 系列动车组的引进以及大规模投入运营,部分车型的车轮出现了不同程度的车轮多边形,有些车型甚至出现了超标的高阶车轮多边形,严重影响行车安全,引起了铁路运营维护部门和科研工作者的极大关注,同时,地铁车辆也相继报道车轮多边形问题,因此,研究车轮多边形的形成条件、成因以及对车辆-轨道系统的影响,已成为轨道交通领域中最受关注的研究方向之一。

国内外学者分别从车轮初始缺陷、轮轨摩擦自激振动、轮轨黏滑振动、轮轨系统 P2 共振、轮对固有模态振动、车轮直径、转向架组成部件引起的共振等方面进行了研究。研究表明上述因素会引起车轮多边形的发生。

金学松等[11-12] 通过跟踪中国高速列车车轮多边形的磨耗特征,发现车轮多边形主要以 2～3 个不同波长的波磨为主,当车轮直径为波长整数倍,波长以单一波长为主,每次轮轨滚动接触相位相同时,车轮多边形磨耗将迅速增长;提出轨道结构不是产生车轮多边形的主因,车辆内部结构的共振、轮轨表面粗糙度、车轮偏心以及镟修后的初始不圆度、钢轨的弯曲共振等原因是产生车轮多边形的主要因素;认为采取变速运行以及应用研磨子可有效降低车轮多边形。李彦夫等[13] 从车轮多边形的形成机理、预测以及对轮轨系统动力响应影响这三方面综述了国内外的研究现状,总结了车轮多边形形成的 6 种典型因素以及 2 种间接检测方法,分析了噪声预测模型以及车轮多边形与车轮噪声之间的关系,建议制定更符合中国情况的车轮镟修方案,从而降低维修成本。朱海燕等[14] 从车轮多边形对车辆系统动力学的影响、车轮多边形的形成机理、车轮多边形的静态和动态监测、车轮多边形的控制等方面进行综述,指出车轮多边形对车辆系统动力响应影响显著,目前最好的处理方法是车轮镟修,建议将动态监测数据与动力学仿真模型结合研究车轮多边形的形成机理及预防措施。陶功权等[15-16] 总结了国内外车轮非圆化磨耗的形成机理、仿真预测和控制措施这三方面过去的研究成果;调研发现国内外轨道交通车辆中广泛存在车轮多边形磨耗,但其表现形式不一,国外车轮多边形主要以低阶为主,而中国车轮多边形主要以高阶为主;总结了车轮非圆化磨耗的三大类形成因素,分别是车轮初始缺陷、车辆-轨道耦合振动与踏面制动时热弹性失稳,指出车轮多边形的形成往往是多因素共同所致,因此,即便对于同一车型的车轮多边形的形成机理,也可以从不同观点出发来解释;总结了车轮非圆化磨耗预测的研究成果,概述了目前广泛应用的方法,即通过车辆-轨道耦合动力学模型仿真得到轮轨接触全局参数,并将全局参数作为局部参数的输入,基于磨耗模型计算车轮非圆化磨耗;最后总结了车轮多边形的控制措施,例如,提高车轮镟修质量,加装研磨子,提高车轮踏面硬度等。

综上所述,基于现有的研究成果,车轮多边形问题已基本得到了有效控制,并提出了相应的抑制措施,但其深层次的机理尚未探究清楚,使得车轮多边

形尚未从根本上彻底解决。随着动车组动态监测技术以及计算机仿真技术的不断提升,更多学者对车轮多边形的产生机理有了更深入的研究。下面将梳理总结近几年国内外关于车轮多边形磨耗机理的研究成果,并探讨存在的分歧以及各成因之间的关联性。

1.1 车轮初始缺陷

车轮初始缺陷多是在车轮加工或镟修时因加工工艺所导致的。Staśkiewicz 等[17]通过实测证实车轮多边形的形成与车床上固定车轮的方式有关。早期轮对加工和镟修主要采用三爪卡盘车床对车轮踏面进行修型,由于夹具作用点在径向存在弹性变形,使得卸载后在夹具作用点处形成了微小的初始3阶多边形[18]。随着不落轮机床的普及,因其具有在车辆不解体的状态下可对轮缘和踏面进行在线加工和等效锥度及多边形在线检测的优点,使得轮对测量和镟修均在不落轮机床中进行。Cui 等[19-20]分析了不落轮机床镟修时影响切削质量的因素,指出1、4~6、10~13阶多发是由于不落轮机床的定位方式导致加工不良所引起的,采用驱动轮定位易导致1阶车轮多边形,驱动轮不圆顺映射到车轮易形成4~6和10~13阶车轮多边形;任德祥等[21]研究发现初始车轮多边形的形成与不落轮机床以2个驱动轮作为定位轮的车轮定位方式有关;苏建等[22]进一步分析了不落轮机床驱动轮偏心与初始车轮多边形的关系,发现驱动轮偏心是造成新镟车轮4阶多边形的主要原因。因而,采用不合理的镟修工艺以及不落轮机床以驱动轮作为定位轮等会造成车轮初始缺陷。

同时,研究表明车轮踏面局部缺陷以及车轮表面材料不均匀等也会引起车轮初始缺陷,进而造成车轮多边形的发生。崔大宾等[20]通过实测和仿真相结合计算了车轮几种典型缺陷对轮轨行为的影响,研究表明车轮踏面局部缺陷会引起较大的轮轨冲击力,进而造成车轮周向材料非均匀硬化,使车轮多边形快速发展;Nielsen 等[23]通过数值仿真分析了轮轨高频振动和非均匀磨损机制,研究表明车轮圆周表面不均匀材料特性会引起车轮多边形磨耗。

综上所述,镟修后的车轮都会存在微小的初始车轮不圆顺,随运营里程的增加,逐渐发展成为车轮多边形。对于不落轮机床可通过在轴箱下部加装支撑装置,如图1所示,从而消除依靠驱动轮定位的先天性缺陷,避免车轮多边形的仿形。其次,对于车轮与驱动轮2接触点形成的弧长是某高阶车轮多边形波长的整数倍时,镟修后仍然表现出该高阶车轮多边形的这种情况,可通过2次进刀镟修,或通过调整驱动轮间距避开整除波长,有效镟修清除该阶次的车轮多边形。另外,可通过控制不落轮机床驱动轮的偏心来抑制因镟修导致的低阶多边形。

