

Wheel–Rail Resonance Dynamic Monitoring and Preventive Grinding

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Abstract: Rail corrugation-induced wheel–rail resonance is one of the most persistent challenges in urban rail transit systems, leading to excessive noise generation, accelerated infrastructure deterioration, and increased maintenance costs. Existing preventive rail grinding practices are predominantly based on geometric measurements of corrugation depth and wavelength, which often fail to accurately identify the optimal maintenance intervention period. To address this limitation, this study proposes a rail dynamic response-based wheel–rail resonance monitoring framework and investigates the dynamic evolution of rail corrugation for preventive maintenance decision-making. A continuous field monitoring system was deployed on corrugated sections of the Beijing Metro network to acquire rail vibration responses during train passages. The collected acceleration signals were analyzed using frequency-domain techniques and a resonance identification algorithm to determine the resonance frequency, vibration amplitude, and the probability of resonance occurrence. Based on long-term monitoring data, a wheel–rail resonance probability index (P) was introduced to quantitatively characterize the severity of resonance phenomena and track the progression of rail corrugation. The results revealed a strong correlation between the development of corrugation and wheel–rail resonance behavior. Type II corrugation exhibited significantly faster resonance evolution than Type I corrugation, with resonance frequencies concentrated around 400 Hz. Furthermore, resonance probability increased consistently with corrugation depth, demonstrating the effectiveness of dynamic indicators in assessing rail deterioration. Based on the observed resonance characteristics, the corrugation deterioration process was successfully divided into three dynamic phases: Dynamic Phase I (non-resonant growth stage), Dynamic Phase II (resonance development stage), and Dynamic Phase III (stable resonance stage). Based on the monitored sections investigated in this study, Dynamic Phase II appears to provide the most suitable intervention window for preventive rail grinding, whereas Dynamic Phase III requires corrective maintenance due to persistent resonance excitation and severe wheel–rail noise. To support maintenance evaluation, a resonance-based effectiveness criterion was also proposed using the duration of Dynamic Phase II as a performance indicator. The proposed framework establishes a novel closed-loop “dynamic monitoring–preventive grinding” maintenance strategy that overcomes the limitations of conventional geometry-based approaches. The developed methodology provides practical support for predictive maintenance, rail noise mitigation, lifecycle cost reduction, and intelligent asset management in urban railway systems.

Keywords: Rail corrugation; wheel–rail resonance; dynamic monitoring; preventive rail grinding; predictive maintenance; urban rail transit.

1. Introduction

In recent years, wheel-rail resonance and noise complaints caused by rail corrugation in urban rail transit systems have become increasingly severe (Connolly et al., 2016), and preventive grinding has proven an effective solution (Niu et al., 2023). Current maintenance standards for the Beijing Metro still rely on geometric measurements of rail corrugation for preventive grinding decisions. This approach exhibits two persistent operational issues: public complaints due to delayed grinding interventions, and significant resource wastage caused by over-maintenance. Geometric measurements alone cannot provide auxiliary decision-making for precise preventive grinding timing.

Rail corrugation predominantly manifests as a recurrent track defect on tight-radius curves ($R < 600\text{m}$) and vibration-damping track beds (Yang et al., 2025). While existing research has established detailed correlations between corrugation severity levels and wheel-rail noise (Thompson, 1996), conventional dynamic monitoring technologies based on rail dynamics require manual analysis of raw data. This approach fails to autonomously assess resonance or guide preventive grinding, while incurring high monitoring costs. Implementing wheel-rail resonance dynamic monitoring enables real-time evaluation of resonance severity (Salehi et al., 2023; Thompson, 1996), providing data-driven decision support for the timing of preventive grinding (Kuppuswamy et al., 2021). This establishes a closed-loop "dynamic monitoring preventive grinding" management framework to rectify over-grinding and under-grinding practices. There are various studies on this subject in the literature.

Popa et al. (2025) comprehensively examined vibration monitoring and measurement technologies used in railway vehicles. The researchers systematically classified existing vibration monitoring methods by evaluating European railway standards, current research results, and industry practices. The study analyzed accelerometer-based measurement systems, data acquisition architectures, and condition monitoring approaches. The findings demonstrated that integrated vibration measurement systems are effective in evaluating vehicle dynamics, improving passenger comfort, and optimizing maintenance activities. This study provides a valuable reference source for engineers and researchers by revealing the current state of vibration monitoring technologies in railway vehicles.

Niu et al. (2023) used Wheel–Rail Vertical Force (WRVF) data and a three-dimensional finite element model to evaluate rail corrugation in high-speed railway systems. The researchers analyzed the relationship between corrugation depth and WRVF across different corrugation wavelengths and developed an indicator to inform rail grinding decisions. Using non-linear least squares modeling and time–frequency domain analyses, they established a reliable assessment framework for rail condition monitoring. The proposed approach achieved 92.5% accuracy in maintenance decision-making. Their study contributed to railway infrastructure monitoring by providing an effective method for corrugation assessment and supporting more accurate maintenance planning.

Fröhling (2007) reviewed the technologies and engineering approaches developed to improve wheel–rail interaction performance in heavy-haul railway systems. The researchers examined wheel–rail stress conditions, wear mechanisms, and maintenance strategies used to extend wheel and rail service life. They analyzed measurement and monitoring technologies to quantify wheel–rail contact stresses and evaluate system performance. In addition, the study discussed the fundamentals of contact mechanics, vehicle dynamics, and the use of software for wheel–rail interface analysis in railway engineering. Their review highlighted the importance of monitoring technologies in reducing maintenance costs and improving operational reliability. The study contributed to the railway sector by providing a comprehensive overview of wheel–rail interaction analysis and maintenance optimization methods for heavy-haul railway applications.

Chen et al. (2025) investigated the effects of grinding carriage frame vibrations on rail surface quality during rail grinding operations. The researchers conducted vibration tests and modal analyses to identify resonance characteristics of the grinding motor operating at 60 Hz. Their analyses revealed that the primary longitudinal beams and crossbeams of the grinding carriage frame exhibited significant vibration responses near the motor excitation frequency, resulting in resonance-induced grinding defects. To mitigate these effects, a structural improvement of the grinding carriage frame was proposed and implemented. Experimental results showed that the vibration increase from idle to grinding conditions decreased by 66% after the modification. Furthermore, rail surface roughness at the critical wavelength was reduced by 22.6%, and the grinding performance improved by a factor of 1.9 compared with the original structure. The study contributed to railway maintenance engineering by demonstrating an effective resonance-based design approach to improve rail grinding quality and reduce the risk of corrugation initiation.

Yang et al. (2025) used data on worn turnout rail profiles and artificial intelligence-based optimization methods to develop a precise rail grinding strategy for high-speed railways. The researchers combined GA-BP-NSGA III, NRBO, Transformer, BiGRU, and KELM algorithms with a vehicle–turnout dynamic model to optimize grinding profiles and improve wheel–rail interaction. The proposed Rail Grinding Strategy Model (RGSM) provided real-time grinding recommendations and achieved training and testing accuracies of 96% and 97%, respectively. After implementation, rail profile deviations were kept within 0.2 mm of the optimized profile, thereby reducing car-body lateral acceleration and vehicle sway. The study contributed to railway maintenance by improving grinding efficiency, operational stability, and turnout performance.

Singla and Aasa (2025) reviewed the fundamental aspects of wheel–rail interaction and their influence on railway safety, performance, and durability. The researchers examined normal, tangential, and lateral contact forces and analyzed their effects on wear, fatigue, vibration, and noise generation. Various wear mechanisms, including adhesive, abrasive, and fatigue wear, were evaluated alongside mitigation techniques such as lubrication, rail grinding, and wheel reprofiling. The study also investigated advanced materials, optimized wheel–rail profiles, and real-time condition-monitoring technologies to improve system reliability. Their review highlighted the potential of smart materials and monitoring systems to enhance

maintenance efficiency and reduce operational costs. The study contributed to the railway field by providing a comprehensive overview of current technologies and future developments in wheel–rail interaction management.

