Influence of Polygonal Wear on Dynamic Performance of Wheels on High-Speed Trains

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Abstract: With increases in train speed and traffic density, polygonal wear of railway wheels arises accordingly, induced by the high impacts between wheels and rails, which is mainly related to operation safety and ride comfort of vehicle system. This work evaluates the effect of wheel polygon shape on the dynamic performance of the wheel set through numerical simulations. The finite element model, which includes the wheel set and the slab track, was established using ANSYS software to study the effects of polygonal wear on the dynamic behavior of the railway wheel. In the model, wheel–rail interaction forces caused by polygon wheel shape were solved using Universal Mechanisms of wear and were then entered into the finite element model. Using the simulation model, the influence of the harmonic order and out-of-roundness amplitude of wheel polygon on transient dynamic behaviors of the wheels namely, the displacement, acceleration, and von Misses equivalent stress were investigated. The results indicate that both the maximum dynamic displacement and Von Misses equivalent stress of the wheel plate show proportionality to the OOR amplitude, the harmonic order and the vehicle velocity. Besides, the maximum Von Misses equivalent stress occurs close to the wheel center, whereas the maximum displacement occurs close to the wheel tread. The findings will provide a theoretical basis for on-board detection methods of monitoring wheel polygonal wear.

Keywords: ANSYS finite element model; dynamic performance; high-speed railway; wheel polygon; wheel set

1 INTRODUCTION

Polygonal wheel wear is a type of long wavelength periodic wear around the circumference of railway wheels, which began to occur with the advent of high-speed trains. In high-speed operations, wheel polygonal wear leads to asymmetrical contact situations between the wheel and rail, making them unable to maintain the ideal state of symmetrical contact. Hence, the increasing dynamic impacts between wheels and rails have an adverse effect on the fatigue life of vehicle system components, threatening the operational safety and ride comfort in addition to bringing about rolling noise problems [1]. On June 3, 1998, the Inter City Express train derailment accident occurred due to wheel hub fracture induced by wheel polygonal wear. Eighty-eight people were injured and 101 people died because of this incident, with a total economic loss of about one billion Deutsche Mark.

Research into the causes of out-of-roundness (OOR) railway wheels reported aspects including inhomogeneous material properties of the wheel tread, faulty brake mechanisms, and dynamic motion of wheels in service [2-5]. However, there is currently no clear explanation as to the origins and the enlargement mechanisms for wheel polygonal phenomena. Refs. [6-10] reported the influence of wheel polygons on vehicle dynamic response and operation stability. The initiation and growth of OOR wheel defects and the damage they cause to the track and vehicle components were discussed in Refs. [11-15].

However, there is little research regarding the dynamic performance of the wheel induced by polygon wheel shape. The aim of this paper is to study the influence of polygon wheel shape on the dynamic displacement and stress of the wheels based on co-simulation using Universal Mechanism (UM) and ANSYS, to provide theoretical guidance as to the choice and optimal placement of sensors for on-board detection systems for polygonal wheel defects.

2 SIMULATION MODELS

In order to study dynamic behavior of wheels caused by polygonal wear, a three-dimensional (3D) finite element model including the wheel set and the slab track was developed using ANSYS software, as shown in Fig. 1. The China railways track structure II (CRTS II) slab ballastless track model is composed by 60 kg/m rails, slab layer, rail fasteners, concrete/asphalt (CA) layer, and a support layer. It is assumed that the slab track is symmetric with respect to the centerline of the track, only half of the slab track was considered to reduce the simulation time and thus the computational cost. The 60 kg/m rail was modeled by 3D solid finite element SOLID45. The concrete slab, concrete/asphalt layer, and support layer were all treated as elastic and were modeled by 3D solid finite element SOLID185. The connections between them were simulated with node freedom coupling technology. The rail fasteners were modeled as linear springs and dampers. The ends of the rail and the slab were constrained, as was the bottom of the support layer. Half of the wheel set was composed of the worn type wheel tread and the hollow axle, and divided by different size finite element meshes. The minimum size of the 3D element was 2.0 mm within 10° around the circumference within the wheel and rail contact area, whereas the size of the other elements was 10 mm. The parameters of the wheel set can be seen in Tab. 1. In view of the fact that the running distance of the wheel on the track is long, it is assumed that the wheel rotates mainly within a certain track section.

