Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 5, No. 2, 2023

Influence of Wheel Polygons on Dynamic Performance of Trains

Yang Dai[1, *], Chao Ye[1]

[1]School of Mechanical & Autonotive Engineering, Qingdao University of Technology, Qingdao 266520, China

[*]Corresponding author: Yang Dai (E-mail address: yangdai@mvrlab.com)

Abstract: With the continuous development of high-speed railroad technology, the operating speed and mileage of moving trains continue to increase, and the phenomenon of wheel-rail contact fatigue and wear is gradually highlighted, and the problem of wheel polygon wear is also prevalent in the operating site. Wheel polygon wear will deteriorate the wheel-rail contact relationship, so that the wheel-rail force surge, the safety and stability of the train caused serious impact. Therefore, wheel polygons become a key problem to be solved, but the formation and development mechanism of wheel polygons has not been fully clarified so far. This paper establishes a dynamic model of the moving train considering the elastic roadbed, and studies the dynamic performance of the moving train with the changing law of the moving train, respectively, in terms of wheel-rail vertical force, car body vibration acceleration, and wheelset vibration acceleration, to explore the influence of wheel polygons on the performance of the moving train. The results show that with the increase of wheel polygon order and wear depth, the safety of the moving vehicle gradually decreases and the wheel-rail vertical force gradually increases, and the wheelset vibration acceleration is more sensitive to the increase of order from 1 to 13.

Keywords: Wheel polygon, Dynamic performance, Vibration acceleration.

1. Introduction

High-speed railroads are important in the sustainable development strategy of transportation with their advantages of high transport capacity, high safety, punctuality, low energy consumption and low environmental pollution. With the rapid development of railroad transportation towards the road of technological innovation such as high-speed and heavy-duty, however, the speed and load increase, intensifying the dynamic effect between the wheels and rails, wheel polygonalization comes to the fore. Wheel polygonalization is a widespread circumferential wear phenomenon in high-speed trains, a special form of wheel misalignment [1], which is manifested by periodic changes in wheel radius along the entire circumferential direction. The appearance of wheel polygonization deteriorates the wheel-rail contact state and affects the safety and stability of train operation, and the high frequency and large vibration also increases the probability of train's derailment.

Scholars have long studied the wheel polygons in rolling stock, high-speed trains, and subway buses through field experiments or numerical simulations, and have explored the mechanisms of their formation and development as well as their operational effects. As early as the 1980s, the Dutch scholar Kaper [2] noticed a "special phenomenon" of wheel polygons when investigating the wheel-track noise of the new Dutch intercity trains, and showed through laboratory experiments that the wheel polygons were caused by tread braking. Subsequently, in the 1990s, Meywerk [3] developed a flexible wheelset and flexible rail model to demonstrate the polygonal evolution of wheel treads, using a multi-timescale regression method to combine the wheel-track interaction with the wear and hardening deformation of the wheel treads. By analyzing the ICE-1 train model, Morys [4] concluded that the track structure and excitation frequency have a crucial influence on the order of wheel polygon wear, and that different travel speeds and different track characteristics dominate different orders of polygons. It has also been suggested [5] [6] that the wheel polygonalization is partly due to the high magnitude contact forces generated at the wheel-rail interface.

Fu et al [7] carried out a linear motor subway vehicle polygon prediction, in which it was concluded that a fourth-order polygon remained after wheel turning, and linear motor vertical vibration contributed to the gradual evolution of the fourth-order polygon to an 8th-9th-order polygon. However, Peng et al [8] showed that wheel polygons may be triggered by the torsional mode of the wheelset when the wheel-rail viscous slip vibration is provoked by the vehicle under extreme conditions such as passing through small radius curves. Wang et al [9] analyzed the effect of tread concave wear on the wheel diameter difference. The effect of wheel polygons on high-speed cracked axlebox bearings was investigated. Tao [10] et al. concluded that traction and braking have a significant effect on wheel wear and that the use of a control mode with variable creep threshold to control creep can reduce wear.

This paper comprehensively investigates the effect of wheel polygon development law on wheel-rail vertical force, body vibration acceleration, and wheelset vibration acceleration, and the elastic roadbed is considered in the modeling of this paper, which is more consistent with the actual law than the rigid road surface and provides a certain theoretical basis for ensuring train safety and stability.