Magel and Kalousek (2002) investigated the influence of wheel–rail contact geometry on railway system performance and maintenance requirements. The researchers developed a pummeling model to evaluate the performance of different rail profiles under loading conditions generated by new and worn wheels. Using RE136-10 " , UIC60, and RE141 rail profiles, they analyzed wheel–rail contact mechanics and their effects on wear, fatigue, corrugation, vehicle stability, and derailment risk. The study also examined the role of rail grinding parameters, including surface roughness, facet width, and grinding intervals, in maintaining optimal wheel–rail interaction. Their findings emphasized the importance of contact geometry in railway maintenance planning and operational safety. The study contributed to railway engineering by providing a framework for evaluating rail profile performance and optimizing rail grinding practices.

Nielsen et al. (2021) reviewed the effects of wheel–rail impact loads generated by surface irregularities such as wheel flats, rail joints, crossings, and rolling contact fatigue defects. The researchers analyzed the mechanisms responsible for railway noise and ground-borne vibrations arising from these discontinuities and investigated their influence on wheel–rail contact forces and component degradation. Non-linear wheel–rail contact models and hybrid time–frequency-domain approaches were used to predict transient impact loads, noise generation, and vibration propagation. The study showed that wheel–rail impacts produce high-magnitude transient loads and vibrations concentrated mainly below 1 kHz, increasing wear and maintenance requirements. The authors emphasized the importance of proper design and regular maintenance to control surface irregularities. The study contributed to railway engineering by improving the understanding of wheel–rail impact mechanisms and vibration mitigation strategies.

Cheng et al. (2011) investigated the effects of vibration and grinding instability during rail grinding operations using a twin-wheel grinding approach. The researchers applied an impedance-based analysis method to evaluate rail vibrations, chatter formation, and grinding performance under conditions of feed-force misalignment and grinding-wheel imbalance. Their results were compared with those of conventional single-wheel rail grinding. The findings showed that twin-wheel grinding significantly reduced rail vibration levels, resulting in lower chatter occurrence and improved surface quality. However, increasing feed force misalignment between the grinding wheels led to higher vibration amplitudes and greater chatter instability, particularly at lower grinding speeds. The study demonstrated that feed force misalignment had a stronger influence on grinding performance than wheel imbalance. This work contributed to railway maintenance by identifying strategies to improve the quality of rail grinding and reduce vibration-induced defects.

Liang et al. (2022) investigated rail grinding limits for metro railway systems using measured rail roughness data, track longitudinal roughness measurements, a coupled vehicle–track dynamic model, and a rolling contact fatigue model. The researchers analyzed the effects of rail corrugation wavelengths and operating speeds on wheel–rail interaction and fatigue behavior. Their results showed that rail grinding criteria should be determined by both the corrugation wavelength and the train speed. The study revealed that long-wavelength corrugation has a lower impact on rolling contact fatigue compared to short-wavelength defects. Based on the obtained thresholds, specific corrugation limits were proposed for metro lines operating at different speed ranges. The study contributed to railway maintenance by providing quantitative rail-grinding criteria to support condition-based maintenance and reduce wheel–rail fatigue damage.

Wang et al. (2024) proposed a hybrid framework for predicting metro-induced environmental vibration by combining physics-based numerical modeling with data-driven machine learning techniques. The researchers first used a numerical model to identify vibration excitation mechanisms and organize field measurement data by their physical characteristics. Subsequently, Self-Organizing Maps (SOMs) were employed to classify vibration signals by train operating conditions, and Bayesian regularization neural networks were developed for each vibration category to establish input–output relationships. Experimental results demonstrated that the proposed hybrid approach reduced prediction variance by approximately 23-fold and improved prediction accuracy by nearly 3-fold compared with conventional neural network models. The study contributed to railway vibration monitoring by integrating physical excitation mechanisms with artificial intelligence techniques, thereby improving the accuracy and reliability of environmental vibration prediction.

Dai et al. (2025) investigated the influence of rail corrugation on the vibration reduction performance of shear-type vibration-damping fasteners in metro systems. The researchers conducted field measurements on a metro section with severe rail corrugation and evaluated the effects of replacing shear-type vibration-damping fasteners with compression-type vibration-damping fasteners, followed by rail grinding. Time–frequency analyses were performed to assess changes in rail vibration characteristics and tunnel noise. The results showed that rail corrugation with wavelengths of 55–60 mm induced wheel–rail resonance within the frequency range of 300.9 to 328.3 Hz. Replacing the fasteners reduced rail vibration acceleration by 36.3%, while subsequent rail grinding further decreased tunnel vibration and reduced the maximum A-weighted sound pressure level by 12.4 dB(A). The study contributed to railway maintenance engineering by demonstrating the relationship among rail corrugation, wheel–rail resonance and vibration mitigation and by highlighting the effectiveness of fastener replacement and rail grinding in improving vibration and noise performance.

Wang et al. (2026) investigated the mechanisms of rail corrugation formation and evolution on ladder-sleeper tracks in small-radius subway curves through long-term field monitoring and numerical analysis. The researchers examined the geometric characteristics, wear behavior, hardness distribution, and metallographic evolution of rail corrugation over time, and employed finite element modeling and steady-state dynamic analyses to evaluate the relationship between track vibration and the development of corrugation. The results showed that rail corrugation exhibited mixed wavelengths and that the formation of White Etching Layers (WELs) accelerated corrugation growth after two months of operation. Furthermore, the lateral overturning resonance of the ladder sleeper track corresponded to the excitation frequency of 200 to 250 mm wavelength corrugation, whereas short-wavelength corrugation (40 to 60 mm) was primarily associated with lateral force

excitation. The study contributed to railway maintenance engineering by providing experimental evidence on the relationship between wheel–rail resonance, metallurgical evolution, and rail corrugation development, thereby supporting the optimization of track structures and maintenance strategies.

Balekwa et al. (2020) investigated the relationship between short-pitch rail corrugation and wheel–rail resonance through experimental measurements and numerical simulations. The researchers conducted experimental modal tests, along with three-dimensional finite element modeling and complex eigenvalue analyses, to examine the dynamic characteristics of a traction wheelset and rail track on the Belfast–Steelpoort railway line in South Africa. The results demonstrated that the excitation frequency generated by short-pitch rail corrugation closely matched the natural frequencies of the wheelset and rail track, with resonance at approximately 100 Hz, consistent with the measured corrugation excitation frequency of 108 Hz. Furthermore, the identified mode shapes confirmed the dynamic interaction between the wheelset and rail track under corrugation-induced excitation. The study contributed to railway dynamics by experimentally validating the correlation between rail corrugation and wheel–rail resonance, thereby providing valuable insights for vibration analysis and railway maintenance planning.