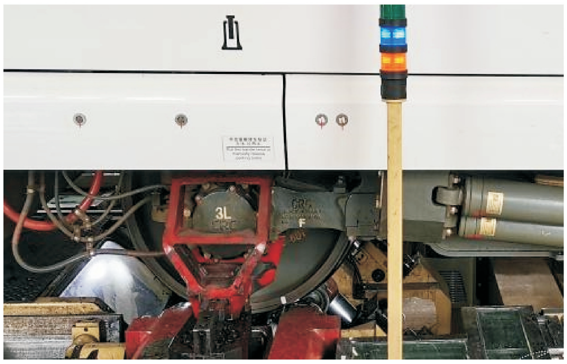


图1 增加轴箱下部支撑

Fig. 1 Increasing lower support of axle box

1.2 轮轨摩擦自激振动

当轮轨接触处于滑动状态时,容易产生摩擦自激振动。陈光雄等[24]通过建立某地铁列车弹性振动的轮轨系统有限元模型,运用 NUCARS 软件分析了曲线通过时轮轨接触点处的接触角以及轴颈上的横向力和垂向力,基于 ABAQUS 软件实现轮轨摩擦系统的有限元离散,分析了2种线路工况下的黏滑振动模态,并通过摩擦动力学运动分析求得振动频率和特征值实部。研究发现:当特征值实部为正时,系统将出现不稳定运动,而该不稳定运动造成的不稳定黏滑振动会导致车轮发生多边形磨耗;当摩擦因数小于0.27以及轮轨垂向支撑刚度不过大或过小时,可有效抑制车轮多边形。随后,该模型以及研究方法被进一步发展用于研究动车组车轮多边形的发生机理[25]。此外,赵晓男等[26]将该方法运用于研究兰新客专动车组出现的14~16阶车轮多边形的形成机理,发现由于列车起动、制动等出现的轮轨饱和蠕滑力会导致车轮发生滑动,从而产生不稳定运动,且不稳定振动频率与实测结果吻合,证实轮轨摩擦自激振动会导致车轮发生多边形。

综上所述,当轮轨接触点处蠕滑力达到饱和时,随摩擦因数的增大,易引起轮轨系统的黏滑振动,这种黏着滑动交替进行下的运动可导致轮轨表面产生波状磨耗。可通过控制轮轨表面粗糙度,降低摩擦因数来避免车轮多边形的发生,同时,可优化电子防滑器,尽量减少列车运行过程中蠕滑力饱和现象的发生。

1.3 轮轨黏滑振动

车辆在运行过程中,轮轨表面接触导致系统存

在干摩擦行为。不仅如此,由于车轮和钢轨间存在横向游隙,并且在轮轨型面特征及接触关系、轴箱定位特性等多因素条件下,会导致蛇行运动的出现[27]。此外,在垂向和横向动载荷以及轮对垂向弯曲的作用下,轮轨接触表面也会发生横向摩擦,且摩擦频率与振动频率相关,存在摩擦振动[28]。Kalousek 等[3]在温哥华地铁轮轨表面上发现波状磨耗,研究表明是由轮轨系统的黏滑振动导致的;Zhao 等[29]通过复特征值分析法研究发现轮轨间的蠕滑力达到饱和时,可引起轮轨系统的低频黏滑振动,进而加剧或导致车轮多边形磨耗;吴丹等[30]通过建立含对称间隙的干摩擦碰撞振动动力学模型来描述轮对黏滑振动动力学行为,推导了系统运动中黏着、滑动和碰撞运动的衔接关系,研究表明在低频区系统表现为大幅振荡和微幅振荡间往复切换变化,为一类典型的周期性颤振运动,并在系统轨迹穿越分界面时发生了擦边行为。颤振使轮轨接触斑内黏滑区发生剧烈变化,引起轮轨接触区车轮相对钢轨横向滑动,从而使横向蠕滑力呈周期性变化,最终诱发车轮多边形的发生。

综上所述,轮轨黏滑振动的本质是轮轨蠕滑特性,由于轮轨列车所有的静动载荷均需通过轮轨接触斑来传递,因此,研究轮轨接触斑处的蠕滑特性是根本,也是分析车轮多边形形成机理最佳的突破口。

1.4　轮轨系统 P2 共振

1974 年,英国 Derby 铁路技术中心在研究车轮通过钢轨接头或车轮局部缺陷时提出轮轨冲击的高频力 P_1 和低频力 P_2 理论[31],其中,力 P_1 为高频冲击荷载,由钢轨接头及车轮扁疤等突出的表面缺陷引起,频率在 500～1 000 Hz,其作用时间极短,主要损伤轮轨表面。力 P_2 是低频准静态荷载,频率在 20～100 Hz[32],其作用时间较长,向上可传递至车辆部件,向下可传递至轨道系统,故对车辆-轨道系统危害极大,而且线路上不可避免的轨道不平顺和车轮周向不圆顺均可能引起轮轨系统的 P2 共振。

关庆华等[33]研究发现当车辆通过钢轨焊接接头或轨面局部不平顺时,车辆簧下质量将对轨道产生力 P_1,由力 P_1 引起簧下质量在轨道中产生力 P_2,因力 P_2 引发的轮轨振动具有同时同向振动、参振质量大等特点,使得其振动范围广且振动能量大,故 P2 共振是造成车轮初始缺陷的原因之一;Tao 等[34]通过实测某地铁车辆车轮多边形、钢轨波磨、轮轨动力相互作用、钢轨焊缝接头不平顺等,研究发现 P2 共振是导致车轮产生 5～8 阶多边形的原因;刘丙林等[35]随机实测了 172 个地铁车辆车轮多边形数据,发现主要以 6～7 阶为主。通过轮轨振动实测验证了 P2 共振是由钢轨焊接接头不平顺所致,且 P2 共振易使车轮产生低阶多边形。

综上所述,轮轨表面缺陷形成的短波不平顺会引起高频力 P_1 和低频力 P_2,力 P_2 对轮对的影响波长导致车轮产生了相应波长的多边形。根据固有频率机理[36],地铁车辆常速运行下车轮多边形的激励频率和力 P_2 引起的振动频率接近,因此,地铁车辆发生的车轮多边形主要是由轮轨系统 P2 共振所致。而高速动车组因其运行速度远高于地铁列车,其常速下高阶车轮多边形的激励频率属于中高频,与 P2 共振频率相差较大,故高速动车组多发的高阶车轮多边形一般不是由 P2 共振直接引起的。

1.5　轮对固有模态振动

大量研究发现轮对的低阶弯曲振动与车轮多边形的形成有关。以地铁车辆为研究对象,Jin 等[37]通过实测和仿真相结合,发现某地铁车辆所主导的 9 阶车轮多边形产生的根本原因是轮对的 1 阶弯曲振动;李伟等[38]通过实测得到某地铁车辆轮对的频响特性,发现 2 个峰值频率 72 和 170 Hz 与轮对的 1 阶和 2 阶弯曲振动频率基本一致,由此确定了轮对 1 阶弯曲的激励共振波长范围,并对一个镟修周期内的车轮多边形发展进行了跟踪测试,发现车轮多边形由镟修一个月后的 4 阶逐步发展为 9 阶,通过加粗改造提高了轮对的 1 阶弯曲振动频率后,则不存在明显的高阶多边形,证实轮对 1 阶弯曲振动是引起车轮多边形的主要原因。由此表明,由常运营的速度或轨道激励等激发的轮对 1 阶弯曲振动会导致地铁车辆发生车轮多边形磨耗。