2. Vehicle-track Coupled Dynamics Model with Polygonal Wheels

2.1. Vehicle-track coupled dynamics model

According to the parameters of a high-speed train in China, a dynamic model of the vehicle considering the gearing was developed, as shown in Fig.1. The vehicle is composed of a car body, two bogie frames, four wheelsets, four motors, four pairs of helical gears. The car body, bogie frames, and wheelsets are joined by primary and secondary suspensions that are replaced by spring and damping respectively. The model also takes into account the elastic subgrade by using spring damping force elements to simulate the rail bed and other structures, which makes the modelling results more accurate.

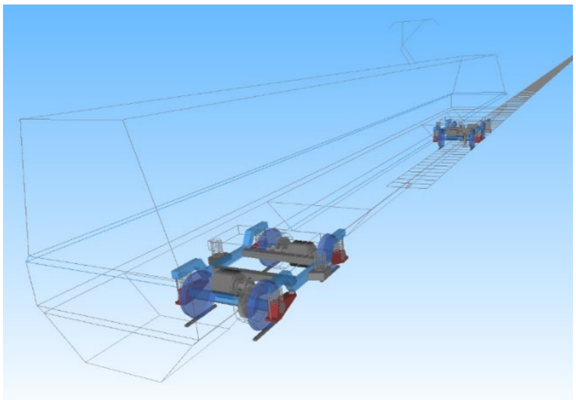


Figure 1. Vehicle model considering track.

2.2. Mathematical model of wheel polygons

Wheel polygons are divided into two categories: periodic and nonperiodic [11]. When there is a dominance of a certain order polygon, it is called periodic discontinuity; if there is no dominance of a certain order polygon, i.e., when the polygon order components are widely distributed, it is called nonperiodic discontinuity, and this type of polygon is formed by the superposition of harmonics with different amplitudes, wear lengths, and phases. In this paper, the method of simple harmonic functions is used to define the periodic discontinuity of the wheel circumference. The difference in wheel circumferential irregularities within one week of wheel roll is considered as a harmonic function as follows

$$\begin{cases} \Delta r(\beta) = A\sin(n(\beta+\beta_0)) \\ r = R - \Delta r \end{cases} \tag{1}$$

Where: β_0 is the initial phase angle; β is the wheel rotation angle; Δr is the wheel diameter difference; A is the uncircular smooth wear depth; n is the wheel polygon order; R is the nominal rolling circle radius; r is the actual rolling circle radius.

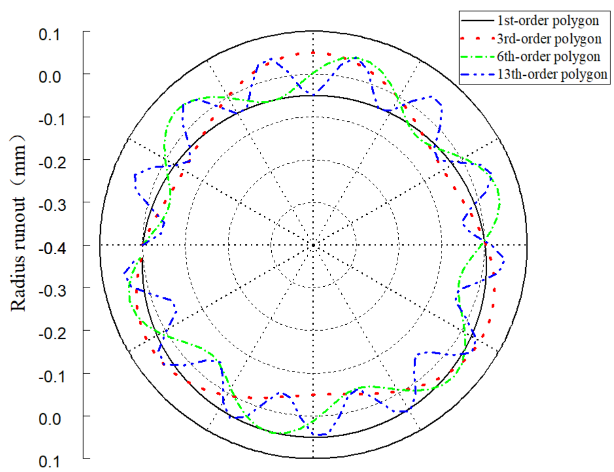
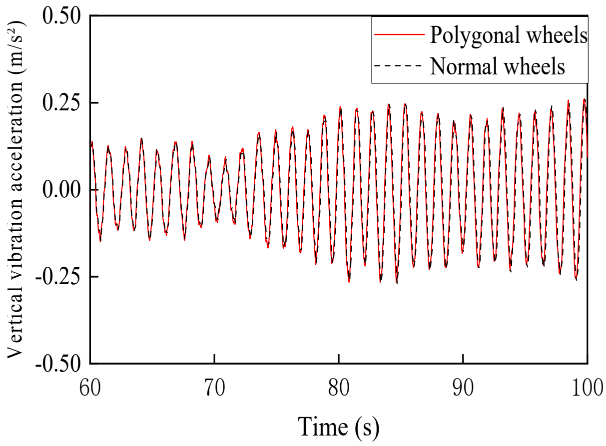


Figure 2. Variation of out-of-roundness with angle for different wheel polygon orders