Despite the considerable progress in geometry-based inspection and vibration-based monitoring, several challenges remain. Existing geometry-based methods primarily assess the physical condition of the rail after corrugation has developed, whereas most vibration-based approaches focus on resonance detection and do not provide quantitative indicators of deterioration for maintenance planning. Furthermore, few studies integrate long-term dynamic monitoring with preventive grinding strategies using an objective evaluation index. Consequently, there remains a need for a practical monitoring framework that can continuously evaluate the evolution of wheel–rail resonance and support condition-based maintenance decisions. To address these research gaps, this study proposes a long-term wheel–rail resonance monitoring framework based on vibration measurements obtained from the Beijing Metro Line. A resonance probability index (P) is introduced to quantify the evolution of resonance, identify deterioration phases, and determine suitable opportunities for preventive rail grinding. The proposed framework integrates continuous monitoring with maintenance decision-making and provides an engineering-oriented methodology for condition-based rail maintenance. When examined in detail in other studies in the literature, this study's research questions can be listed as follows. RQ 1: How effectively can rail vibration signals be utilized to detect and quantify wheel–rail resonance associated with rail corrugation? RQ 2: What is the relationship between rail corrugation evolution and the probability, frequency, and amplitude of wheel–rail resonance? RQ 3: Can the proposed dynamic deterioration phases be used to determine the most appropriate timing for preventive rail grinding? RQ 4: To what extent does the proposed resonance-based monitoring framework support predictive maintenance and improve railway asset management compared with conventional maintenance practices?

The main contributions of this study can be summarized as follows:

- A rail dynamic response-based wheel–rail resonance monitoring system was developed to continuously detect resonance conditions and evaluate rail corrugation development in urban railway networks.
- A novel three-stage corrugation deterioration model (Dynamics I, II, and III) was proposed, enabling the characterization of corrugation growth and wheel–rail resonance evolution throughout the rail lifecycle.
- An optimal preventive rail grinding criterion based on wheel–rail resonance behavior was established, overcoming the limitations of conventional maintenance strategies that rely solely on corrugation depth measurements.
- A closed-loop “dynamic monitoring–preventive grinding” maintenance framework was introduced, supporting data-driven maintenance decisions, reducing over-grinding and under-grinding practices, and improving noise mitigation and maintenance efficiency in metro systems.

The remainder of this paper is organized as follows. Section 2 presents the principle of the wheel–rail resonance monitoring system based on rail dynamic response and describes the field monitoring setup. Section 3 analyzes the collected monitoring data and investigates the relationship between the development of rail corrugation and wheel–rail resonance characteristics. Section 4 introduces the dynamic phase model of corrugation deterioration and defines the different stages of corrugation growth and resonance evolution. Finally, Section 5 summarizes the study's main findings, discusses the practical implications of the proposed approach, and provides recommendations for future research and for preventive rail maintenance applications.

2. Wheel-Rail Resonance Monitoring Principle Based on Rail Dynamic Response

The proposed wheel–rail resonance dynamic monitoring system is designed to provide continuous condition assessment of rail corrugation and support data-driven preventive maintenance decisions in urban railway networks. The system comprises two major components: trackside monitoring equipment and a remote data analysis platform. The trackside subsystem continuously acquires the vertical acceleration response of rails during train passages using high-sensitivity accelerometers installed at critical track locations. The collected vibration signals are subsequently processed through time-domain and frequency-domain analyses to identify wheel–rail resonance characteristics and quantify their severity. The extracted dynamic indicators, including resonance frequency, vibration amplitude, and the probability of resonance occurrence, are transmitted to the remote analysis platform for further evaluation. By correlating measured rail dynamic responses with the evolution of rail corrugation, the system enables real-time detection of resonance-induced deterioration and provides quantitative support for preventive rail-grinding decisions. Compared with conventional maintenance approaches that rely solely on geometric measurements of rail corrugation, the proposed framework incorporates dynamic behavior into the maintenance decision-making process, thereby improving the accuracy of condition assessment and facilitating the implementation of predictive maintenance strategies.

3. System Principles

The wheel–rail resonance monitoring system developed in this study uses rail dynamic responses to continuously assess railway track condition and identify resonance phenomena associated with rail corrugation. The system acquires vertical rail vibration signals through trackside accelerometers installed at selected monitoring locations. As illustrated in Fig. 1, the measured vibration response is represented by the acceleration component (a_x), corresponding to the rail forced vibration in the direction perpendicular to the rail base during normal train operation. Since wheel–rail resonance is directly reflected in the rail's dynamic behavior, the measured acceleration signals provide valuable information on the severity and evolution of corrugation-related defects.

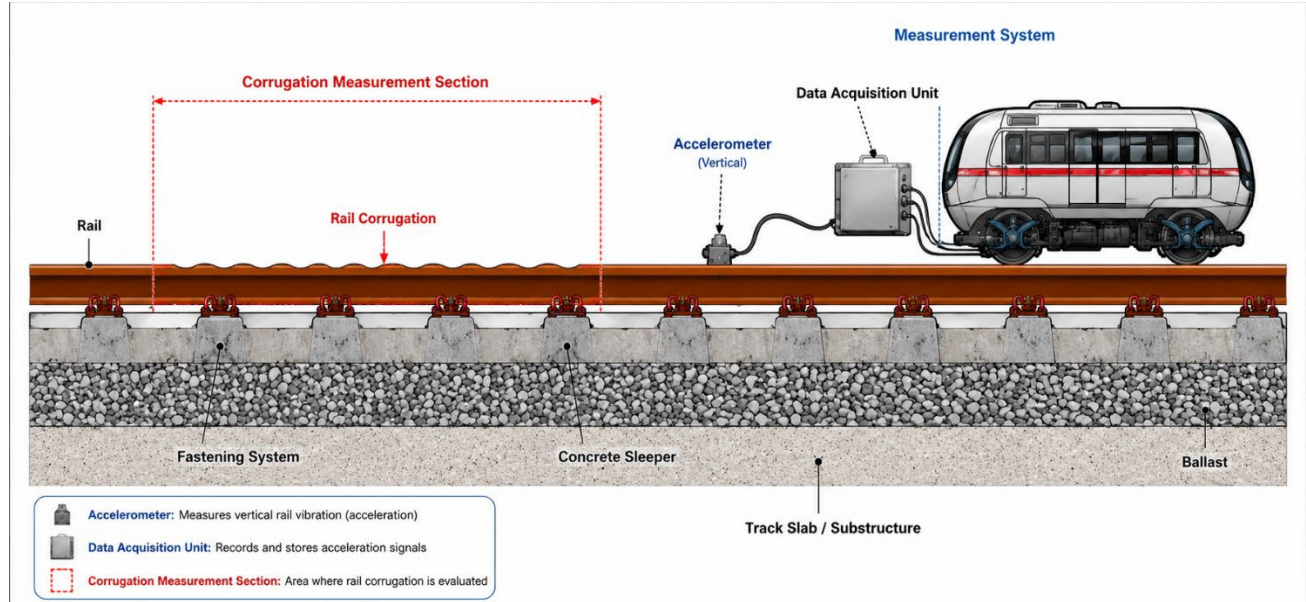


Fig. 1. Schematic diagram of the wheel-rail resonance monitoring principle based on rail dynamic response

Following signal acquisition, the acceleration data are processed using a dedicated wheel–rail resonance evaluation algorithm. As shown in Fig. 2, the measured time-domain signal ($a_x(t)$) is first subjected to noise filtering and signal conditioning procedures to eliminate unwanted disturbances. The filtered signal is subsequently transformed into the frequency domain ($a_x(f)$) using the Fast Fourier Transform (FFT). The resulting frequency spectrum is analyzed within the resonance frequency band determined by the relationship between train operating speed and corrugation wavelength. The vibration energy in this frequency range is calculated via energy integration and compared against predefined resonance criteria. For the monitored Type II corrugation sections, long-term field measurements showed that resonance events were predominantly concentrated in the 350 to 450 Hz range, with a dominant resonance at around 400 Hz. Accordingly, the resonance identification algorithm first searches for the dominant spectral peak within this frequency band. A train passage is classified as a resonance event when the dominant peak frequency falls within the predefined resonance band, and the corresponding peak vibration acceleration exceeds the predefined threshold of 10g. Otherwise, the vibration response is classified as non-resonant. These threshold values were established using long-term monitoring data collected from the Beijing Metro network and can be adjusted for different railway systems based on their vehicles, tracks, and operational characteristics. Based on the extracted frequency-domain features, the algorithm automatically determines whether wheel–rail resonance has occurred during a train passage. In addition, the dominant resonant frequency, vibration amplitude, and characteristics of the resonant response are identified and recorded. These indicators provide a quantitative basis for evaluating rail condition, monitoring corrugation development, and supporting preventive rail grinding decisions. By incorporating dynamic response information rather than relying solely on geometric measurements, the proposed approach enables more accurate condition assessment and facilitates the implementation of predictive maintenance strategies for urban railway systems. The extracted resonance events are subsequently used to calculate the resonance probability index (P), which forms the basis for deterioration phase identification and preventive maintenance decision-making. The resonance identification algorithm consists of signal preprocessing, FFT-based frequency-domain analysis, evaluation of resonance frequency bands, threshold comparison, resonance classification, and resonance probability calculation.