By combined simulation with multibody system dynamic simulation software Universal Mechanism (UM), taking polygonal wheels as input excitation, the harmonic periodic impacts induced by wheel polygonal wear were solved by a coupled vehicle/track dynamic model, and then entered into the ANSYS finite element model in the form of an array. The vehicle model consists of one vehicle body, two bogies and four wheel sets. The body and bogies are considered as rigid, including all rotational and translational degrees of freedom. Flexible wheel sets are built up in ANSYS environment and then coupled with the vehicle subsystem model in UM simulation software. The slab track model is implemented with UM Flexible Railway Track Module. Flexible slab track parameters, such as cross–sections of rails and their parameters, and vertical and lateral stiffness of the track, were consistent with those of finite element track model built in ANSYS as described above. For more details see Ref. [16].

Before performing transient dynamic analysis, a load step was first adopted to generate an initial displacement and stress. The maximum time interval was less than 10^{-4} s. The effects of track irregularities and other types of wheel damage on the dynamic performance of the wheels were not considered in this study.
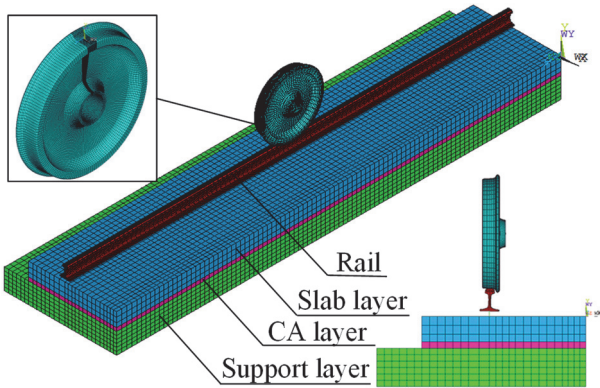

Figure 1 The finite element model of coupled wheel/track system

Table 1 Parameters of the wheel set

Parameter	Value
Wheel diameter	0.92 m
Wheel inner diameter	0.2 m
Axle load	14 t
Young modulus	206 GPa
Poisson ratio	0.29
Density	7800 kg/m³

3 RESULTS AND DISCUSSION

In order to examine the influence of polygon wheel shape on the dynamic displacement and stress of the wheels three points located at different positions of the wheel plate are taken into account, as shown in Fig. 2.
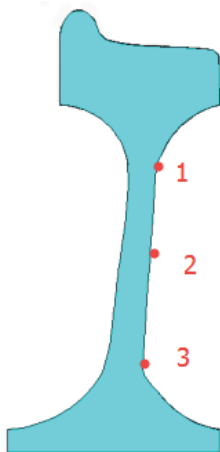

Figure 2 Positions of wheel plate considered for the calculation of the dynamic behavior

Simulation cases are shown in Tab. 2.

Table 2 Simulation cases

Cases	Speed / km/h	Harmonic order	OOR amplitude / mm
1	300	6	0.01, 0.03, 0.06, 0.09, 0.12
2	300	3, 6, 9, 11, 15, 21	0.03
3	200, 250, 300, 350	6	0.03

3.1 Effect of Amplitude of Wheel Polygon on Dynamic Performance of the Wheels

The effects of the OOR amplitude of the sixth-order wheel polygon on the maximum dynamic displacement and Von Misses equivalent stress of the wheel plate at the speed of 300 km/h are illustrated in Fig. 3 and Fig. 4, respectively. The polygonal wear amplitude varied between 0.01 mm and 0.12 mm with a step of 0.02 mm. The results state that both the dynamic displacement and maximum Von Misses equivalent stress at the same position of the wheel plate show proportionality to the OOR amplitude; e.g., the maximum dynamic displacement of points on Ring 1 increases from 0.018 mm to 0.04 mm when the amplitude of polygonal wear increases from 0.01 mm to 0.12 mm.
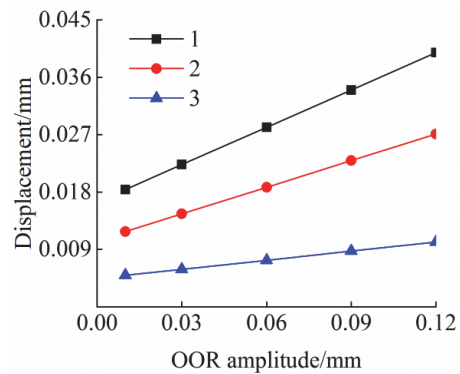

