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DYNAMIC CHARACTERISTICS OF GEARBOX HOUSING VIBRATION ON THE BEIJING-SHANGHAI LINE

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Abstract: Gearbox housing vibration critically impacts the operational safety and reliability of high-speed trains. However, existing research mainly relies on the track spectrum of Wuhan-Guangzhou Line, lacking analysis tailored to the unique characteristics and curve negotiation conditions of Beijing-Shanghai Line. To address this gap, this study establishes an experimentally validated vehicle-track coupled dynamics model, conducting multi-condition simulations to explore gearbox vibration correlations with operating parameters, track conditions, and wheel polygon excitation under Beijing-Shanghai Line scenarios. Key findings show that as speed increases, vertical (Z) and lateral (Y) vibration responses of three measurement points converge. Low speeds are dominated by 11th-order wheel polygon effects, while high speeds are influenced more by the 23rd-order polygon. Upper gearbox points exhibit prominent Y-direction vibration, and lower points show significant Z-direction vibration. Beyond 300 km/h, speed becomes the dominant factor, with polygon order's influence on vibration acceleration RMS values diminishing. Gearbox vibration intensifies at 275 km/h under 23rd-order polygon excitation, and vibration severity increases with wheel polygon amplitude. Curve negotiation analysis reveals that smaller radii induce more severe vibration: Z-direction vibration decreases monotonically with increasing radius. Y-direction vibration behaves differently by speed—increasing with radius at 250 km/h but decreasing at other speeds. Local peaks occur at 9,000 m radius (275/325 km/h) and 8,000 m radius (350 km/h) due to enhanced wheel-rail excitation.
Keywords: Gearbox housing vibration; Beijing-Shanghai Line; Wheel polygon; Curve radius

1 INTRODUCTION

Under complex operating conditions, high-speed train gearboxes experience excessive vibration and dynamic stress due to multi-source excitations (including traction system dynamic loads, wheel-rail coupled vibrations) and high-frequency impacts induced by track irregularities/wheel polygonalization, accelerating fatigue damage and threatening operational safety. To address this issue, researchers have conducted a series of studies: Parey et al. established multi-degree-of-freedom dynamic models for gear transmission systems [1-2]; Carbonelli et al. revealed the inherent modal shapes of gearbox housings through finite element analysis [3]; Kahraman et al. investigated vibration response characteristics under external excitations [4]. Zhang et al. identified stress distribution patterns under external excitations via dynamic stress testing [5], while Wang et al. quantified the impacts of track irregularities and wheel polygonalization on dynamic stresses, emphasizing speed, track conditions, and wheel tread profiles as critical factors [6-7]. Notably, Huang et al. demonstrated that time-varying meshing stiffness and transmission errors significantly amplify vertical vibrations, with spectral characteristics dominated by gear meshing frequencies, highlighting the importance of internal excitations [8]. Hu et al. revealed through multi-domain analysis that coupled effects of wheel-rail excitation and casting defects reduce fatigue strength, proposing that optimized casting processes could prevent resonance between excitation frequencies and structural natural frequencies [9]. Zhang et al. developed finite element modal analysis methods to identify local resonance and stress concentration points caused by external excitations, based on gearbox crack failure databases [10]. Currently, most studies adopt the Wuhan-Guangzhou (Wuguang) track spectrum, primarily because the Wuguang high-speed railway, as one of China's early-built mainlines, had its track spectrum data publicly available earlier, providing a more mature research foundation. Early simulations and tests were predominantly based on Wuguang data, and subsequent studies have continued using this spectrum to maintain comparative consistency. However, with the sustained development of China's economy, the operational frequency of the Beijing-Shanghai High-Speed Railway has continuously increased in practical application, making it the busiest rail line in the country. Designed for a speed of 380 km/h, which is higher than the Wuhan-Guangzhou line's 350 km/h, the track spectrum of the Beijing-Shanghai line more accurately reflects wheel-rail excitation characteristics under ultra-high-speed conditions. Therefore, this paper establishes a vehicle-track coupled dynamics model incorporating wheel polygonal wear, aiming to systematically investigate the vibration characteristics of the high-speed train gearbox under Beijing-Shanghai line conditions.