3.1. Resonance Identification Procedure

The proposed wheel–rail resonance monitoring framework consists of four consecutive stages: signal acquisition, signal preprocessing, resonance identification, and resonance evaluation. First, the vertical rail acceleration signal $a_x(t)$ is continuously acquired by the trackside accelerometer during each train passage. The recorded signal is automatically segmented into individual train passages before further processing. In the preprocessing stage, the acceleration signal is detrended and filtered to remove low-frequency structural vibration and high-frequency noise. The processed signal is then transformed into the frequency domain using the FFT, resulting in the amplitude spectrum $A(f)$. The dominant spectral peak is identified from the FFT spectrum. Based on long-term monitoring results from the investigated metro sections, resonance events are identified within the characteristic resonance frequency band of 350 to 450 Hz, which corresponds to the dominant

excitation frequency of Type II corrugation. For each train passage, the resonance decision is performed according to two criteria:

(1) The dominant peak frequency must lie within the predefined resonance frequency band.

(2) The dominant spectral peak must satisfy the predefined resonance threshold established from long-term field measurements.

When both conditions are satisfied, the train passage is classified as a resonance event (R). Otherwise, it is classified as a non-resonant dynamic response (ND). The resonance probability index P is calculated as the ratio between the number of resonance events and the total number of monitored train passages over the evaluation period. This index is subsequently used to identify the deterioration phase and to support preventive rail grinding decisions.

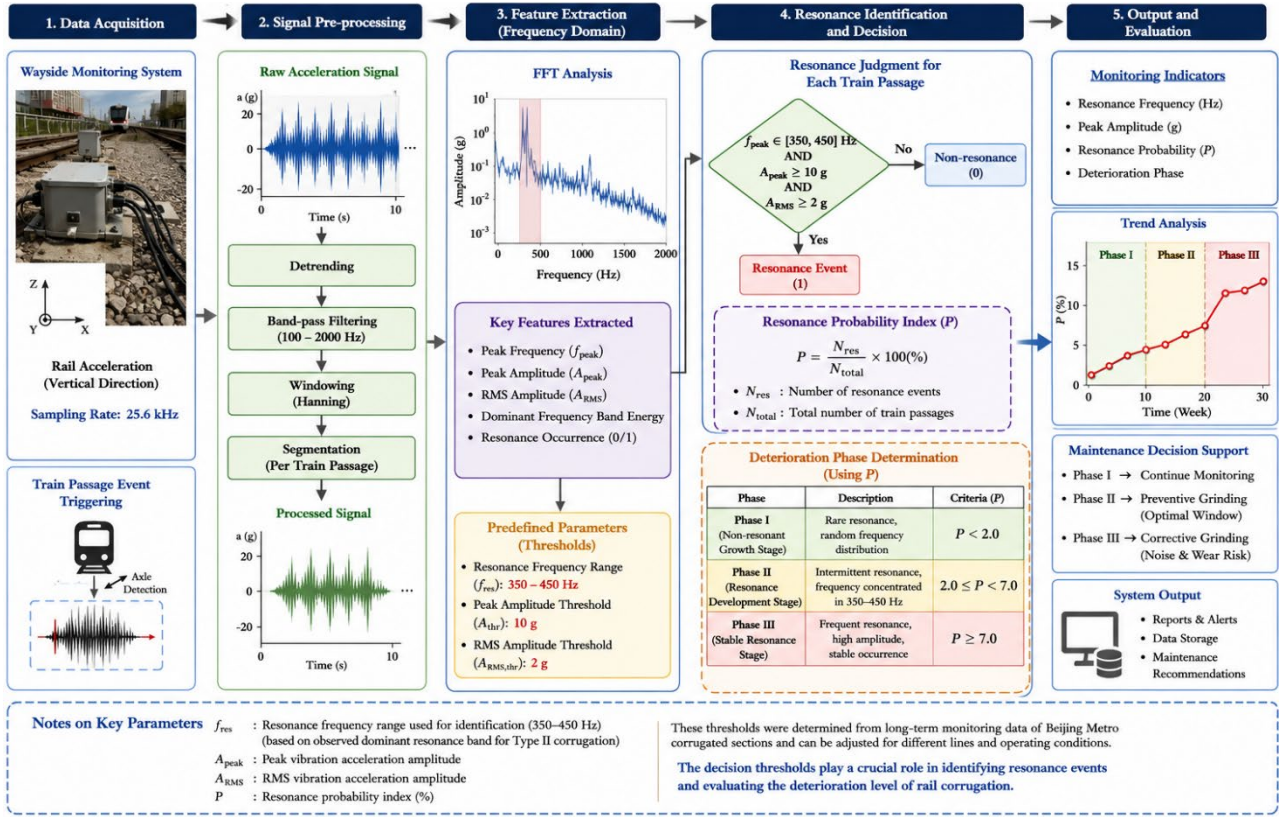


Fig. 2. Overall framework of the proposed wheel–rail resonance monitoring and preventive maintenance algorithm

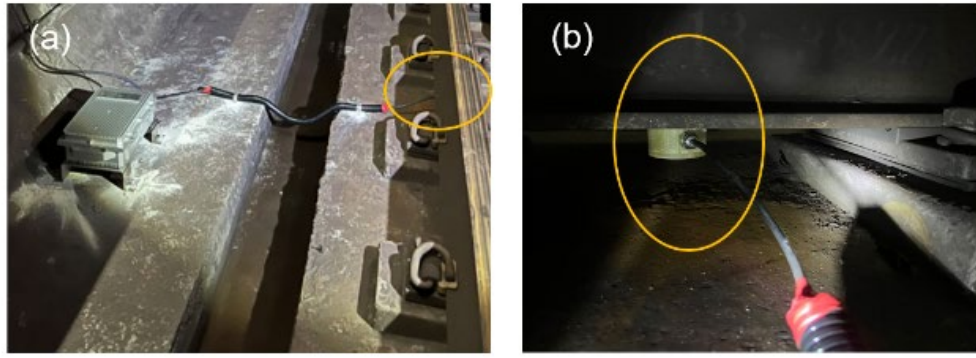
4. On-Site Monitoring Situation

4.1. Field Monitoring Setup

Rail vibration monitoring equipment was installed along the track, with exact locations selected based on site-specific conditions and accessibility requirements. The monitoring system was powered through the nearest available 220 V AC supply along the railway line. The arrangement of accelerometers, signal transmission cables, power cables, and data acquisition units is illustrated in Fig. 3(a). To ensure accurate measurement of wheel–rail interaction-induced vibrations, accelerometers were rigidly mounted on the rail base of the low rail within the test section, as shown in Fig. 3(b).