Figure 3 Displacement versus OOR amplitude

It can be seen from Fig. 3 that the displacement of points on Ring 1 is larger than other points in the same cross-section of the wheel plate; i.e., the closer to the wheel tread, the greater the displacement. The maximum displacements of points on Rings 1, 2, and 3 induced by the sixth-order wheel polygonal wear with 0.01 mm OOR amplitude are 0.018 mm, 0.012 mm, and 0.005 mm, respectively. The maximum displacement of points on Rings 1, 2, and 3, increases to 0.040 mm, 0.027 mm, and 0.010 mm, respectively, when the amplitude of polygonal wear increases to 0.12 mm. This phenomena is because of the normal force variations induced by the change in OOR amplitude.
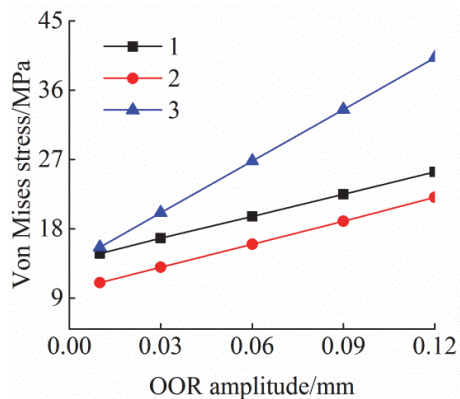

Figure 4 Von Misses stress versus OOR amplitude

It is observed from Fig. 4 that the maximum Von Misses equivalent stress occurs close to the wheel center; i.e., the dynamic stress of points around the circumference

of Ring 3 is larger than for Rings 1 and 2. In addition, the increases in amplitude of polygonal wear have greater influence on the dynamic stress of points located near the wheel center. This is because of the bending oscillation of the wheel set axle excited by vertical wheel displacement.

Fig. 5 shows the variations in dynamic displacement of the wheel plate induced by the wheel rotation. It can be observed that the waveform of displacement expresses the shape of a sinusoidal wave, including six wave lengths around the circumference of all three Rings on the wheel. It is induced by periodic irregularities along the wheel circumference, resulting in the variations of the wheel compression.
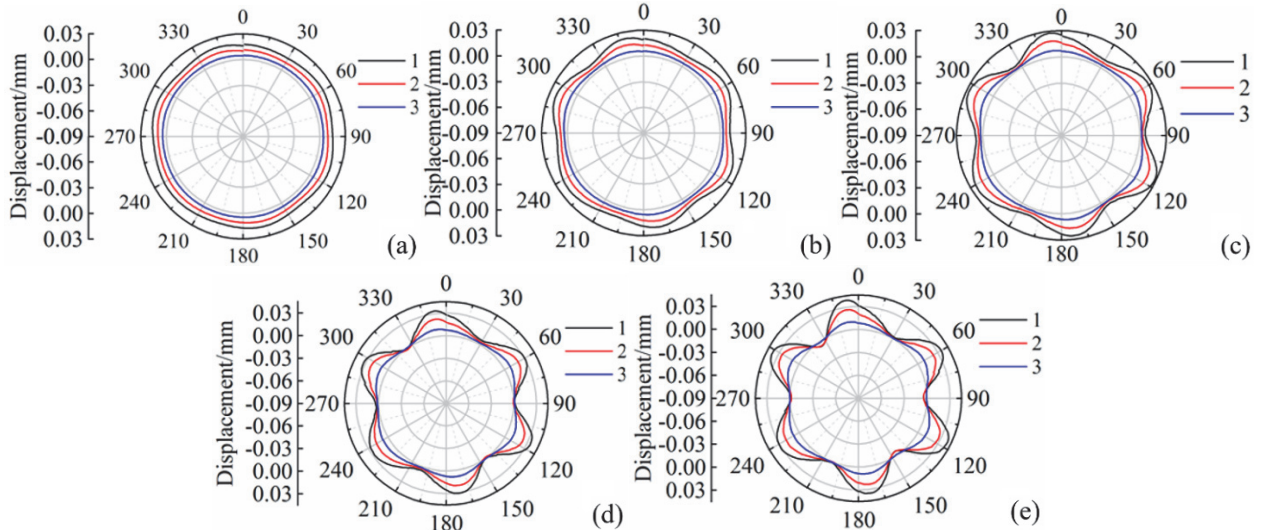