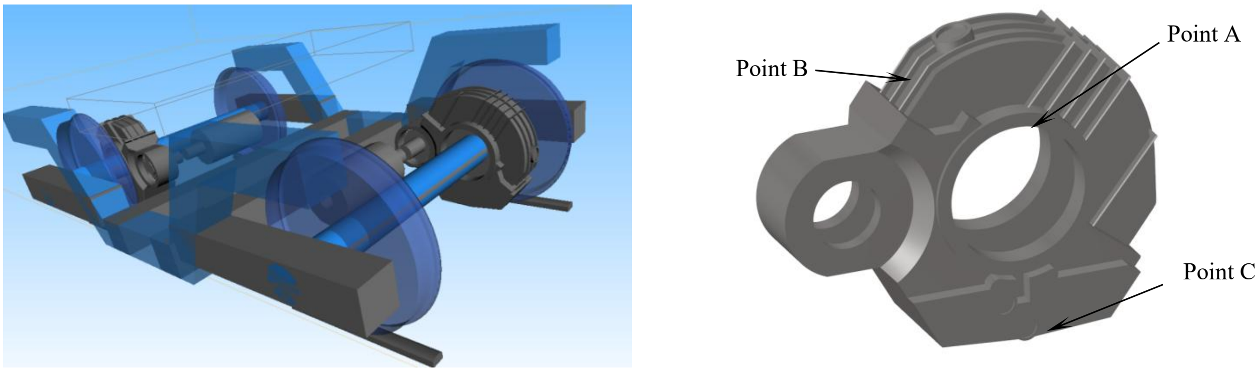
2 DYNAMIC MODEL CONSTRUCTION

Based on the given vehicle parameters, this study establishes a full vehicle dynamics model. Given the significant influence of the transmission system on the gearbox vibration characteristics, key components such as the motor, drive shaft, pinion, driven shaft, gear(parameters detailed in Table 1), and gearbox housing are incorporated in detail into the model. The gear meshing interactions are characterized using the F225 force element in SIMPACK, as illustrated in

Figure 1(a). To further investigate the local dynamic response of the gearbox, three key points are selected as observation points on its flexible body: the gear bearing hole seat (Point A), the gear tooth observation hole (Point B), and the oil level observation hole (Point C), with their locations shown in Figure 1(b) [11-12].

Table 1 Gear Parameters

	Pinion	Gear
Teeth	35	85
Tooth width(mm)	66	65
Profile shift	0.225	0.024
Helix angle(deg)	18	-18
Module	6	
Normal pressure angle(deg)	20	
Center distance(mm)	380	
Stiffness Ratio	0.8	
Young's Modulus(Pa)	2.1e11	
Poisson's Ratio	0.3	
Damping Coefficient(N•s/m)	5000	



(a) Dynamic model construction (b) Observation points

Figure 1 Dynamic Model Construction and Observation Points

3 KINEMATIC THEORY AND EXCITATION

3.1 Kinematic Theory

For the matrix form of the motion differential equations of the vehicle system:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F\} \tag{1}$$

Based on the gear transmission system dynamics theory, a coupled bending-torsion-axial-lateral vibration dynamic model of helical gears is established. The model incorporates nonlinear factors such as time-varying mesh stiffness, transmission error, and backlash of helical gears, while tooth surface friction is neglected.The meshing force $F_{\mathrm{mesh}i}(i=x,y,z)$ acting on the large gear can be expressed as [13]:

$$\begin{bmatrix} F_{\mathrm{mesh}\,x} \\ F_{\mathrm{mesh}\,y} \\ F_{\mathrm{mesh}} \end{bmatrix} = \begin{bmatrix} F_{\mathrm{m}}\sin\alpha\cos\beta \\ F_{\mathrm{m}}\sin\beta \\ F_{\mathrm{m}}\cos\alpha\cos\beta \end{bmatrix} \tag{2}$$

$$F_{\mathrm{m}} = k_{\mathrm{m}}\left(\delta + e_0\right) + c_{\mathrm{m}}\dot{\delta} \tag{3}$$

In the equation, $k_{\mathrm{m}}, c_{\mathrm{m}}$ represent the time-varying mesh stiffness and damping of the helical gears, respectively. δ denotes the dynamic transmission error. e_0 represents the transmission error. $x_i, y_i, z_i (i = p, w)$ are the translational displacements of the pinion and wheel, respectively. β is the helix angle. α is the pressure angle. F_m is the normal force acting on the helical gear tooth surface.

3.2 The Wheel Polygonalization Excitation Function

Considering the functional relationships between wheel polygon radius deviation, order number, out-of-roundness, and rotation angle, these parameters are modeled in the form of harmonic functions to derive the mathematical expression for wheel polygonization [14].

$$\Delta R(\beta) = CA\sin(n(\beta+\beta_0)) \qquad \beta \in \left(0,2\pi\right] \tag{4}$$

Where ΔR denotes the wheel radius deviation; A represents the amplitude; n indicates the polygonal order of the wheel; C stands for the out-of-roundness; β corresponds to the wheel rotation angle; and β_0 signifies an additional relative rotation and offset.By configuring the relevant settings in Simpack, the corresponding simulations can be performed.

4 MODEL VALIADATION

Based on field measurement data of gearbox housing vibrations on the Wuhan-Guangzhou Line(train speed: 300 km/h), a comparative analysis was conducted between simulations and operational conditions regarding the lateral and vertical vibration accelerations and power spectral density (PSD) of the gearbox. As shown in Figure 2, the experimental test results showed that the lateral and vertical vibration accelerations of gearbox housing fluctuated within ranges of approximately -70 to 60 m/s² and -124.58 to 136.47 m/s², respectively, while the simulation results showed ranges of approximately -68.08 to 58.88 m/s² and -117.69 to 64.85 m/s², respectively. The main vibration range and maximum amplitude of both vertical and lateral vibration accelerations were similar between simulation and experiment. In the frequency domain, as illustrated in Figure 3, both simulations and measurements exhibited consistent trends, though the measured spectra displayed more complex components. These discrepancies primarily originated from three factors: the simulated track excitation spectrum failed to fully account for short-wave irregularities induced by rail weld joints and fasteners; the actual track conditions deteriorated after prolonged service; and the rigid-body simplification of components in the simulation model. These limitations collectively led to lower vibration responses in simulations compared to field data. Nevertheless, this comparative study validates the accuracy of the proposed vehicle-track transmission system dynamics model, thereby providing a robust foundation for further theoretical investigations.