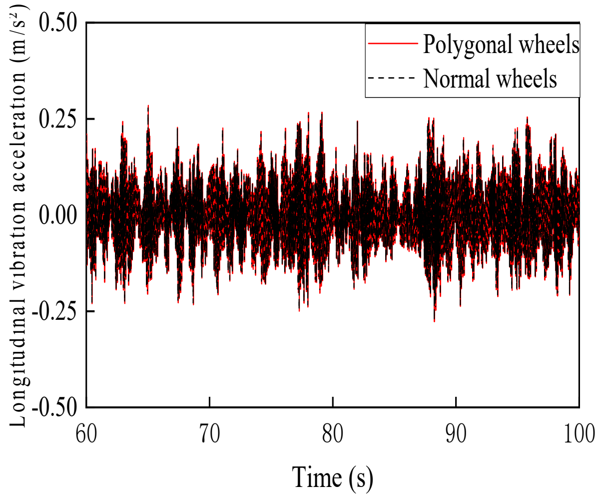
3. Realistic Simulation

3.1. The acceleration of Car body

The wheel polygon condition is set to the wheel polygon order of 8, the wear amplitude is 0.1mm, and the road excitation is adopted from the measured road excitation, and the car body is kept at a uniform speed from 60s to 100s during operation, with the same conditions for other working parameters. The vibration acceleration of the vehicle body is compared as follows:



(a) Vertical vibration acceleration

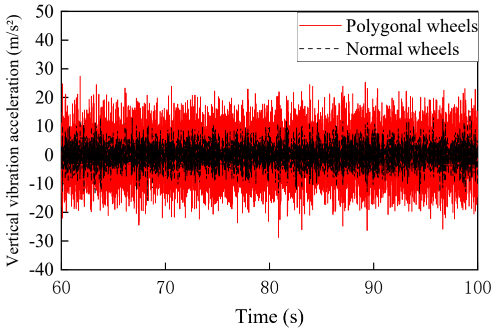


(b) Longitudinal vibration acceleration

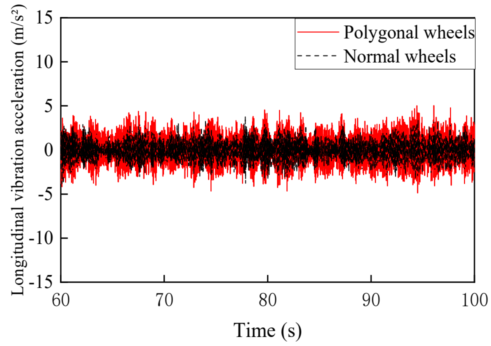
Figure 3. Vibration acceleration of car body

The fig.3 shows the time domain curves of the vertical and longitudinal vibration acceleration for the moving car model running at a constant speed of 200 km/h. Looking at the two curves within each graph, the trend and amplitude are also almost the same, and it can be concluded that the wheel vibration acceleration has basically no effect on the vertical and longitudinal vibration acceleration of the moving car. This is mainly due to the fact that the excitation needs to pass through the first system suspension, second system suspension and other structures in order to affect the car body, due to the stiffness and damping of the midway suspension to play a certain damping effect, so if it is a small degree of wheel polygon excitation or gear drive excitation for the car body almost no effect.

3.2. Wheelset vibration acceleration

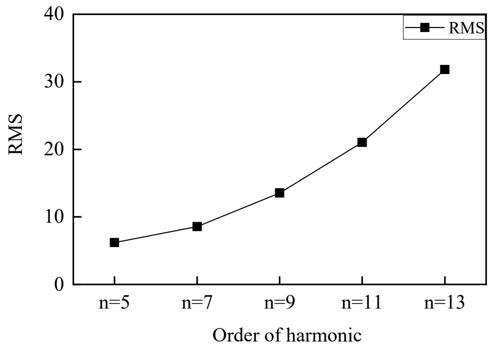


(a) Vertical vibration acceleration

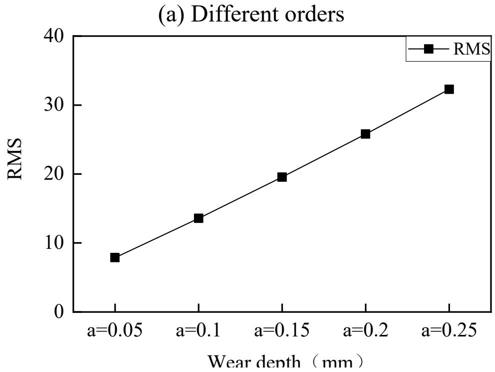


(b) Longitudinal vibration acceleration

Figure 4. Vibration acceleration of Wheelsets



(a) Different orders



(b) Different wear depths

Figure 5. Vertical vibration acceleration of wheelsets with different orders and amplitudes