Figure 5 Displacement of the wheel in the polar coordinate system: a) OOR amplitude 0.01 mm; b) OOR amplitude 0.03 mm; c) OOR amplitude 0.06 mm; d) OOR amplitude 0.09 mm; e) OOR amplitude 0.12 mm

The effect of the amplitude of wheel polygon on the maximum Von Misses equivalent stress for points around different rings of the wheel plate is demonstrated in Fig. 6. According to the comparison analysis of Fig. 6a-c, the dynamic stress of points around Ring 2 decreases gradually from the angle 0° to 90°, and then increases slightly from the angle of 90° to 180°. Whereas, the dynamic stress of points around Rings 1 and 3 decreases gradually from the angle of 0° to 90°, and then increases obviously from the angle of 90° to 180°. It implies that the minimum Von Misses equivalent stress occurred at an angle of 90°; this is because of the bending deflection of the wheel.
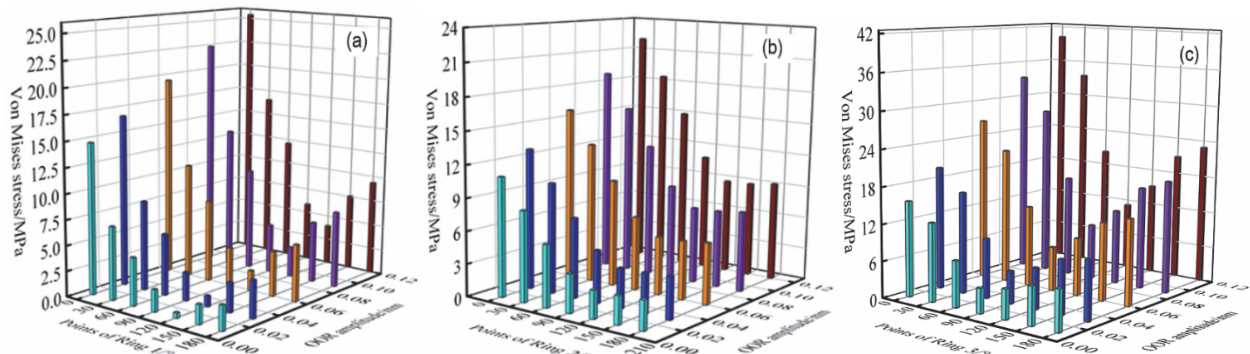

Figure 6 Influence of OOR amplitude on Von Misses equivalent stress of wheel plate: a) Von Misses equivalent stress of points around Ring 1; b) Von Misses equivalent stress of points around Ring 2; c) Von Misses equivalent stress of points around Ring 3

3.2 Effect of the Order of Wheel Polygon on Dynamic Performance of the Wheels

When a polygonal wheel with OOR amplitude of 0.03 mm runs on the track under the speed of 300 km/h, the effects of the harmonic order on the dynamic displacement and Von Misses equivalent stress of the wheel are illustrated in Fig. 7 and Fig. 8, respectively. As can be seen, the overall trend for both the displacements and Von Misses equivalent stresses is to increase as the harmonic order rises, for the points around the circumference of Rings 1, 2 and 3.
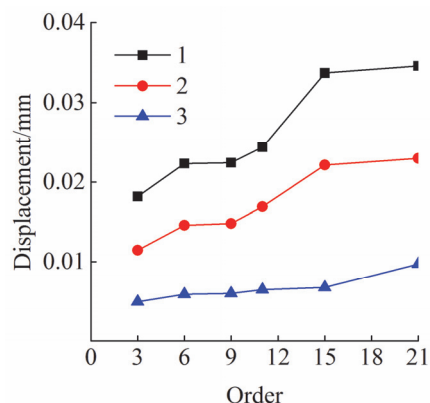