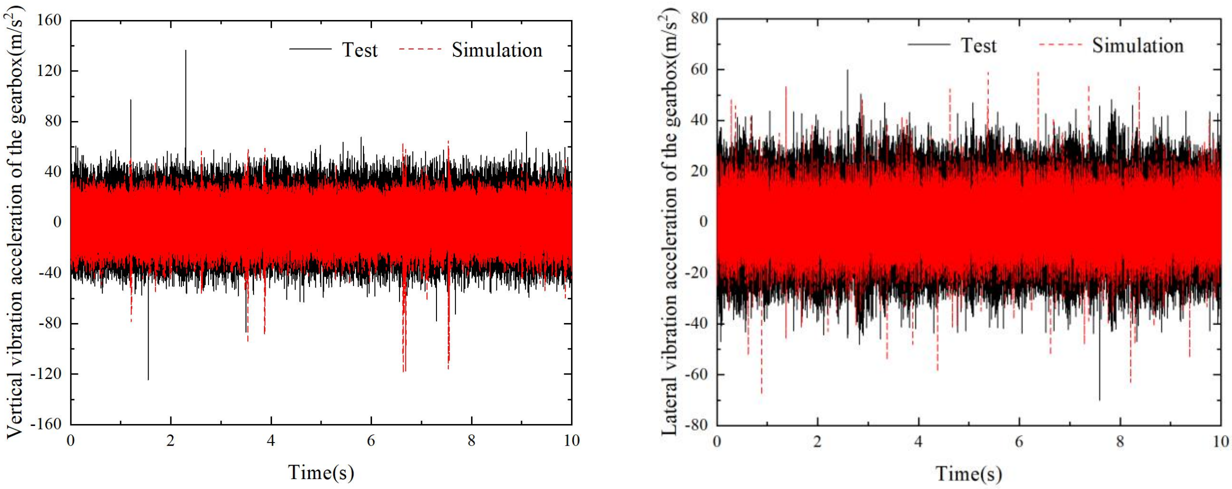


Figure 2 Gearbox Vibration Acceleration

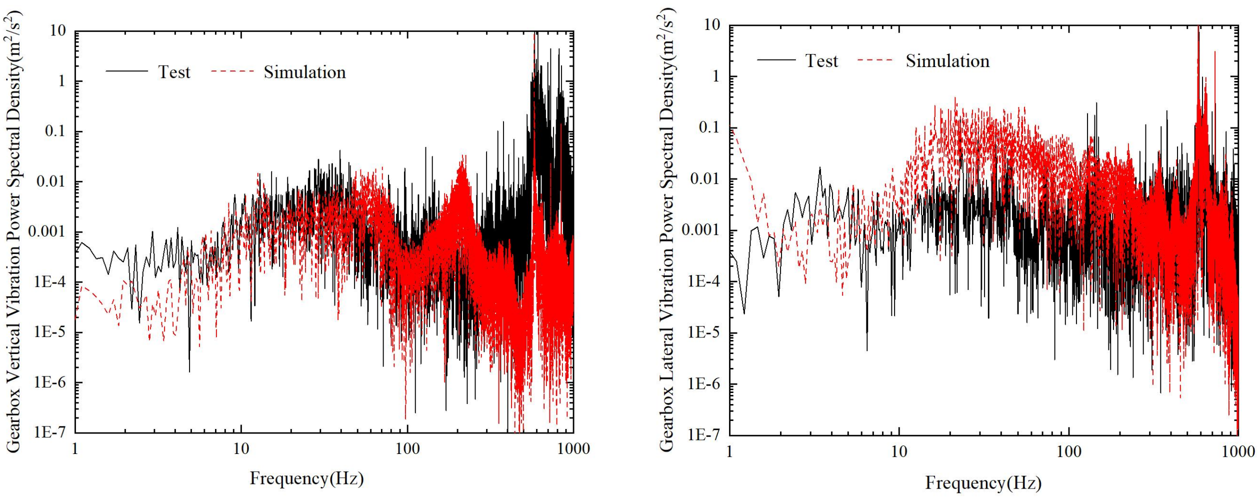


Figure 3 PSD of Gearbox Vibration Acceleration

5 GEARBOX HOUSING VIBRATION ANALYSIS

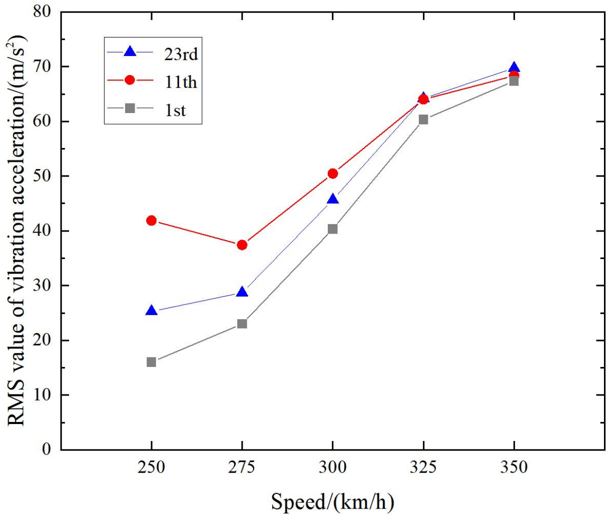
5.1 Effect of Wheel Polygon Excitation on Gearbox Housing Vibration Characteristics

Wheel-rail excitation is the primary source of gearbox housing vibration. Wheel polygonalization can significantly exacerbate the impact loads within the wheel-rail system, thereby influencing the dynamic response of the gearbox. Therefore, a thorough investigation into its impact is necessary.