同样,在机车车轮多边形磨耗机理的研究中,也发现轮对的 1 阶弯曲振动对车轮多边形的形成有直接关系。Tao 等[39]对电力机车车轮多边形的产生机理进行了试验研究,得到车轮多边形的生长规律,发现大多数电力机车产生车轮多边形的主要原因是轮对的 1 阶弯曲振动被激发,从而造成 1/3 倍频程带中心波长为 200 mm 的车轮多边形;刘欢等[40]通过建立考虑轮轨柔性和牵引行为的某电力机车刚柔耦合动力学模型,对比分析了典型阶次和幅值下的轴箱振动特性以及轮轨法向力,研究表明 18 阶车轮多边形在 70 km·h^{-1}速度下的通过频率与轮对的 1 阶弯曲振动频率接近,引起轮对的 1 阶弯曲共振,从而导致车轮形成更严重的多边形。

也有研究表明轮对的低阶扭转振动与车轮多边形激励频率接近时，容易形成车轮多边形。Fröhling等[41]从理论和试验上证实机车车轴的扭转振动可能导致车轮多边形的发生；Spangenberg[42]通过试验分析了南非重载线路上运行的机车出现异常振动是由车轮多边形引起的，研究发现机车以 40 km·h^{-1}运行时，牵引系统与轮对扭转形成耦合共振，导致车轮形成 20 阶车轮多边形。

吴丹等[43]通过建立某型动车组刚柔耦合动力学模型，研究了车轮多边形对轴箱和构架振动加速度频谱特性的影响，并揭示了其规律。图 2 为 200 km·h^{-1}速度下车轮多边形幅值为 0.2 mm、阶次分别为 4、10、16 和 22 阶时轴箱与构架的振动频谱特性。由图 2 可知，4、10、16 和 22 阶时轴箱与构架的振动响应主频分别为 77.2、192.4、307.6 和 422.9 Hz，这和各阶次下车轮多边形的激励频率接近，其中轴箱在 351.6Hz 处振动幅度最大，其原因是车轮转频的倍频激励轮对的同向伞形模态，使轴箱在该频率处产生共振。

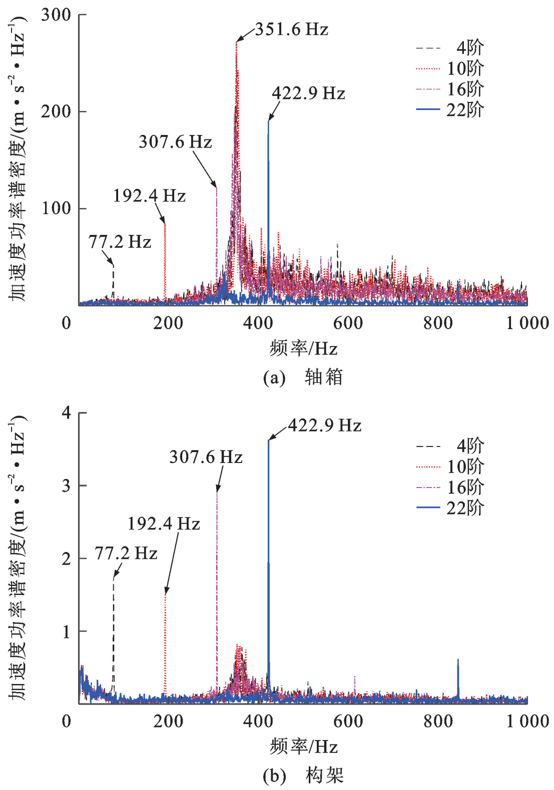


图 2 200 km·h^{-1}下轴箱和构架的振动频谱

Fig. 2 Vibration spectra of axle box and frame at 200 km·h^{-1}

综上所述，虽然动车组、地铁和机车的结构及运营环境有所不同，但均适用于车轮多边形发展的固有频率机理，即车辆在运行过程中轮对与钢轨之间存在 1 个固有频率的振动激扰，该频率应是某一结构的模态频率。这也是目前国内外学术界解释车轮多边形磨耗的形成与发展机理认可度较高的观点[44]。

1.6 车轮直径

根据固有频率机理，车轮直径与激励频率的关系为

$$f = \frac{nv}{3.6\pi d}$$

式中：f 为车轮多边形所产生的激励频率；n 为多边形阶次；v 为速度；d 为车轮直径。

吴越等[45]通过现场实测某高速铁路的钢轨波磨和车轮多边形，推测出车轮多边形的产生与车轮受到的固有频率存在相关性，研究表明当车轮直径为钢轨波磨波长的整数倍，钢轨波磨的波长为一定值或波磨变化幅度很小，轮轨滚动接触时车轮均以同一位置与钢轨波磨相接触这 3 种情况下，车轮多边形磨耗发展迅速；高阳等[46]分析了轮辋厚度对车轮多边形的影响，发现其影响规律符合固有频率机理，即随着轮辋厚度的减小，当车轮周长不能整除外激励波长时，车轮多边形发展缓慢，反之，则车轮多边形发展迅速；赵新利等[47]统计分析了线路上运营的动车组车轮直径与车轮多边形阶次之间的关系，发现车轮多边形主要以 18～20 阶为主，且车轮直径越小越易发生多边形，通过建立车辆-轨道耦合动力学模型及 Archard 磨耗模型仿真验证了固有频率机理的正确性，基于实测发现车轮偏心、钢轨波磨、轮轨异常冲击是车轮多边形产生的外激励因素。

综上所述，尽管车辆在实际线路运行时所受到的外激励(轮轨表面缺陷以及轨道不平顺等)是随机的，但是运营一段时间后车轮产生的周期性磨耗遵循固有频率机理，当车轮直径满足固有频率时，也会造成车轮多边形磨耗发展及加剧。

1.7 转向架组成部件引起的共振

研究发现当转向架中某些部件的振动频率与车轮多边形激励频率接近时，容易形成车轮多边形磨耗。吴越等[48]基于车辆-轨道耦合动力学模型分析了高速列车车轮多边形对轮轨相互作用力的影响，研究表明轮轨相互作用力随车轮多边形幅值和速度的增大而增大，最大轮轨力分布与车轮多边形幅值之间存在相位差，但同车轮多边形幅值关于角度的 1 阶导数相对应，进而提出构架和轮对耦合振动可能是造成高速列车车轮多边形激励频率多发生在 580 Hz 的原因；马卫华等[49]分析了地铁车辆发生 9 阶车轮多边形的原因，提出车轮滚动接触多周振