Based on extensive field investigations of the geometric characteristics of rail corrugation and wheel–rail dynamic response behavior, rail corrugation defects were categorized into two distinct types. Type I corrugation is characterized by wavelengths ranging from 100 mm to 300 mm and wave depths greater than 0.1 mm. This type is predominantly observed on the low rail of sharp curves (radius ≤ 600 m) with insufficient cant and on the high rail of sharp curves exhibiting excessive cant. The wheel–rail dynamic interaction associated with Type I corrugation typically excites low-frequency rail resonance, generating rolling noise primarily below 150 Hz.

Type II corrugation exhibits significantly shorter wavelengths, ranging from 40 mm to 60 mm, with wave depths generally below 0.1 mm. This corrugation form is mainly found on large-radius curves ($R > 800$ m) and tangent track sections, particularly in vibration-absorbing track structures. The dynamic resonance induced by Type II corrugation commonly generates high-frequency squeal noise in the 200 to 400 Hz range.



(a) Photos of trackside equipment installation (b) Photo of the accelerometer installation

Fig. 3. Photos of the measurement point

Geometric measurements of rail corrugation were conducted using an electronic straightedge positioned along the rail running surface. Ten representative measurement locations were selected within each test section, and the arithmetic mean of the measurements was used to characterize the local corrugation condition. Visual inspections confirmed the presence of corrugation defects at all selected locations. The geometric parameter evaluation methodology for both corrugation types is illustrated in Figs. 4(a) and 4(b). Corrugation wavelength was determined by averaging the distances between multiple consecutive peaks or alternatively across twenty successive troughs. Corrugation depth was calculated as the vertical distance between adjacent peaks and troughs. For each measurement point, multiple depth measurements were obtained and averaged to determine the representative local corrugation depth.

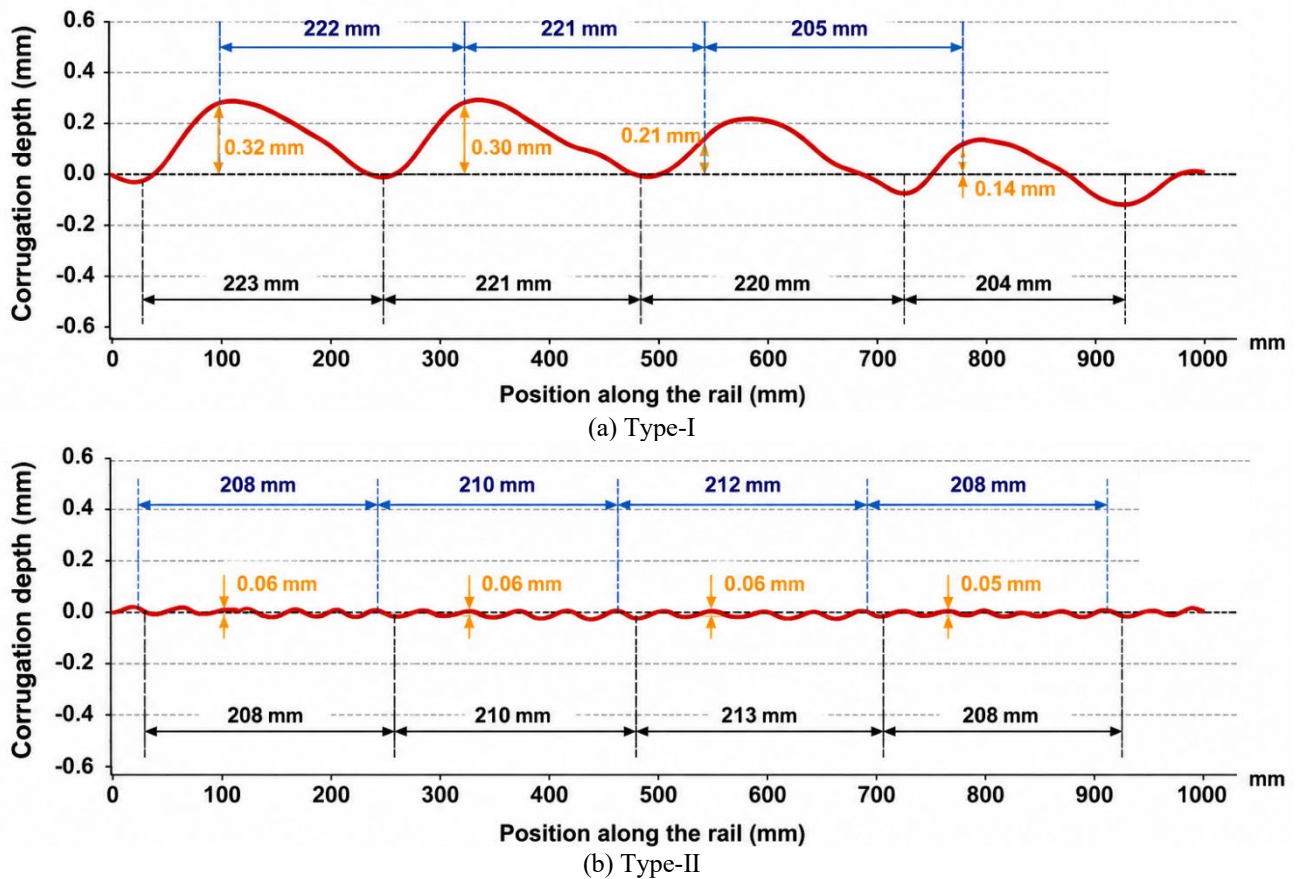


Fig. 4. Measurement and marking diagram of geometric dimensions of the Type-I and Type-II rail corrugation

Based on long-term onboard noise monitoring campaigns, track sections exhibiting intermittent noise generation and early-stage corrugation development were selected for detailed investigation. To ensure reproducibility of the proposed deterioration model, objective classification criteria were established based on the resonance probability index (P) and the stability of the resonance frequency distribution. Dynamic Phase I is defined as the non-resonant growth stage, where the resonance probability remains below 2.0 ($P < 2.0$), indicating that resonance events are rare and vibration frequencies are randomly distributed. Dynamic Phase II corresponds to the resonance development stage, where the resonance probability increases to $2.0 \leq P < 7.0$ and resonance frequencies progressively concentrate within the characteristic resonance band

(approximately 350 to 450 Hz). Dynamic Phase III is identified when the resonance probability reaches $P \geq 7.0$, indicating that resonance occurs during most train passages and that the resonance frequency remains stable at around 400 Hz. These thresholds were derived from long-term monitoring data collected in this study and provide objective criteria for deterioration-phase classification and preventive maintenance decision-making. These sections represent the initial deterioration phase in the evolution of rail corrugation, thereby providing an opportunity to evaluate the relationship between geometric degradation and wheel–rail dynamic responses.

Accordingly, four representative track sections were chosen as case studies:

- A standard track bed section with an R400 curve exhibiting Type I corrugation;
- A standard track bed section with an R600 curve exhibiting Type I corrugation;
- A floating slab track bed tangent section exhibiting Type II corrugation;
- A vibration-absorbing track bed section with an R600 curve (non-steel-spring vibration mitigation system) exhibiting Type II corrugation.

For each section, comprehensive geometric measurements and rail vibration monitoring were performed throughout the observation period. The evolution of corrugation geometric parameters was evaluated at weeks 0, 10, and 20. The corresponding average values of wavelength and wave depth are summarized in Table 1. For each monitored section, ten representative locations were measured, and the arithmetic mean was used to characterize the corrugation condition. Since only the averaged maintenance records were retained, statistical dispersion measures (e.g., standard deviation) are not available.