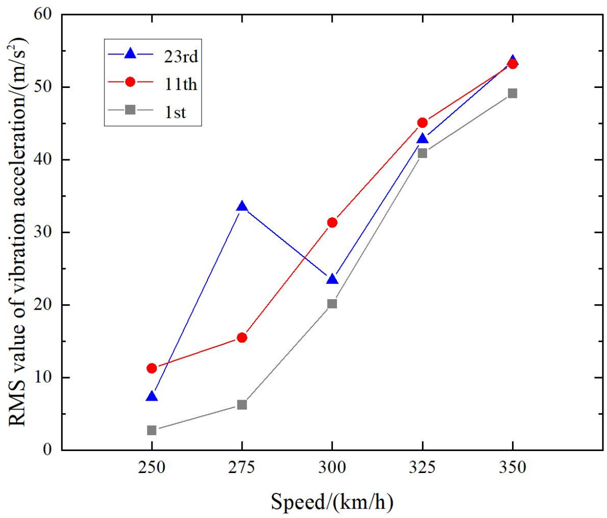
5.1.1 Effect of wheel polygon order on gearbox housing vibration characteristics

The polygon order is a key parameter characterizing wheel polygonal features. To investigate its influence, this study compares and analyzes the vibration acceleration amplitudes at three measurement points on the gearbox housing under combined conditions of five train speeds (250, 275, 300, 325, and 350 km/h) and three polygon orders. Based on vibration test data of a certain EMU gearbox and wheel polygon statistics, the polygon orders selected for this study include the 1st, 11th, and 23rd orders [15-16].

As shown in Figure 4, the vibration trends in the Z-direction are generally consistent across the three observation points, but the amplitude at Point C is higher than at the other two points. In the low-speed range (e.g., 250 km/h), the 11th order polygon induces the most pronounced vibration. As the speed increases, the vibration levels under the three orders gradually converge, with the 23rd order exhibiting a relatively more prominent influence. A notable phenomenon is observed at 250 km/h, where the vibration caused by the 11th order is substantially greater than that of the other orders. This is attributed to the stronger vertical vibrations of both the pinion and gear under this specific order condition. When the speed exceeds 300 km/h, the influence of the polygon order on the root mean square (RMS) values of vibration acceleration at each measurement point diminishes, with speed becoming the dominant factor. In the Y-direction, the vibration amplitudes follow the order Point B > Point C > Point A, yet the overall trends remain relatively consistent. Specifically, the vibrations under the 11th and 1st orders show a general increasing trend with speed, while the 23rd order exhibits a distinct peak at 275 km/h. This peak occurs because the wheel-rail excitation frequency at this speed (approximately 643 Hz) coincides with the natural frequency of the gearbox, leading to resonance.