动是引起车轮多边形的主要原因，并基于直线电机地铁车辆-轨道耦合动力学模型，分析表明直线电机振动会引起车轮多边形的产生，特别当运行速度在 72～80 km・h-1，也就是频率在 39.08～43.84 Hz 时，容易形成车轮 9 阶多边形；高阳等[50]跟踪测试了兰新客专运营列车的车轮多边形情况，在完整运营周期(120 万公里)内，发现第 3～7 单个镟修周期内车轮主要表现为 14～16、20～23、25～27 阶多边形，其中 14～16 阶占主导地位。通过实测分析发现构架与轮对在 320 和 540 Hz 处产生的共振频率是车轮发生多边形磨耗的周期性激励。

吴丹等[51]通过对某型动车组转向架构架进行了模态分析，去除前 6 阶刚体模态，在有限元分析软件中提取构架第 7～60 阶自由模态，发现构架的整体扭转、弯曲及剪切模态频率均在 230 Hz 以下，只有局部存在 580 Hz 左右的模态频率，但由于构架局部模态与轴距不相关，因此，580 Hz 左右的激振频率与构架不存在因果关系，与转向架整体是否存在因果关系尚需进一步探究。由于篇幅所限，选取构架部分整体模态和局部模态，其模态频率和振型如表 1 和图 3 所示。

表 1　构架模态分析结果

Table 1　Frame modal analysis results

模态	阶数	频率/Hz	振型
整体模态	7	32.95	侧梁绕横轴竖直方向的扭转
	11	77.58	两侧梁在水平面内的同向剪切
	12	84.28	两侧梁在竖直方向的 1 阶弯曲
	20	224.88	侧梁和横梁的 2 阶弯曲
局部模态	21	237.35	轴箱弹簧套筒变形
	34	428.85	轴箱弹簧套筒和转臂座变形
	51	567.19	轴箱弹簧套筒和转臂座变形
	52	596.50	轴箱弹簧套筒和转臂座变形

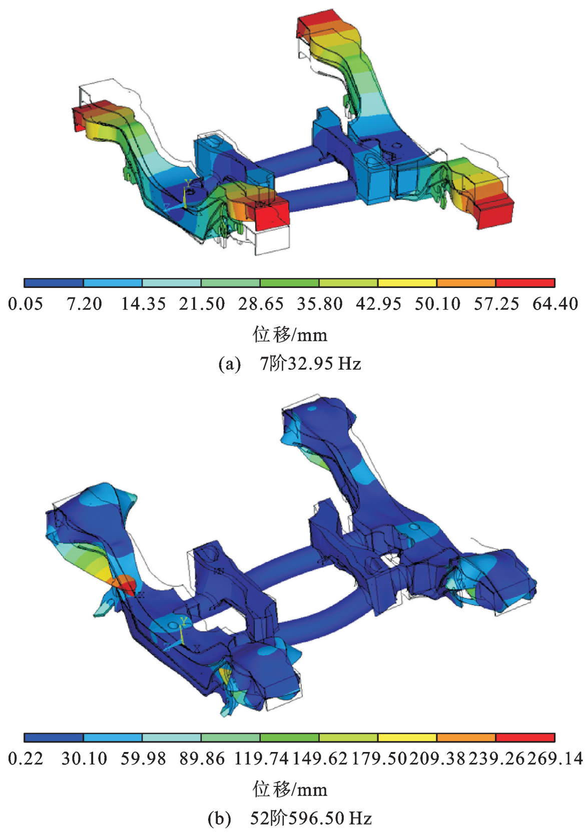


图 3　构架模态振型

Fig. 3　Modal vibration modes of frame

综上所述，车轮多边形的形成是一个长期且复杂的过程，因现有试验条件的局限性以及数值模拟的不全面性，使得其形成机理有待进一步完善。但随着试验条件的升级，动态监测技术的发展，大数据技术的应用以及车辆-轨道耦合系统动力学模型的改进，影响动车组、地铁、机车、普速客货车等各类车辆的车轮多边形磨耗的因素可能被一一识别，从而对其形成和生长过程将有更深的理解。

2　车轮多边形的抑制

关于车轮多边形的形成机理，国内外科研工作者虽然取得了丰硕的研究成果，也提出了一些具有代表性的观点，但其深层次的机理尚未探究清楚，因此，面对实际运营过程产生的车轮多边形问题，亟需提出具体可行且有效的多边形抑制措施，以保证列车的行车安全和运行稳定性，并降低列车运营维护成本。

由于车轮多边形的抑制措施可通过试验验证，因此，关于车轮多边形抑制措施的理论和试验研究具有良好的辨识性。截至目前，代表性的观点有提高车轮镟修质量、增加研磨子、提高车轮踏面硬度、增大扣件阻尼、变速运行、改变轮对固有振动频率、避开系统固有振动频率、控制线路不平顺等。

2.1　提高车轮镟修质量

由于不需改变现有车辆部件和轨道线路的结构，因此，提高车轮镟修质量是目前最易实现的控制措施。相关研究成果在 1.1 节中已经详述，同时，张志波等[52]对镟修工艺改进前后的车轮表面粗糙度进行对比，证实通过控制驱动轮径向跳动、两刀镟修工艺以及采取轴箱体支撑镟修可明显改善车轮多边形的镟修质量。

2.2　增加研磨子

研磨子，也称为踏面修型器。研究发现通过在车轮踏面上加装研磨子，进而修复车轮踏面不圆顺，

可以起到抑制车轮多边形发展的作用。乔青峰等[53]通过搭建研磨子试验平台，发现研磨子可以明显抑制车轮多边形，并通过建立非动力轮对摩擦自激振动有限元模型，分析轮轨滑动和黏着 2 种状态对车轮多边形发展的影响，结果表明轮轨滑动状态下最易激发的摩擦自激振动频率与实际车轮多边形的振动频率接近，而轮轨黏着状态下，轮轨系统不会发生自激振动，故研磨子可有效抑制车轮多边形的发展；伍安旭等[54]跟踪实测分析了恒速拖磨和制动拖磨 2 种工况下研磨子对抑制车轮多边形的效果，发现恒速拖磨工况下研磨子抑制车轮多边形的效果明显优于制动拖磨工况，同时，跟踪测试发现研磨子不会影响踏面的等效锥度，能有效抑制车轮高阶多边形的发生。