Figure 7 Displacement of the wheel versus harmonic order

In Fig. 7 it is implied that, on the same cross-section of the wheel set, the dynamic displacement of points on Ring 1 is larger than that of Rings 2 and 3; i.e., the closer to the wheel tread, the larger the displacement. In addition, the dynamic displacement induced by high-order polygonal wear is larger than that caused by low-order polygonal wear; i.e., the maximum displacement induced by 21st-order polygonal wear reaches 0.031 mm, which is approximately two times larger than the 0.016 mm for third-order polygonal wear. The reason is that the high-order polygonal wear induces high frequency wheel/rail contact vibration.

It can be deduced from Fig. 8 that the Von Misses equivalent stress induced by the harmonic order of wheel polygon increases sharply in the range between the 11th and 21st order. Moreover, the difference in the Von Misses equivalent stress for points on different Rings of the wheel plates increases; i.e., the maximum Von Misses equivalent stress of points on Ring 1 caused by the 21st order polygonal wear reaches 34.56 kPa, approximately two

times larger than the 16.3 kPa for Ring 2. It is mainly due to the wheel/track coupled vibration that becomes more dominating, as the harmonic order increases.
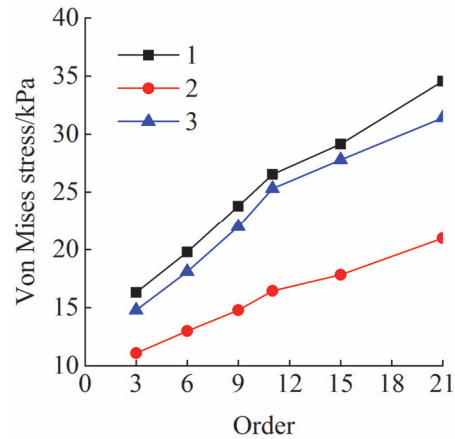

Figure 8 Von Misses stress of the wheel versus harmonic order
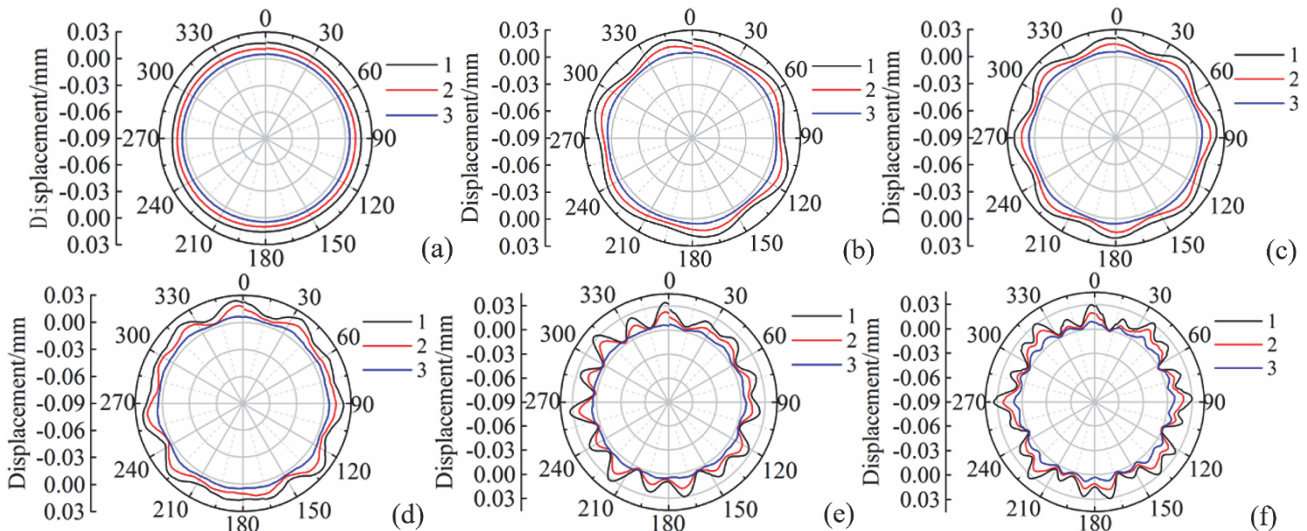