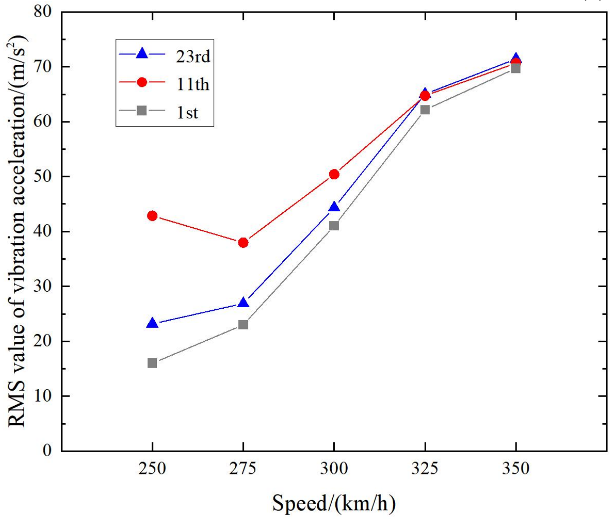


(i) z-direction

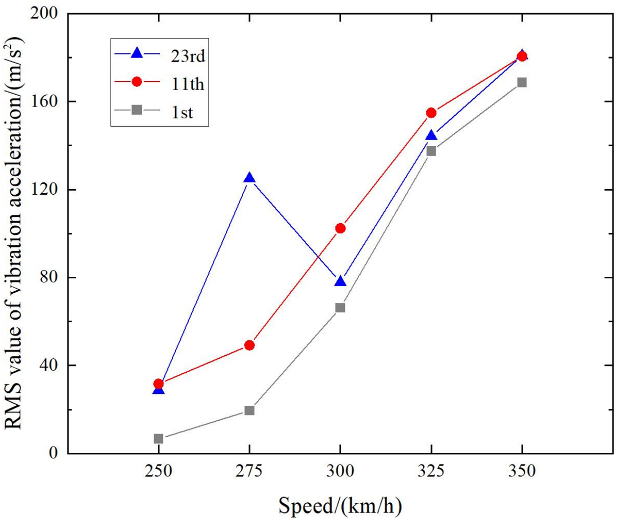


(ii) y-direction

(a) Point A

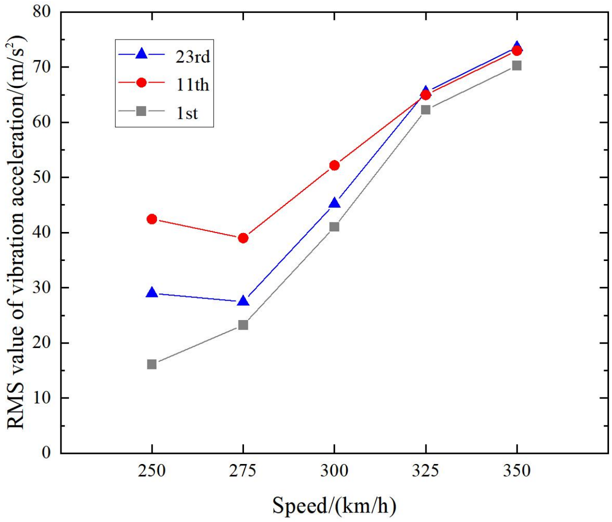


(i) z-direction

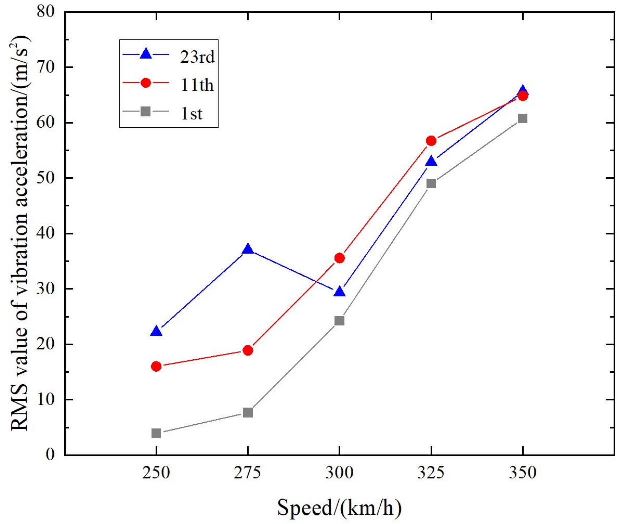


(ii) y-direction

(b) Point B



(i) z-direction



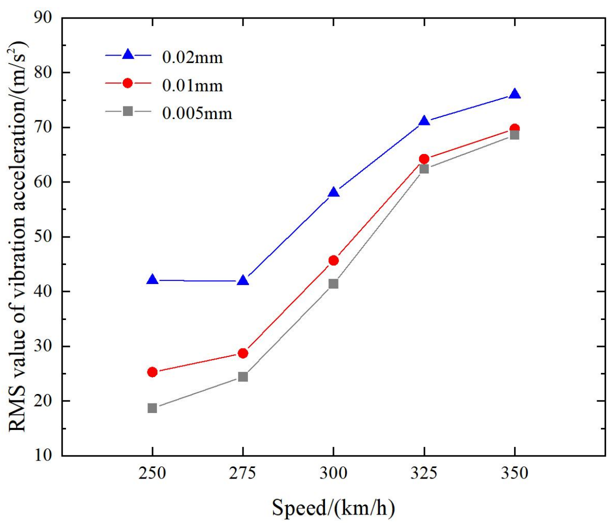
(ii) y-direction

(c) Point C

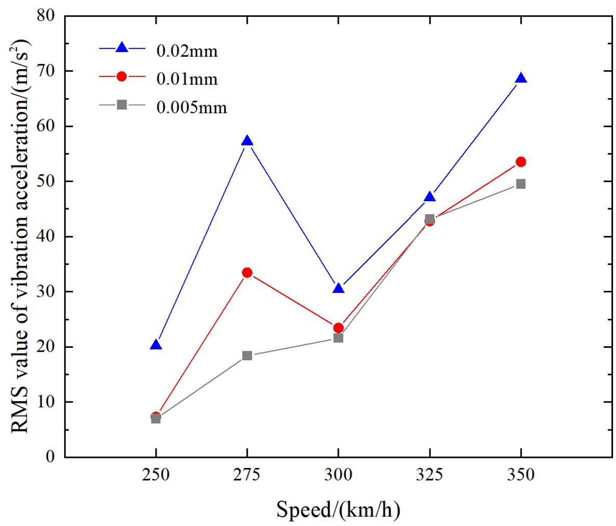
Figure 4 Effect of Wheel Polygon Order on the RMS Value of Gearbox Vibration Acceleration at Different Speeds

5.1.2 Effect of wheel polygon amplitude on gearbox housing vibration characteristics

Under high-speed conditions, vibrations intensify, with the 23rd-order wheel polygon causing the most significant impact. Therefore, this study sets the polygon order to 23. According to literature, the amplitude limit for wheel polygons of orders 18–24 is typically below 0.020 mm. Simulations were conducted with amplitudes of 0.005 mm, 0.010 mm, and 0.020 mm, at speeds ranging from 250 to 350 km/h, to analyze the effect of amplitude on gearbox housing vibration.As shown in Figure 5, at a given speed, the RMS values of vibration acceleration are highest at an amplitude of 0.020 mm, with overall trends remaining consistent. Comparative simulations for the 11th-order polygon yielded similar results, which are not detailed here. Among the three measurement points, Point B shows the most intense vibration response overall, requiring special attention in fatigue analysis.