综上所述，加装研磨子可有效抑制车轮多边形的发展，而且在新造复兴号动车组(CR300AF/BF、CR400AF/BF)中均加装了研磨子，经调研发现使用研磨子的复兴号动车组的车轮踏面形状运用状态良好，未出现车轮多边形异常磨耗[53]。在现有轨道交通车辆中加装研磨子属于局部改进，其可操作性较高，因此，该方法是现阶段最理想的抑制措施。

2.3　提高车轮踏面硬度

车轮硬度分为车轮踏面硬度和轮辋断面硬度，车轮踏面硬度高于轮辋断面硬度，且在径向车轮轮辋断面硬度呈阶梯式降低分布。常崇义等[55]通过在 Amsler 磨损试验机上对 3 种动车组常用车轮材料和 3 种钢轨材料相互组合共 9 种工况进行磨耗试验，发现轮轨不同硬度比下的车轮发生多边形磨耗的程度不一，当轮轨匹配材料硬度比小于 1.05 时，易产生车轮多边形，当硬度比大于 1.36 时，几乎不产生车轮多边形，且硬度比在 0.80～1.05 时，随硬度比的增大，车轮多边形径跳值呈降低趋势；沈文林等[56]通过实测 22 794 个车轮多边形数据，发现随车轮直径的减小车轮出现多边形磨耗的比例呈增长趋势，提出通过不落轮机床液压装置对车轮进行滚压，进而提高车轮踏面硬度，可有效缓解车轮多边形磨耗，而且滚压不会造成车轮表面状态以及接触疲劳等损伤。

综上所述，通过适当提高车轮踏面硬度，可降低车轮磨耗。但是，车轮和钢轨作为一对滚动接触对，其接触表面硬度比决定了车轮和钢轨的磨耗程度，车轮踏面硬则钢轨磨耗快，易形成钢轨波磨；钢轨轨面硬则车轮磨耗快，易形成车轮多边形。故不能单一靠增大车轮踏面硬度来降低车轮磨耗，需要研究车轮多边形与钢轨波磨之间的因果关系，优化轮轨接触硬度，达到最佳匹配关系。

2.4　增大扣件阻尼

无论是无砟轨道还是有砟轨道，扣件系统作为钢轨与轨下基础连接的关键部件，其刚度和阻尼对轮轨间的振动与冲击起着重要作用。陈光雄等[25]分析了扣件刚度、阻尼以及轮轨摩擦因数对车轮多边形的影响，研究表明减小摩擦因数、适当增大扣件阻尼能抑制车轮多边形，扣件刚度对车轮多边形的影响很小；赵晓男等[57]运用负特征值分析法研究了车轮多边形的形成机理，根据系统的等效阻尼比来评价摩擦自激振动发生的趋势，当等效阻尼比为负且绝对值越大时，越易发生摩擦自激振动，计算得到某高速列车发生制动时轮轨系统摩擦自激振动的频率为 495.01 Hz，对应的等效阻尼比小于 0，当增大扣件刚度时，系统在 2 个不稳定的振动频率 495.20 和 495.21 Hz 处仍存在等效阻尼比小于 0 的点，且数值变化轻微，但随着扣件阻尼的增大，系统没有出现等效阻尼比小于 0 的情况，因此，扣件刚度对车轮多边形的影响较小，但适当增大扣件阻尼可有效抑制车轮多边形磨耗；Wu 等[58]研究发现较高的扣件刚度会加速车轮磨耗，更有可能导致低阶车轮多边形化，适当增大扣件阻尼可以有效降低高阶车轮多边形的增长速度；Tao 等[34]通过现场试验对比了 2 种地铁轨道扣件对轴箱垂向加速度的影响，研究表明采用软刚度扣件的轨道上轮轨接触力较低，通过降低扣件刚度可减缓车轮多边形磨耗的发展。

综上所述，适当增大扣件阻尼可以有效抑制车轮多边形的发展速度，这一结论得到学者们的普遍认同。但对扣件刚度的变化对车轮多边形的影响有不同见解，有认为增大扣件刚度可抑制高阶车轮多边形的产生和发展[44]，有认为扣件刚度对车轮多边形的影响较小[25,57]，有认为扣件刚度的增大会导致低阶多边形的产生[58]，有认为降低扣件刚度是减少多边形磨耗形成的有效措施[34]，因此，扣件刚度对车轮多边形的影响尚需根据试验做进一步验证。

2.5　变速运行

通过改变列车运行速度，进而避免固有频率的振动激扰，以防止和车轮多边形磨耗导致的激扰频率吻合。Wu 等[59]通过跟踪调查以及现场试验对车轮多边形磨耗的形成因素进行研究，发现车轮受周期性外激励的影响，使转向架系统在 550～600 Hz 内发生共振，从而导致车轮多边形的产生，经跟踪测试车辆振动特性，发现通过频繁改变列车往返途中

的运行速度,可有效降低车轮多边形磨耗的生长;王宏谋[60]通过实测分析了兰新客专某型动车组制动盘出现异常振动的原因,是由于车轮多边形激励频率以及钢轨波磨激励频率与制动盘的固有模态频率接近,引发共振所致,提出变速运行以及改变制动盘结构模态频率来缓解高频振动;刘韦等[61]基于弹性体轮对下的刚柔耦合动力学模型分析了车轮多边形对轮轨垂向力的影响,提出应尽量避开与车轮主导阶次下产生激振频率相对应的行车速度。

通过频繁改变某一交路区间列车往返的运行速度可以防止共振频率的产生,但在实际操作过程中,势必又会给调度工作带来更多不便,显然这一措施的可行性还有待商榷。

此外,还可通过改变轮对的固有振动特性来避开固有频率。李伟等[38]通过加粗改造提高了轮对的 1 阶弯曲共振频率,发现不存在明显的高阶多边形。也可以通过主动振动控制来避开系统固有振动,进而抑制车轮多边形的发展。Hung 等[62]通过建立车-桥耦合动力学模型,分析表明长波长不平顺诱发的低频激励可能接近车辆悬挂系统的固有频率,引起车体剧烈振动,提出通过在轨垫下加装减振板以避免车辆悬挂共振。但是,这 2 种抑制措施在现有车辆中实施有较大困难,但在新造车中可以考虑。

当然,控制线路不平顺是抑制车轮磨耗的根本,所以高速铁路线路均采用无缝钢轨,但无缝钢轨存在焊接接头,因此,要控制焊接接头的不平顺[34],此外,钢轨波磨[45]、轨下支承不均匀和道岔[59]等也会产生周期性外激励,运行一段时间后车轮会产生周期性磨耗,当周期性磨耗符合固有频率机理时,将产生车轮多边形并使其快速生长。