Figure 9 Displacement of the wheel in the polar coordinate system: a) 3rd order; b) 6th order; c) 9th order; d)11th order; e)15th-order; f) 21st order
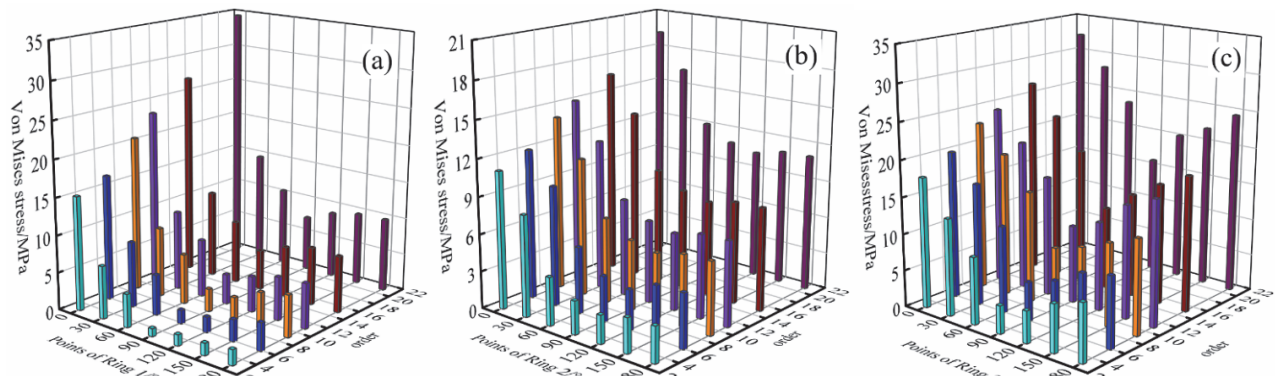

Figure 10 Influence of harmonic order on stress of the wheel: a) Von Misses equivalent stress of points around Ring 1; b) Von Misses equivalent stress of points around Ring 2; c) Von Misses equivalent stress of points around Ring 3

The influences of the harmonic order of wheel polygon on the dynamic displacement of the wheel plate induced by wheel rotation are illustrated in Fig. 9. It can be concluded that the waveforms of dynamic displacement follow a similar pattern to a sinusoidal wave, including 3rd, 6th, 9th, 11th, 15th and 21st wavelengths around the circumference of all three rings. The variations of radial irregularity along the wheel circumference cause periodic impact loads and result in corresponding wheel compression.

Fig. 10 indicates the variations in Von Misses equivalent stresses for points on different rings of the wheel set with the increase of harmonic order, during the rotation of the wheel set. From comparisons of Fig. 10a-c, it is concluded that the maximum Von Misses equivalent stress of points around the circumferences of Ring 1 and 2

decreases gradually from the angle of 0° to 90°, and then increases slightly from the angle of 90° to 180°. Whereas, the maximum Von Misses equivalent stress of points around the circumference of Ring 3 decreases sharply from the angle of 0° to 90°, and then increases obviously from the angle of 90° to 180°. The behavior of the wheel set depends mainly on large normal forces in the wheel/rail contact field.

3.3 Effect of Train Speed on Dynamic Performance of the Wheels

When the OOR amplitude is 0.03 mm, the effect of train speed on the displacement and Von Misses equivalent stress of the wheel with sixth-order polygon shape is shown in Fig. 11 and Fig. 12, respectively.
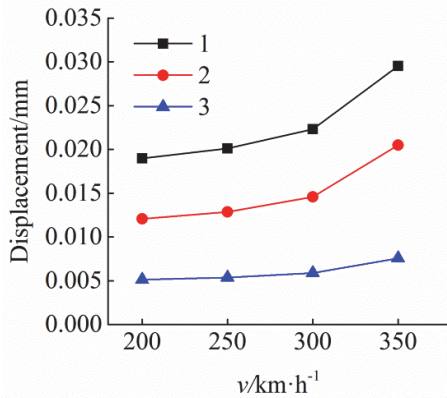

Figure11 Displacement of the wheel set versus train speed

Fig. 11 illustrates that the dynamic displacement at the same position of the wheel plate increases slightly in the range between 200 km/h and 300 km/h, and then rises sharply between 300 km/hand 350 km/h. That is, when the velocity increased from 200 km/h to 350 km/h, the maximum dynamic displacement of points on Rings 1, 2, and 3 increased, respectively, by 32.47%, 40.40%, and 28.13%. It is also observed that for the same cross-section

of the wheel plate, the dynamic displacement of Ring 1 is larger than that of the other two rings. Therefore, it can be concluded that the increase in velocity has important influence on the dynamic displacement of the wheel web.