Figure 4 shows the time domain curves of the vertical and lateral vibration acceleration of the wheelset when the vehicle is running at a constant speed, and it can be seen that the vibration acceleration with the polygon is significantly larger than that without the wheel polygon. It can be inferred that the wheel polygon has a great influence on the vibration acceleration of the wheelset, which is due to the fact that the wheel polygon occurs directly on the wheelset and therefore has a direct influence on the vibration acceleration of the wheelset. Comparing Fig. 4(a) and (b), it can be found that the wheel polygon exerts a more significant effect on the vertical vibration acceleration of the wheelset compared to the longitudinal vibration acceleration.

Figure 5(a) shows the variation of the RMS value of the vibration acceleration from 5 to 13 for wheel polygons with a wear depth of 0.1 mm. Figure 5(a) shows the variation of the RMS value of vibration acceleration from 0.05 mm to 0.25 mm for a wheel polygon order of 9. As the polygon order increases, the rate of increase of vibration acceleration becomes larger and larger. The overall trend of the RMS values of vibration acceleration at different orders in the range from order 0 to order 13 shows an approximate quadratic function relationship. It can be clearly observed that the increasing value of vibration acceleration remains constant with increasing wear depth, which means that the overall trend of RMS values of vibration acceleration for different wear depths is a linear function.

3.3. Wheel-rail vertical force

The wheel-rail vertical force is the direct cause of vibration, impact, fatigue, damage to the moving vehicle and track line system, is an important information indicator for vehicle safety monitoring, and is of great significance to ensure the safety of the vehicle. The wheel in the process of driving by the wheel track longitudinal force, wheel track transverse force and wheel track vertical force, where the longitudinal force to provide the wheel forward momentum, vertical force to provide support for the role of the wheel, the wheel steering needs transverse force. The change of wheel-track force is the direct factor that causes vehicle derailment, and the abnormal wheel-track force will also lead to increased wheel wear, reduce wheel life, cause abnormal vibration of the vehicle, and affect the comfort of the ride. When the wheel-rail vertical force is 0, the wheel-rail instantaneous separation phenomenon will occur, also known as rail jumping, causing serious harm to the vehicle and the track. According to the dynamics standard in UIC 518: the wheel-rail vertical force limit is not more than 170 kN. when the wheel-rail vertical force of the vehicle is more than 170 kN, it will seriously affect the driving safety, by the risk of derailment, and will cause damage to the track, so it is necessary to study the effect of wheel polygon on wheel-rail vertical force.