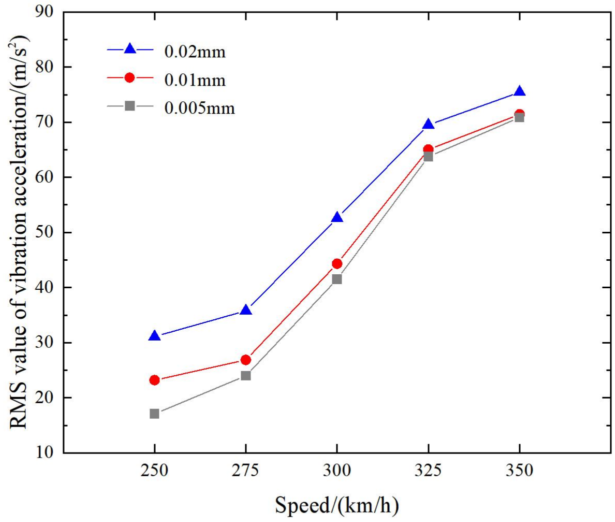


(i) z-direction

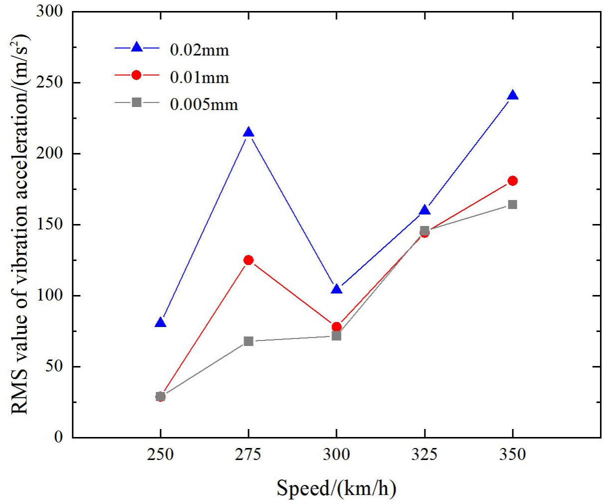


(ii) y-direction

(a) Point A

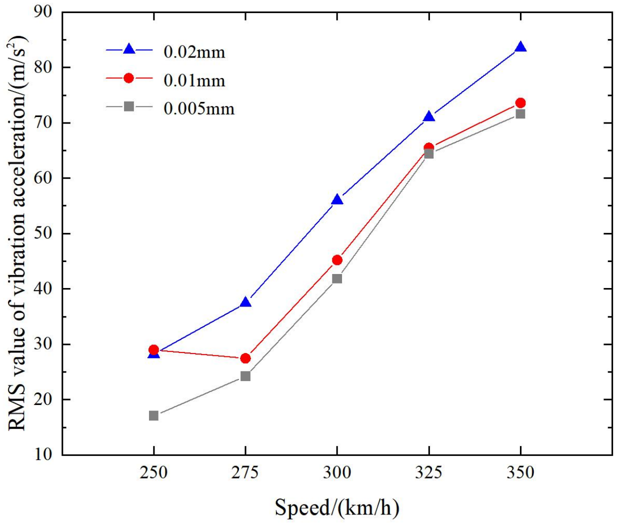


(i) z-direction

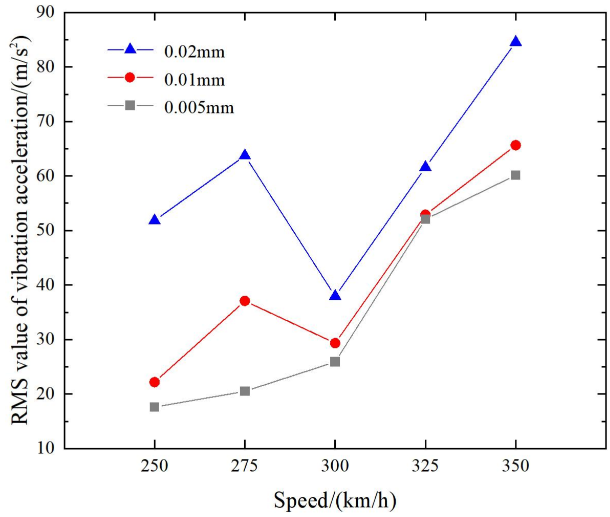


(ii) y-direction

(b) Point B



(i) z-direction



(ii) y-direction

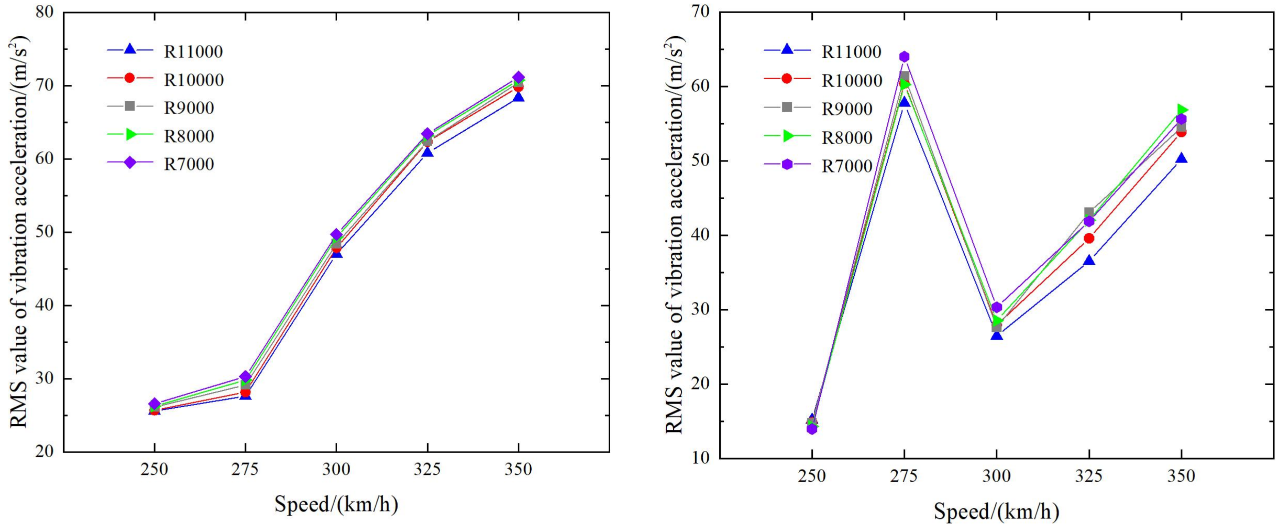
(c) Point B

Figure 5 Effect of Wheel Polygon Amplitude on the RMS Value of Gearbox Housing Vibration Acceleration at Different Speeds

5.2 Effect of Curve Radius on Gearbox Housing Vibration Characteristics

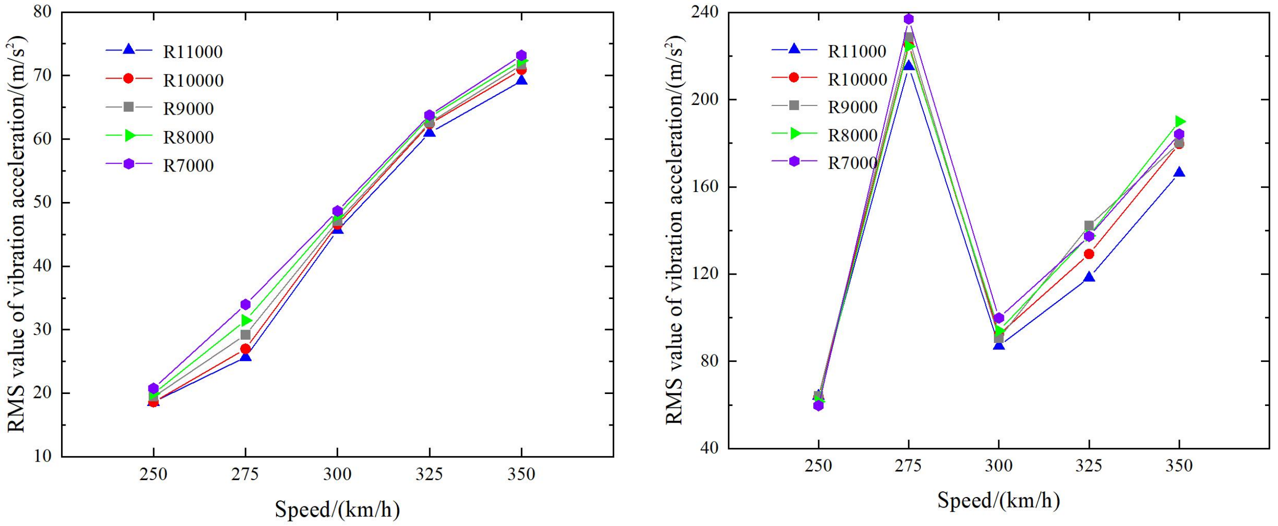
Curve negotiation performance is a key indicator for evaluating the operational quality of electric multiple units (EMUs), and the vibration characteristics of the gearbox under curve negotiation conditions are also a major research focus. Taking the Beijing-Shanghai High-Speed Railway, a trunk line designed for a speed of 380 km/h, as an example, the minimum curve radius standard for its alignment is 7,000 meters. To systematically investigate the influence of curve radius on gearbox housing vibration, this study selects a range of five typical curve radii for detailed simulation analysis: 7,000 m, 8,000 m, 9,000 m, 10,000 m, and 11,000 m. The operational speed is set within the common high-speed range of 250–350 km/h. Track parameters, including superelevation and transition curve lengths, are configured according to real-world design specifications and operational scenarios to ensure the simulations accurately reflect practical dynamic interactions.