综上所述,在通过一系列的理论探索、现场试验与工程实践,轨道交通列车车轮多边形问题基本得到了控制,但深层次的机理尚未完全探究清楚。

3　车辆-轨道耦合动力学模型与动力学响应

车轮多边形的形成机理涉及多因素,很多因素很难通过现场试验进行分析,需借助基础理论以及动力学数值模拟开展研究,而数值模拟最根本的就是动力学模型,其模型的准确与否对计算结果尤为重要。同时,研究车轮多边形对车辆系统动力响应的影响,也往往采用动力学模型进行仿真分析。当然,同一工况现场试验或实验室试验所得结论最具有说服力,因此,采用试验与仿真相结合的方式开展车辆-轨道耦合动力学的研究是目前最理想的方式。

3.1　车辆-轨道耦合动力学模型

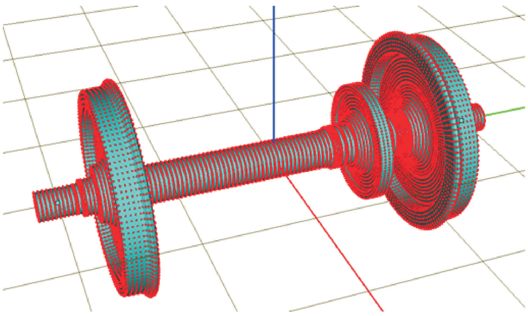
关于轨道交通动力学模型的建立,最早可追溯到 1867 年,捷克工程师 Winkler 在计算铁路路轨时提出的一个弹性地基模型[63],后经不断改进,直到 1982 年 Clark 等[64]提出弹性点支承连续梁轨道模型,使轨道模型的构建趋于成熟。车辆动力学模型的构建经历了单轮对模型、转向架模型、整车动力学模型的发展过程。轮轨滚动接触理论模型经历了 Carter 理论、Vermeulen-Johnson 理论、Kalker 线性理论、Kalker 简化理论。值得指出的是,虽然上述三大经典动力学模型可满足当时的计算所需,但随着铁路运输的高速化和重载化,轮轨动态相互作用问题日益突出,在此背景下,翟婉明[65]首次提出并创建了车辆-轨道耦合动力学理论体系,建立了车辆-轨道统一模型(称为“翟模型”),并提出了车辆与线路最佳匹配设计原理及方法。

在此模型基础上,国内外学者们通过局部改进建立了不同类型的动力学模型。Baeza 等[66]建立了考虑轮对柔性的车辆-轨道刚柔耦合动力学模型;Zhang 等[67]在此模型的基础上,加入了电机和齿轮传动系统;Ling 等[68]在此模型的的基础上,考虑了柔性车体的影响;Han 等[69]建立了旋转柔性轮对的车辆-轨道刚柔耦合动力学模型,在轮轨滚动接触计算时考虑了轮对柔度和旋转效应的影响;吴丹等[43]基于此模型建立了车辆-轨道刚柔耦合动力学模型,由于动力学模型中加入柔性体后会显著增加计算量,从而使计算时长明显增加,故在部件柔性化时,应重点将分析对象以及模态频率较高的部件予以柔性化,综合考虑车辆-轨道耦合系统各部件的振动频率以及研究对象,兼顾计算时长和精度,可主要对轮对进行柔性化处理,其建模过程如图 4 所示。

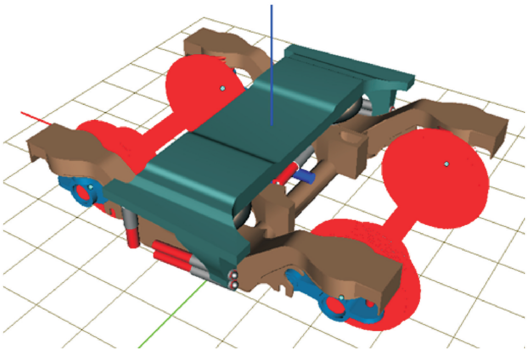
综上所述,以上模型均没有考虑纵向,属于车辆-轨道垂向和横向空间耦合模型。

随着长编组重载列车纵向冲击所带来的影响,车辆-轨道耦合动力学模型的构建逐渐从垂向-横向耦合模型发展成垂向-横向-纵向三维耦合模型[70]。Liu 等[71]通过建立重载列车-轨道三维耦合动力学模型,计算了行车和制动 2 种工况下轮轨间动作用力,并通过试验验证了模型的准确性。

随着对车辆-轨道耦合动力学模型的进一步研究,仅仅将轨道线路考虑成路基结构显然是不够的,实际线路中除了路基结构外,还有桥梁和隧道。于是,Zhai 等[72]建立了车辆-轨道-桥梁动力学模型,并



(a) 柔性轮对



(b) 含柔性轮对的转向架动力学模型

(c) 整车刚柔耦合动力学模型

图 4 车辆-轨道刚柔耦合动力学模型

Fig. 4 Vehicle-track rigid-flexible coupling dynamics model

通过试验验证了模型的准确性；Xu 等[73]建立了车辆-轨道-隧道耦合动力学模型，详细分析了隧道内车辆的振动特性。

综上所述，车辆-轨道耦合动力学模型在最初“翟模型”的基础上，逐渐从垂向延伸扩展考虑横向和纵向的三维耦合模型，同时，轨道线路模型也更全面，为研究轮轨接触动力学提供了高效的计算模型。由于高速运行下弓网接触会影响列车的平稳性，故后续可建立考虑弓网系统的车辆-轨道耦合动力学模型。