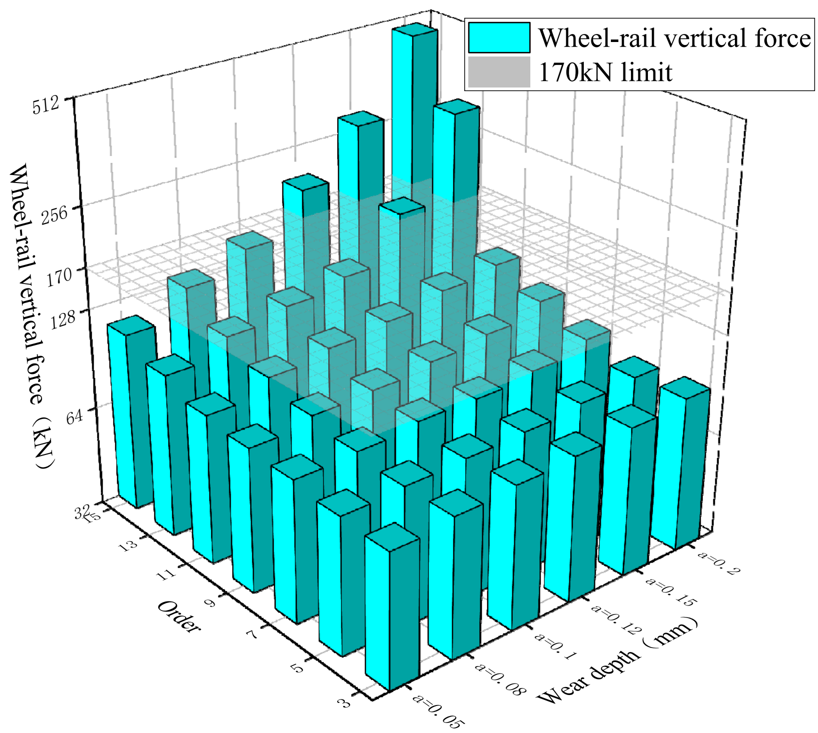


Figure 6. Wheel-rail vertical force with different orders and wear depths

The variation of the maximum value of wheel-track vertical force with different wear depths and orders for a train running speed of 200 km/h is shown in Figure 6. The cyan cube represents the wheel-rail vertical force for different polygon conditions. The gray plane represents the 170kN limit, which may affect the train safety when the wheel-rail vertical force exceeds 170kN. The wheel-rail vertical contact pressure for a 13-order polygon wheel with a wear depth of 0.15 mm is 177 kN, which exceeds the 170 kN limit, implying a risk of derailment of the vehicle. When the polygon order is 15, the wheel-rail vertical contact force exceeds the limit value of 170 kN when the wear depth is greater than 0.12 mm. It is obvious from Fig. 6 that the maximum value of wheel-rail vertical force increases with the increase of polygon order and wear depth.

4.Conclusion

In this paper, according to the multi-body dynamics theory, the wheel polygon mathematical modeling method is used to establish a multi-body dynamics model of the moving vehicle considering the wheel polygon, and the effect of wheel polygonization on the dynamic performance of the moving vehicle is studied in depth, and its conclusions are shown as follows:

As the stiffness and damping of the first and second system suspensions play a certain damping effect, the wheel polygons have basically no effect on the vibration acceleration of the vehicle body. The wheel polygon has a significant impact on the vibration acceleration of the wheel set, with a greater impact on the vertical vibration acceleration and a smaller impact on the vertical vibration acceleration. The RMS curves of different orders and wear depths show that the RMS curves of vibration acceleration due to order change are quadratic functions, and the RMS curves of vibration acceleration due to wear depth change are primary functions. Therefore, in the wheel orders from 1 to 13, the vibration acceleration of the wheel is more sensitive to the order. The wheel polygon has a dramatic effect on the wheel-rail vertical force, which increases with the increase of polygon orders and wear depths.

Acknowledgment

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Ma C , Gao L , Cui R , et al. The initiation mechanism and distribution rule of wheel high-order polygonal wear on high-speed railway. Engineering Failure Analysis, 2020, 119.

[2] KAPER H P. Wheel corrugation on Netherlands railways (NS): origin and effects of polygonization in particular. Journal of Sound and Vibration, 1988, 120(2): 267-274.

[3] MEYWERK M. Polygonalization of railway wheels. Archive of Applied Mechanics, 1999, 69(2): 105-120.

[4] MORYS B. Enlargement of out-of-round wheel profiles on high speed trains. Journal of Sound and Vibration, 1999, 227(5): 965-978.

[5] Rode W, Miiller D, Vitman J, Results of DB AG investigations "Out-of-Round Wheels", in: Proceedings of the Corrugation Symposium, Technische Universitäat Berlin Germany ,1997.

[6] Meywerk M. Polygonalization of railway wheels, Arch. Appl. Mech ,1999, 69: 105–120.

[7] FU B, BRUNI S, LUO S. Study on wheel polygonization of a metro vehicle based on polygonal wear simulation. Wear, 2019, 438-439: 203071.

[8] PENG B, IWNICKI S, SHACKLETON P, et al. The influence of wheelset flexibility on polygonal wear of locomotive wheels. Wear, 2019, 432-433: 102917.

[9] WANG Z, ALLEN P, MEI G, et al. Influence of wheel-polygonal wear on the dynamic forces within the axle-box

bearing of a high-speed train. Vehicle System Dynamics, 2020, 58(9): 1385-1406.

[10] TAO G, WEN Z, LIANG X, et al. An investigation into the mechanism of the out-of-round wheels of metro train and its mitigation measures. Vehicle System Dynamics, 2019, 57(1): 1-16.

[11] Cai W , Chi M , Wu X , et al. Experimental and numerical analysis of the polygonal wear of high-speed trains. Wear, 2019, 440-441:203079.