Table 1. Types, geometric features and environment of rail corrugation in tested section

Corrugation Pattern	Mean of Corrugation Length (mm)	Mean of Corrugation Depth (mm)			Rail Corrugation Environment	
		week 0	10 weeks	20 weeks	Curve Radius	Types of Track Beds
Type I	123	0.13	0.24	0.32	R400	Ordinary track-bed
	201	0.11	0.20	0.28	R600	
Type II	43	0.01	0.03	0.06	$R\infty$	Floating slab track-bed
	52	0.01	0.03	0.05	R600	Shock-absorbing track-bed

The results presented in Table 1 demonstrate distinct growth characteristics of rail corrugation under different track geometries and support structures. For both Type I and Type II corrugations, the corrugation depth increased continuously throughout the 20 week monitoring period, indicating progressive surface deterioration under repeated wheel–rail contact loading. Type I corrugation was significantly more severe than Type II corrugation. In the ordinary track-bed sections, the mean corrugation depth increased from 0.13 mm to 0.32 mm in the R400 curve and from 0.11 mm to 0.28 mm in the R600 curve. The sharper R400 curve showed a higher corrugation growth rate, suggesting that increased lateral wheel–rail interaction and creep forces accelerate material removal and corrugation propagation. Furthermore, the larger corrugation wavelengths observed in Type I defects (123 to 201 mm) are consistent with low-frequency wheel–rail resonance mechanisms typically associated with sharp-curve operation. Type II corrugation developed in both the floating slab track and vibration-absorbing track sections exhibited substantially shorter wavelengths (43 to 52 mm) and considerably smaller depths. Although the corrugation depth increased by approximately five to six times over the monitoring period, the final values remained below 0.06 mm, indicating a much slower deterioration process compared with Type I corrugation. This behavior suggests that resilient track support systems effectively mitigate wheel–rail dynamic forces and limit the progression of severe surface irregularities. A comparison of track structures further reveals that vibration-isolation systems influence not only the magnitude but also the evolution pattern of rail corrugation. The floating slab track section exhibited the highest final depth among the Type II cases (0.06 mm), while the vibration-absorbing track section reached 0.05 mm. Although both values are relatively small, the results indicate that differences in track stiffness and vibration attenuation characteristics may alter the energy distribution within the wheel–rail system, thereby affecting corrugation growth rates. The findings confirm that the curve radius and track support conditions play critical roles in the development of rail corrugation. Sharp curves combined with conventional track structures are more susceptible to the rapid formation of severe Type I corrugation, whereas resilient track systems predominantly experience lower-amplitude Type II corrugation. These observations highlight the importance of considering both geometric alignment and track structural characteristics when developing maintenance strategies and predictive models for rail corrugation management.

Following the installation and commissioning of the trackside monitoring system, continuous wheel–rail vibration measurements were performed for all trains operating on the monitored line throughout the day. The system automatically acquires, processes, and evaluates rail vibration signals in real time, enabling long-term monitoring of wheel–rail dynamic interactions and resonance behavior. The monitoring output format is presented in Table 2. For each train passage, the system

records the train serial number, passage time, vibration category, identified resonance frequency, and corresponding resonance amplitude. Based on the spectral characteristics of the measured rail vibration signals, the monitoring algorithm classifies the wheel–rail dynamic state into two categories. The output label “ND” (Non-Resonant Dynamic Response) indicates that the frequency spectrum of the rail vibration acceleration signal ($a_x(f)$) exhibits a random distribution without a dominant frequency component. This condition corresponds to normal wheel–rail interaction, where no significant resonance occurs. The output label “R” (Resonant Response) indicates the presence of a distinct resonance peak within the vibration spectrum. In this case, the wheel–rail dynamic excitation is concentrated at a specific frequency, suggesting wheel–rail resonance. The associated resonance frequency and amplitude are subsequently extracted and stored for further analysis. By continuously tracking the occurrence, frequency, and magnitude of resonant events, the system provides an effective means for evaluating the evolution of rail corrugation and identifying sections susceptible to abnormal wheel–rail dynamic behavior.

Table 2. List of examples of raw data formats

Index	Train Passing Time	Frequency of Resonance Peak	Peak Vibration Acceleration	Resonance Threshold Identification
1	4:28	—	—	ND
2	4:47	409	22.58	R
3	4:55	420	16.05	R
4	5:02	392	22.89	R
5	5:09	402	20.45	R
6	5:18	405	29.83	R
7	5:25	394	8.62	R
8	5:32	399	16.12	R
9	5:41	412	15.45	R
10	5:48	413	15.54	R

Table 2 presents representative raw outputs generated by the wheel–rail resonance monitoring system during a sequence of train passages. The results demonstrate the capability of the proposed monitoring approach to distinguish between normal wheel–rail dynamic responses and resonance-induced vibration events in real operating conditions. Among the ten recorded train passages, only the first event was classified as ND (Non-Resonant Dynamic Response), indicating the absence of a dominant resonance frequency within the measured vibration spectrum. For this passage, no resonance frequency or peak vibration acceleration was identified, suggesting that wheel–rail interaction remained within normal dynamic operating conditions. The remaining nine train passages were classified as R (Resonant Response), indicating the occurrence of significant wheel–rail resonance. The identified resonance frequencies were concentrated within a narrow range of 392 to 420 Hz, with an average of approximately 405 Hz. This relatively small frequency variation suggests a stable, repeatable dynamic excitation mechanism, typically associated with rail corrugation-induced wheel–rail interaction. The measured peak vibration accelerations exhibited greater variability, ranging from 8.62 m/s² to 29.83 m/s². The highest vibration level was recorded at 405 Hz, reaching 29.83 m/s², while the lowest resonant response occurred at 394 Hz with an acceleration amplitude of 8.62 m/s². These differences indicate that although resonance frequencies remain relatively constant, the severity of wheel–rail dynamic interaction varies among train passages due to factors such as train speed, axle load, wheel condition, and instantaneous wheel–rail contact characteristics. The resonance frequencies observed in Table 2 are concentrated around 400 Hz, which corresponds closely to the characteristic frequency range associated with Type II rail corrugation. This observation supports the hypothesis that the detected resonance events are directly related to the presence of short-pitch corrugation defects. The repeated occurrence of resonance peaks within this frequency band further demonstrates the effectiveness of the proposed monitoring system in identifying corrugation-related dynamic abnormalities. The results confirm that the monitoring framework can reliably detect resonance events, quantify their frequency and intensity, and provide valuable information for assessing rail condition and early identifying the development of corrugation. The ability to continuously monitor resonant behavior offers significant potential for predictive maintenance and condition-based management of rail infrastructure.

4.2. Monitoring Data Analysis

To investigate the relationship between the development of rail corrugation and wheel–rail dynamic behavior, long-term vibration monitoring was conducted throughout the corrugation deterioration process. For each monitored train passage, the occurrence of wheel–rail resonance was identified using the proposed resonance detection algorithm. Based on these results, a wheel–rail resonance probability index, denoted as P , was defined as the ratio of resonant train passages to the total number of train passages within a day. For ease of interpretation, P was normalized to a 10-point scale, where a resonance occurrence rate of 100% corresponds to $P = 10.0$, as expressed in Eq. (1).

$$P = \frac{N_{res}}{N_{total}} \quad (1)$$

Unlike conventional resonance occurrence statistics, which simply report the number or percentage of resonance events during a monitoring period, the proposed resonance probability index (P) is designed as a normalized indicator of deterioration for maintenance decision-making. Because P is calculated from all monitored train passages, it enables consistent comparisons across different monitoring periods, track sections, and operating conditions. More importantly, the proposed index is directly linked to the stages of deterioration in rail corrugation and therefore provides an engineering-oriented criterion for preventive rail grinding. Instead of evaluating resonance events individually, P summarizes the overall resonance condition of the monitored rail section and enables continuous tracking of deterioration progression over time.