3.2 车辆振动响应的仿真分析

基于车辆-轨道耦合动力学模型，通过仿真和实测相结合，研究车轮多边形对车辆振动响应的影响，进而分析车轮多边形的发生机理。Liu 等[74]基于车辆-有砟轨道垂向耦合动力学模型，研究了车轮多边形对轮轨动态相互作用的影响，研究表明车轮多边形将导致轮轨相互作用力大幅波动，车轮多边形的短波长成分会激发钢轨和轨枕的高频振动；陈美等[75]通过建立车辆-板式轨道垂向耦合动力学模型，分析了车轮多边形以及车轮多边形与钢轨焊缝不平顺叠加 2 种工况下对轮轨动态特性的影响，研究表明车轮多边形不平顺变化率最大点与钢轨焊缝区不平顺最大点重合时，轮轨垂向力最大，反之最小。车轮多边形不平顺与焊缝不平顺叠加后引起的各项垂向动力响应明显高于单一车轮多边形下的各项指标。Song 等[76]通过建立轮对-板式轨道耦合动力学模型，研究了车轮多边形的阶次和幅值对轮轨接触瞬态动力学行为(位移、加速度和 Mises 等效应力等)的影响，研究表明位移和 Mises 等效应力与车轮多边形阶次、幅值和速度成正比；尹振坤等[77]通过实测车轮多边形以及轴箱振动加速度，基于车辆-轨道动力学模型数值分析了速度以及车轮多边形阶次、幅值对轮轨垂向力的影响，研究表明垂向力随幅值和速度的增大而增大，且多边形阶次也基本呈现这一规律，但某些阶次下的车轮多边形激励频率由于与轨道固有频率接近，发生共振导致出现大幅度跳跃；干锋等[78]分析了车轮 20 阶多边形对等效锥度和蛇行运动的影响，研究发现车轮多边形对等效锥度和蛇行运动波长无显著影响，对轮对纵向速度、接触半径、摇头角速度以及横向加速度影响显著；彭来先等[79]通过实测车轮多边形以及轴箱和垂向止挡的振动加速度，发现轴箱及垂向止挡的振动峰值频率与显著车轮多边形的激励频率接近，通过对垂向止挡进行约束状态下的有限元模态分析，发现其模态频率与车轮 27 阶多边形激励频率相近，引发共振造成垂向止挡发生疲劳断裂；杨润芝等[80]通过实测与仿真相结合分析了车轮多边形对轮轨以及轴箱振动响应的影响，并分析了考虑制动力时车轮多边形对制动盘横向振动的影响，发现当车轮多边形的激振频率与车辆-轨道系统某些部件的固有模态频率接近时，其振动加剧，施加制动力时，制动盘的振动加速度远小于无制动时的振动加速度，且轮对的 4 阶弯曲模态频率因施加了制动而消失；Wu 等[81]通过建立考虑轮对、轴箱以及轨道柔性的车辆-轨道耦合动力学模型，通过测试得到车轮多边形磨耗以及轴箱振动加速度，并对模型的准确性进行了验证，研究表明高阶车轮多边形会引起轮轨间的高频振动，并激励轮对和轴箱的固有模态振型，使轴箱产生较大的振动加速度和动应力。

吴丹等[82]通过跟踪测试了部分车型动车组镟修前后的车轮多边形，测试现场如图 5 所示。统计

图 5　车轮多边形实测

Fig. 5　Measurement of wheel polygon

分析了车轮多边形的振动频率与车轮直径、速度和轴距的关系，并基于主导阶次和不同幅值，分析了车轮多边形分别与 3 种轨道激励组合作为轮轨周期性磨耗工况下的轮轨振动响应，其中工况 1 为仅考虑车轮多边形，工况 2 为车轮多边形与残余波磨的叠加，工况 3 为车轮多边形与钢轨波磨的叠加。研究表明动车组车轮多边形产生的激励频率在 550～600 Hz 之间，当车辆或轨道部件固有模态频率与该频率接近时，易发生共振，使轮轨垂向力增大，进而加剧车轮多边形的生长，如图 6 所示。

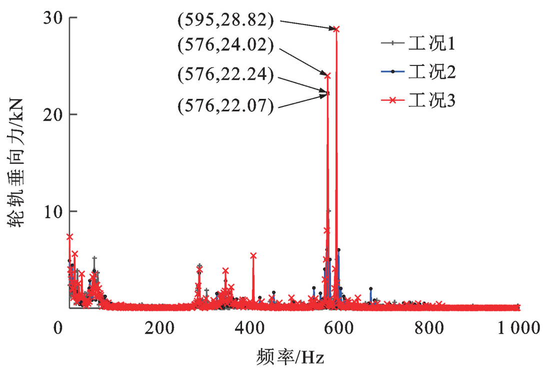


图 6　300 km・h^{-1}速度下的轮轨垂向力频域

Fig. 6　Frequency domains of wheel-rail vertical force at 300 km・h^{-1}

3.3　车辆振动响应的实测分析

通过现场实测转向架各部件的振动响应，在频域内分析车轮多边形对车辆振动响应的影响规律，进而分析车轮多边形的发生机理。对于动车组车轮多边形引起的振动响应，Shi 等[83]通过跟踪测试 200 万公里的动车组车轮磨耗演变情况及车辆动力学性能，发现磨损率随运行距离的增大而增大，由于车轮踏面的磨损导致表面软化，易形成车轮多边形，并且车轮等效锥度随车轮磨耗近似呈线性增大，等效锥度的增大加剧了车辆振动；罗光兵[84]对动车组车轮多边形进行了现场测试并对比分析了镟修前后轴箱的振动特性，发现镟后振动频谱中没有高频振动，同时通过实测得到了镟修前轴箱、构架以及电机的振动频谱规律，发现在车轮多边形下该部件的振动明显增强，且存在高频振动。

同时，为研究重载货运纵向冲击对车轮磨耗的影响，王晨等[85]通过实测得到了机车车体发生剧烈颤振的纵向振动主频为 20.6 Hz，轮对纵向振动的主频为 19.2 和 20.6 Hz，造成车体颤振的原因是轮对纵向振动，试验验证了通过加装一系纵向减振器可有效抑制 17～19 Hz 的纵向振动，从而能减小车轮踏面损伤。

为定量分析地铁车辆车轮多边形的磨耗程度，迟胜超等[86]实测得到了青岛地铁 2 号线某地铁列车所有车轮多边形数据，统计发现其车轮多边形主要以前 5 阶和 7～9 阶为主，并根据实测数据给出了车轮多边形的拟合经验公式。

综上所述，实测分析在研究车辆振动响应时具有准确性高等优势，但在分析产生机理以及磨耗预测等方面有其局限性，因此，学者普遍采用实测和仿真相结合的方式研究车轮多边形的产生机理及其影响因素。

4　车轮多边形对疲劳损伤的影响

车轮多边形会导致轮轨振动加剧，而且国内外研究表明，车辆结构和轨道系统某些部件的损伤几乎均与车轮多边形有关。

4.1　车轮多边形对车辆部件疲劳损伤的影响

国内外关于车轮多边形对车辆结构部件疲劳损伤的研究，现有成果主要涉及转向架构架、齿轮箱体、车轮及车轴。Fu 等[87]分析了地铁车辆转向架构架发生疲劳裂纹的原因，指出是由于钢轨接头造成的低频轮轨冲击和车轮多边形激发了构架的固有模态，产生高频共振所致；Wang 等[88]通过实测分析了地铁车辆转向架构架发生疲劳损伤的主要因素，分析了车轮多边形、钢轨波磨、钢轨接头等对构架疲劳损伤的影响，研究表明钢轨波磨伴随车轮多边形是转向架构架发生疲劳损伤的主要因素；王斌杰等[89]通过建立构架的疲劳可靠性模型，分析了常见轮轨缺陷对地铁车辆转向架构架疲劳损伤的影响，研究表明直线区间钢轨焊缝对构架的疲劳损伤影响不大，钢轨波磨、车轮多边形与速度关联的激扰，会引起高幅高频动应力，从而加剧构架的疲劳损伤，因此，车轮多边形和轨道激励（钢轨波磨、钢轨焊接接头）叠加形成的轮轨周期性激励引起的高频振动是导致转向架构架疲劳损伤的主因。