In Fig. 12, it is observed that the Von Misses equivalent stress for points on Ring 1 and 2 increases slightly with increased speed. The Von Misses equivalent stress of points on Ring 3 increases slightly in the range between 200 km/h and 300 km/h, and then rises markedly between 300 km/h and 350 km/h. It implies that in the presence of wheel polygons, the increase in operating speed has great influence on the dynamic stress of points at the wheel spoke attached to the axle.
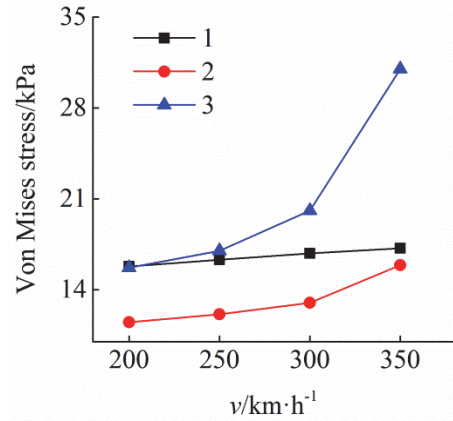

Figure 12 Von Misses equivalent stresses of the wheel set versus running speed

Fig. 13 shows dynamic displacements of points around the circumferences of Rings 1, 2, and 3 in the polar coordinate system with different velocity. It states that the waveform of dynamic displacement of all three rings shows the same shape as a sinusoidal wave, including six wavelengths around the circumference. The fluctuation amplitude of dynamic displacement increases as the velocity grows. This is because the exciting frequency of the wheel/rail coupled vibration rises, resulting in larger elastic deformation of the wheel.
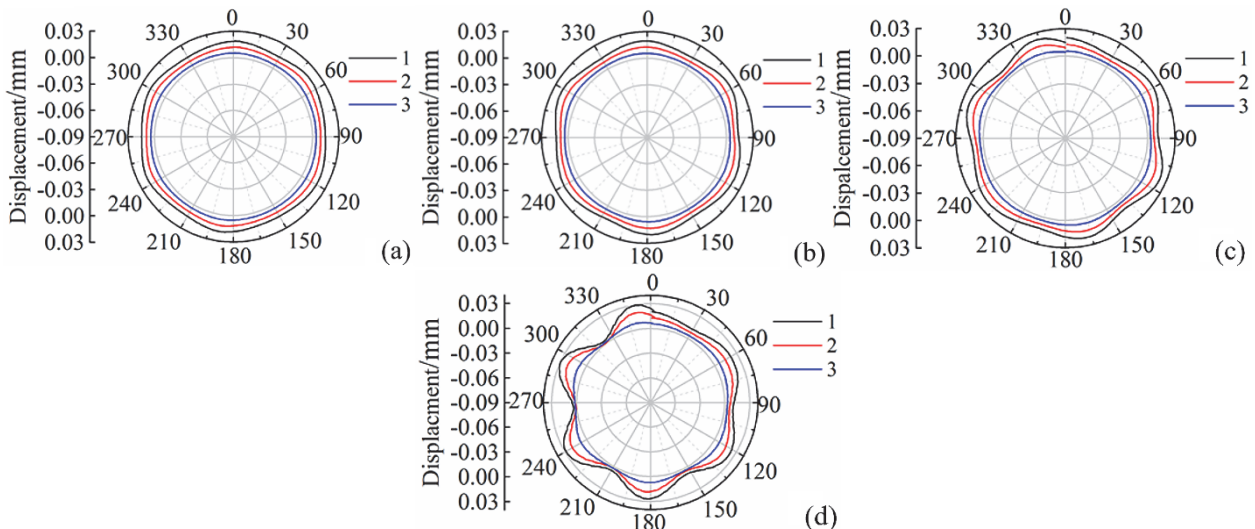

Figure 13 Dynamic displacements of points on Rings 1, 2, and 3 in the polar coordinate system: a) 200 km/h; b) 250 km/h; c) 300 km/h; d) 350 km/h

Fig. 14 illustrates the Von Misses equivalent stress for points on Rings 1, 2, and 3 as the operation speed grows.