The proposed index differs from conventional geometric indicators such as corrugation depth or wavelength because it directly reflects the dynamic interaction between the wheel and rail. While geometric measurements indicate the physical condition of the rail surface, the resonance probability index evaluates the operational dynamic response of the wheel–rail system. Consequently, P provides complementary information to support condition-based maintenance decisions and to optimize preventive grinding schedules.

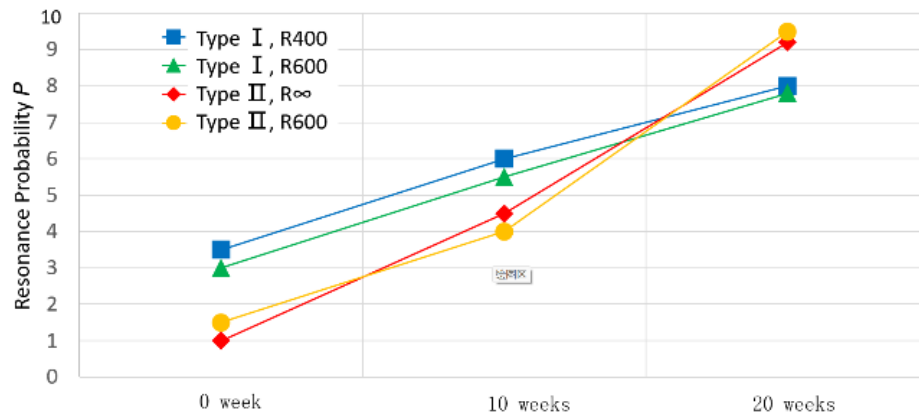


Fig. 5. Trend chart of wheel-rail vertical vibration P with corrugation growth of rail corrugation in tested section

Fig. 5 illustrates the evolution of P for the four representative track sections described in Table 1. The monitoring period began when corrugation was in its early stages of development (week 0). As shown in Fig. 5, all sections exhibited a clear positive correlation between wheel–rail resonance probability and corrugation depth throughout the 20 week observation period. As rail surface irregularities progressively increased, the likelihood of resonance excitation also increased. However, distinct differences were observed between the two corrugation categories. For the Type I corrugation sections, P increased gradually despite significant growth in corrugation depth. In contrast, Type II corrugation sections demonstrated a much faster increase in resonance probability. This behavior suggests that short-pitch corrugation is considerably more effective in exciting wheel–rail dynamic resonance than long-pitch corrugation. The results indicate that the occurrence of resonance is influenced not only by corrugation depth but also by corrugation wavelength and the associated excitation frequency. Consequently, Type II corrugation exhibits a stronger coupling effect with the natural vibration characteristics of the wheel–rail system. To further investigate the complete evolution process of wheel–rail resonance, an additional track section exhibiting Type II corrugation was selected for full-life-cycle monitoring. The temporal evolution of resonance probability P and corrugation depth is presented in Fig. 6.

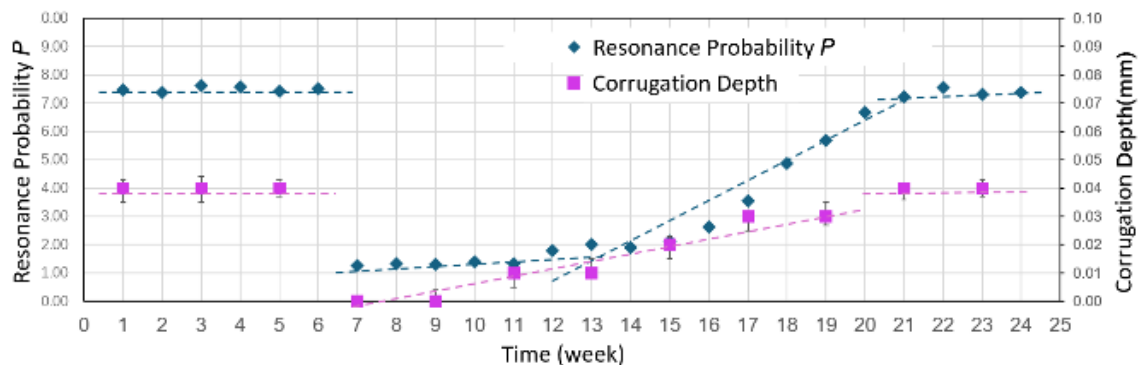


Fig. 6. Trend chart of wheel-rail vertical vibration index and corrugation depth with corrugation growth cycle

As shown in Fig. 6, during the initial monitoring stage (weeks 1–6), the average corrugation depth remained approximately 0.04 mm, with localized values reaching 0.08 mm. Despite the relatively small geometric irregularity, the resonance probability consistently exceeded $P = 7.0$, indicating frequent wheel–rail resonance events and correspondingly high levels of wheel–rail noise. These observations suggest that the monitored section had already entered an active resonance state before maintenance intervention. Following rail grinding performed at week 6, a substantial reduction in resonance activity was observed. During weeks 7–12, resonance probability remained below $P = 2.0$, indicating that wheel–rail resonance was effectively suppressed. As illustrated in Fig. 6, field measurements conducted during this period revealed

corrugation depths ranging between 0 and 0.02 mm. Although minor corrugation growth had reappeared after grinding, the defect depth remained insufficient to generate the excitation energy required to trigger resonance. Consequently, the measured vibration responses were dominated by random wheel–rail dynamic interactions rather than resonance-induced vibration. As corrugation continued to develop, resonance activity gradually re-emerged. During weeks 13–20, the resonance probability fluctuated between $P = 2.0$ and $P = 6.0$, with a clear upward trend over time. Simultaneously, the measured corrugation depth increased to approximately 0.02 to 0.04 mm. The similar evolution patterns of these two indicators, as shown in Fig. 6, demonstrate a strong relationship between corrugation growth and resonance excitation. During this period, resonance occurred intermittently, indicating a transitional state between stable non-resonant and fully resonant wheel–rail interaction conditions. When corrugation deterioration approached a critical level, the wheel–rail system entered a stable resonance regime. During weeks 21 to 24, P remained consistently above 7.0 with limited fluctuation, as illustrated in Fig. 6. Correspondingly, corrugation depth stabilized between 0.03 and 0.04 mm. These results indicate that once a critical corrugation threshold is reached, resonance becomes self-sustaining and occurs during most train passages, resulting in persistent wheel–rail noise and elevated vibration levels. Based on the observed resonance evolution characteristics, the deterioration process was divided into three distinct dynamic stages:

- Dynamic Stage I (weeks 7–12): Resonance Suppression Stage
- Dynamic Stage II (weeks 13–20): Resonance Development Stage
- Dynamic Stage III (weeks 21–24): Stable Resonance Stage

To further examine the dynamic characteristics of each stage, the distributions of vibration frequency and vibration amplitude were analyzed, as presented in Fig. 7.