Wu等[90]通过建立了考虑齿轮箱体和轮对柔性以及非线性轮轨接触的三维多体车辆系统动力学模型，实测得到运营动车组的车轮多边形的主导阶次为20阶，并将其作为轮轨激励输入，计算了车轮多边形不同幅值下的齿轮箱体动应力；基于核密度估计法对齿轮箱体上的动应力进行外推以评估其疲劳损伤，并对比分析了无多边形磨耗下齿轮箱体的疲劳损伤，结果表明车轮20阶多边形对齿轮箱体疲劳损伤造成的影响比无多边形时增大了63%。Hu等[91]针对动车组齿轮箱体出现的疲劳裂纹进行研究，发现车轮多边形和轨道不平顺叠加激发了齿轮箱体在571和602 Hz时的固有模态，引起共振，从而导致疲劳裂纹的出现，因此，无论是高速列车还是地铁车辆，车轮多边形均是造成转向架齿轮箱体疲劳损伤的诱因。

肖乾等[92]通过建立CRH2型动车组车辆轨道耦合系统动力学模型，计算了不同阶次和幅值下轮轨纵、横向蠕滑力/率，并将其作为安定图和损伤函数的输入参数，分析了多边形磨耗车轮的疲劳特性，研究表明车轮滚动接触疲劳随阶次和幅值的增大而加深，且对波深的变化更敏感；张波等[93]通过建立车辆-轨道耦合动力学模型和车轮踏面疲劳损伤预测模型，分析了高、低轮轨黏着接触条件下，车轮多边形对踏面疲劳损伤的影响，研究表明高黏着条件下，严重的车轮多边形会加剧踏面疲劳损伤，低黏着条件下，车轮多边形会加剧踏面磨耗；Yan等[94]通过测试不同角度车轮的裂纹扩展速率，揭示了车轮多边形对裂纹车轮寿命的影响，研究表明随车轮多边形阶次的增加，车轮裂纹扩展寿命显著降低。

吴丹等[51]基于车辆-轨道耦合动力学模型分析了车轮多边形对高速动车组车轴疲劳损伤的影响，根据疲劳累积损伤理论，采用Brown-Miller法计算得到了考虑车轮多边形磨耗的车轴疲劳寿命，其对数里程疲劳寿命云图如图7所示。研究表明考虑车轮多边形后车轴的疲劳寿命小于《铁路动车组运用维修规程》(TG/CL 127—2013)中设计寿命20年的规定，由于该寿命为基于车轮镟修前的高阶车轮多边形下的疲劳寿命，因此，不能表明该车轴不满足设计要求，但需对高阶车轮多边形引起足够重视，如不及时对其进行镟修处理，便会严重影响车轴的使用寿命。

4.2 车轮多边形对轨道部件疲劳损伤的影响

当车轮多边形产生的振动向下传递时，影响轨道系统各部件的疲劳寿命。Kang等[95]基于轮轨系统刚柔耦合动力学模型对扣件弹条进行动力学仿真分析，基于Miner准则，分析了多边形幅值对弹条疲劳寿命的影响，结果表明轮对以237 km·h^{-1}的速度在轨道上运行时，24阶多边形车轮外载荷对弹条Mises等效应力无明显影响；当24阶车轮多边形幅值达到0.225 mm及以上时，约1 172 Hz的激励频率从轮轨系统传递到扣件系统，从而降低了弹条的疲劳寿命。张笃超等[96]通过建立带车轮多边形的轮轨滚动接触疲劳裂纹扩展模型，分析了车轮多边形对钢轨疲劳裂纹扩展行为的影响，研究表明车轮多边形会造成法向和切向轮轨力显著的周期性波动，随着多边形幅值和阶次的增加，会显著加速钢轨的疲劳裂纹扩展。

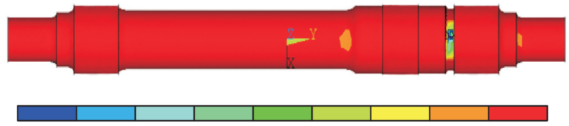


图7 车轴疲劳寿命分布

Fig. 7 Distribution of axle fatigue life

综上所述，车辆在轮轨接触良好的轨道上运行时，主要受来自轨道不平顺的低频激扰影响[97]，轮轨间的动态相互作用力波动不大，且相互作用力向上传递经一系、二系悬挂的衰减，向下传递受扣件系统以及轨道板的衰减，使得车辆和轨道部件满足设计寿命的规定，但当车轮存在高阶多边形后，轮轨激励频率会有所增大且范围分布更广，当激励频率与车辆某些部件的固有振动频率接近时，易引发共振，从而导致其动应力显著增大，进而影响其疲劳寿命。但目前考虑车轮多边形或钢轨波磨等轮轨周期性磨耗下的结构疲劳寿命的研究相对较少，因此，分析考虑车轮多边形等轮轨周期性磨耗下的车辆结构和轨道系统零部件的疲劳损伤是一个新方向。

5 结语

(1)车轮多边形是轨道交通列车普遍存在但又尚未彻底解决的一种车轮非正常磨耗。当车轮产生初始缺陷后，每次与轨道冲击均会在缺陷位置处产生磨耗，并且磨耗沿踏面圆周呈波浪形延伸，当波浪形磨耗头尾相连后，便形成了初始车轮多边形[98]。初始车轮多边形又进一步加剧了轮轨振动，使车辆在运行过程中逐渐形成了1个固有频率的振动激励，当该振动激励频率同车辆或轨道某些部件的固

有模态频率接近时,易引起共振,进而使车轮形成更严重的多边形[99]。

(2)车轮多边形的抑制在经过一系列的理论探索、现场试验以及工程实践后取得了良好的效果。从车轮多边形的形成机理可知,车轮初始缺陷是起源,因此,控制车轮初始缺陷是抑制车轮多边形形成及发展的根本,并从可行性角度而言,在已运营车辆上加装踏面研磨子无疑是最理想的措施,在此基础上,进一步优化研磨子的材料,改善踏面与研磨子的匹配关系,增大两者的共形度[100],从而使研磨子的抑制效果更理想。

(3)避免轮轨耦合共振仍是抑制车轮多边形最为根本的方法,还可通过改变速度或交路等运行方式,使车轮圆周上不均匀磨耗的波长反复改变,从而抑制单一短波长的生长。

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