As can be seen, Von Misses equivalent stress apparently rises with the increase of speed. When the speed remains

unchanged, the Von Misses equivalent stress of points on Rings 1 and 3 first decreases and then increases, and the minimum stress is reached at the angle of 90°. Whereas, the Von Misses equivalent stress of points on Ring 2 gradually decreases from 0° to 90°, and the change then flattens out from 90° to 180°.
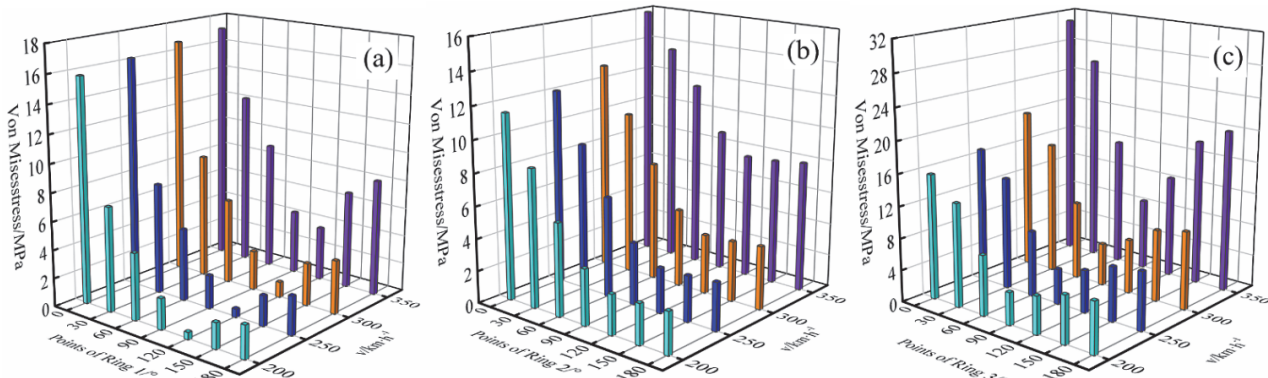

Figure 14 The Von Misses stress of the wheel plate versus running speed: a) Von Misses equivalent stress of points on Ring 1; b) Von Misses equivalent stress of points on Ring 2; c) Von Misses equivalent stress of points on Ring 3

4 CONCLUSIONS

The effect of polygon wheel shape on the dynamic performance of wheel set of high-speed train is investigated, based on ANSYS finite element analysis and Universal Mechanism dynamic simulation. Some conclusions have been drawn as follows.

Polygonal wears would cause variations in the dynamic displacement and stress of the wheel. Moreover, the overall trend of dynamic behavior of the wheel increases as the OOR amplitude and harmonic order and vehicle velocity rise, which deteriorates the safety of railway system components.

The maximum displacement occurs close to the wheel tread in the same cross-section of the wheel plate, i.e., the closer to the wheel tread, the greater the displacement. Nevertheless, the maximum Von Misses equivalent stress occurs close to the wheel center. In addition, the increases in amplitude of polygonal wear have greater influence on the dynamic stress of points located near the wheel center.

Both the dynamic displacement and the Von Misses equivalent stress induced by high-order polygonal wear are larger than those caused by low-order polygonal wear. Besides, the increase in vehicle velocity has great influence on the dynamic stress of points at the wheel spoke attached to the axle.

The variations of polygonal radial irregularity along the wheel circumference cause periodic impact load, and result in the waveforms of dynamic displacement and Von Misses equivalent stress follow a similar pattern to a sinusoidal wave.

Consequently, it is necessary to monitor the wheel shape on line and re-profile regularly to increase service life of the wheel set and reduce maintenance costs. However, the track is imperfect in actual engineering. Thus, the influence of both track irregularities and wheel damage on the behavior of the wheels is under investigation.

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