The results indicate a clear relationship between curve radius and vibration intensity: smaller curve radii generally induce more intense gearbox vibrations. In the vertical (z) direction, vibration amplitude consistently decreases as the curve radius increases, showing a clear monotonic trend. However, the lateral (y-direction) vibration exhibits a more complex, speed-dependent behavior. At 250 km/h, y-direction vibration amplitude actually increases with larger curve radii, contrary to the overall trend. Under other speeds, it decreases as the radius increases. Notable local vibration peaks are observed at specific speed-radius combinations: at 275 km/h and 325 km/h, a local peak occurs at a curve radius of 9,000 meters; at 350 km/h, a local peak appears at 8,000 meters.Spectrum analysis reveals that, under these specific conditions, the combination of speed and curve radius intensifies wheel-rail excitation, which in turn amplifies gearbox vibration. Furthermore, comparing the vibration response across the three measurement points (A, B, C), the y-direction patterns are consistent with those observed under straight-line operation. In the z-direction, the location of maximum vibration shifts with speed: it is initially at point A under lower speeds, but gradually transitions to point C as the operating speed increases.



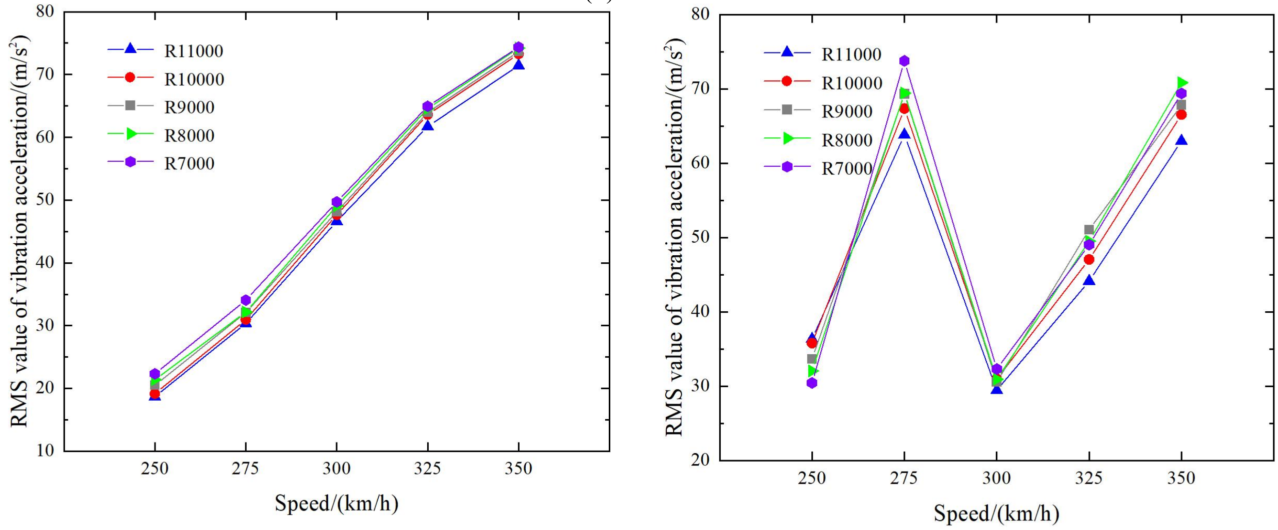
(i) z-direction (ii) y-direction

(a) Point A



(i) z-direction (ii) y-direction

(b) Point B



(i) z-direction (ii) y-direction

(c) Point C

Figure 6 Effect of Curve Radius on the RMS Value of Gearbox Housing Vibration Acceleration at Different Speeds

6 CONCLUSION

This study investigates the correlation between gearbox housing vibration characteristics and train operating parameters, track conditions, and wheel polygon excitation under the Beijing-Shanghai High-Speed Railway scenario by establishing a vehicle dynamics model, combined with experimental data validation and multi-condition simulation analysis. The main findings are summarized as follows:

(1) As the operating speed increases, the vibration responses at the three measurement points in the Z (vertical) and Y (lateral) directions gradually converge. In the low-speed range, the 11th-order polygon has a more pronounced impact on vibrations, whereas under high-speed conditions, the influence of the 23rd-order polygon becomes more significant. Additionally, the Y-direction vibration response is more prominent at the upper measurement point of the gearbox (e.g., Point B), while the Z-direction vibration is more noticeable at the lower measurement point (e.g., Point C). These two types of locations should be regarded as key areas of focus. When the speed exceeds 300 km/h, the influence of the polygon order on the root mean square (RMS) values of vibration acceleration at each measurement point diminishes, and speed becomes the dominant factor affecting vibration characteristics. Notably, under the 23rd-order polygon condition, gearbox vibration intensifies at 275 km/h. Furthermore, as the amplitude of the wheel polygon increases, the vibration intensity of the gearbox exhibits an increasing trend.

(2) When the train passes through curved sections, a smaller curve radius leads to more severe gearbox vibrations. Specifically, the Z-direction vibration decreases monotonically as the curve radius increases, while the Y-direction vibration exhibits differentiated patterns depending on the operating speed. At 250 km/h, the Y-direction vibration increases with larger curve radii, whereas under other speed conditions, it generally decreases with increasing curve radii. It is worth noting that under the 275 km/h and 325 km/h conditions, a local peak in Y-direction vibration occurs at a curve radius of 9,000 meters. In contrast, under the 350 km/h condition, the local peak appears at a curve radius of 8,000 meters.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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