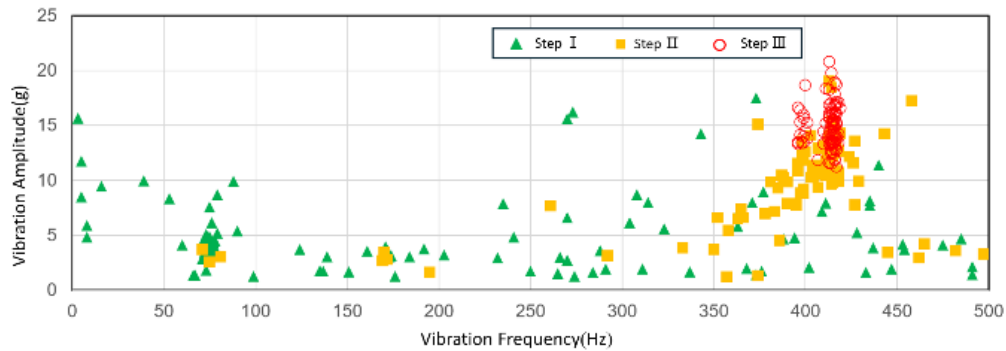


Fig. 7. Scatter plot of vibration amplitude and frequency distribution in different dynamic stages

During Dynamic Stage I, immediately after rail grinding, corrugation depth remained extremely small and was unable to effectively excite wheel–rail resonance. As shown in Fig. 7(a), vibration frequencies were broadly distributed across the 0 to 500 Hz range, reflecting predominantly random wheel–rail interactions. Most vibration amplitudes remained below 10 g, indicating relatively low dynamic excitation levels. In Dynamic Stage II, increasing corrugation depth led to a progressive increase in the occurrence of resonance. Fig. 7(b) shows that vibration frequencies began to concentrate in the 350 to 450 Hz range, corresponding to the characteristic resonance band associated with Type II corrugation. Simultaneously, vibration amplitudes increased significantly, with numerous events exceeding 10g. This behavior indicates a transition from random dynamic excitation to resonance-dominated wheel–rail interaction. During Dynamic Stage III, the corrugation geometry reached a relatively stable state while resonance excitation became highly concentrated. As illustrated in Fig. 7(c), most resonance events occurred within the narrow frequency range of 400 to 430 Hz, and vibration amplitudes generally exceeded 10g. The concentration in both frequency and amplitude distributions indicates that the wheel–rail system had entered a stable resonant condition characterized by persistent dynamic excitation and severe noise generation. The results presented in Figs. 5–7 demonstrate that the wheel–rail resonance probability is highly sensitive to the development of corrugation and can effectively characterize the deterioration state of rail surface defects. The strong correlation among resonance probability, vibration characteristics, and corrugation depth suggests that the proposed monitoring index P can serve as a reliable indicator for the early detection, tracking, and assessment of rail corrugation evolution. Furthermore, the identification of distinct dynamic stages provides valuable insight into the mechanisms governing corrugation growth and offers a practical basis for condition-based maintenance planning and rail grinding optimization.

4.3. Dynamic Phase Model of Corrugation Deterioration Trend

According to wheel–rail dynamic interaction theory, rail corrugation acts as a periodic geometric excitation source during train operation. When the excitation frequency generated by the interaction between corrugation wavelength and vehicle operating speed approaches the natural frequencies of the wheelset–bogie–track system, wheel–rail resonance can be triggered. Under these conditions, wheelsets repeatedly impact successive corrugation troughs and peaks as they travel along the rail, producing a hopping-like dynamic behavior. The resulting cyclic impacts significantly amplify vibration energy within specific frequency bands and constitute the fundamental mechanism that generates corrugation-related noise. Once resonance is established, the wheel–rail contact force increases substantially, accelerating rail wear and promoting further corrugation growth. Simultaneously, the amplified vibration energy can induce fatigue damage in both rail components and vehicle running gear, thereby increasing maintenance requirements and potentially affecting operational reliability and safety.

Consequently, understanding the dynamic evolution of corrugation is critical to condition-based maintenance and lifecycle management of urban rail transit systems.

Based on the long-term monitoring results presented in Figs. 5–7, a dynamic-phase deterioration model is proposed to describe the complete evolution process of rail corrugation. As illustrated in Fig. 8, the deterioration process can be divided into three distinct dynamic phases according to the occurrence and severity of wheel–rail resonance. The transition between successive deterioration phases is determined using the resonance probability index (P) together with the stability of the resonance frequency distribution observed during long-term monitoring. Based on the monitored data, Dynamic Phase I corresponds to a non-resonant condition with $P < 2.0$, where resonance events are rare and vibration frequencies remain randomly distributed. Dynamic Phase II is identified when the resonance probability increases to $2.0 \leq P < 7.0$ and resonance frequencies begin to concentrate within the characteristic resonance band (approximately 350 to 450 Hz). Dynamic Phase III is reached when $P \geq 7.0$, indicating that resonance occurs during most train passages, with stable, high-amplitude vibration concentrated around 400 Hz. These quantitative criteria provide an objective basis for identifying the transition between deterioration phases and for determining the appropriate timing of preventive maintenance.

Dynamic Phase I: Non-Resonant Growth Stage

The first stage, represented by the green region in Fig. 8, corresponds to the initiation and early growth of rail corrugation. During this phase, corrugation depth increases approximately linearly with accumulated traffic load, as indicated by the blue dashed trend line in Fig. 8. Although geometric irregularities progressively develop on the rail surface, the defect amplitude remains insufficient to excite significant wheel–rail resonance. Train passages generate predominantly random wheel–rail vibrations, and resonance-induced noise is rarely observed. Since the dynamic amplification effect is absent, the deterioration process remains relatively slow and does not produce significant secondary fatigue damage. From a maintenance perspective, this stage represents a monitoring period during which condition assessment should be intensified, while corrective actions are generally unnecessary.

Dynamic Phase II: Resonance Development Stage

As corrugation depth continues to increase, the system enters the second stage, represented by the yellow region in Fig. 8. During this phase, the geometric excitation generated by the corrugation becomes sufficiently strong to intermittently excite wheel–rail resonance in a portion of passing trains. The frequency and intensity of resonance events increase progressively as corrugation develops. Consequently, wheel–rail noise becomes increasingly noticeable, and dynamic contact forces begin to accelerate rail wear and defect propagation. This stage is characterized by a strong coupling between corrugation growth and resonance, forming a positive feedback mechanism in which resonance promotes further corrugation growth. From an engineering maintenance perspective, Dynamic Phase II represents the most critical intervention window. Preventive rail grinding performed during this stage can effectively suppress the development of resonance before severe deterioration occurs, thereby minimizing maintenance costs and reducing service disruptions.

Dynamic Phase III: Stable Resonance Stage

The final stage, represented by the red region in Fig. 8, corresponds to a stable resonance condition. At this point, corrugation depth reaches a critical threshold and remains relatively stable due to the balance between wear generation and material removal mechanisms.

The dashed vertical lines in Fig. 8 indicate the transition thresholds between successive deterioration phases, as defined by the resonance probability index (P). As shown in Fig. 8, nearly all train passages during this phase excite wheel–rail resonance, resulting in persistent high-amplitude vibration and continuous noise generation. The wheel–rail system operates in a dynamically unstable condition characterized by concentrated resonance frequencies and elevated vibration levels. Under these circumstances, both rail and vehicle components experience increased fatigue loading, leading to accelerated degradation and higher maintenance demands. Once Dynamic Phase III is reached, corrective rail grinding or other mitigation measures become unavoidable to restore acceptable wheel–rail dynamic performance. The dynamic-phase model provides a practical framework for evaluating the effectiveness of rail corrugation mitigation and noise reduction strategies. In particular, it enables quantitative assessment of friction management techniques, rail grinding programs, lubrication systems, and vibration mitigation measures used in urban rail transit networks. As illustrated in Fig. 9, the duration of Dynamic Phase II is defined as (t_2) . This period represents the interval during which corrugation continues to develop while resonance remains only partially excited. Since Dynamic Phase II corresponds to the optimal maintenance intervention window, extending its duration is highly desirable from both operational and economic perspectives. To quantify maintenance effectiveness, a new performance indicator is introduced in Eq (2).

$$\Delta t_2 = t'_2 - t_2 \quad (2)$$

where (t_2) and (t'_2) denote the duration of Dynamic Phase II before and after the implementation of a mitigation measure, respectively. A positive value of Δt_2 indicates that the applied remediation strategy successfully delays the transition to stable resonance conditions, thereby slowing corrugation deterioration and extending rail service life. Conversely, a small or negative value suggests limited effectiveness of the implemented measure.

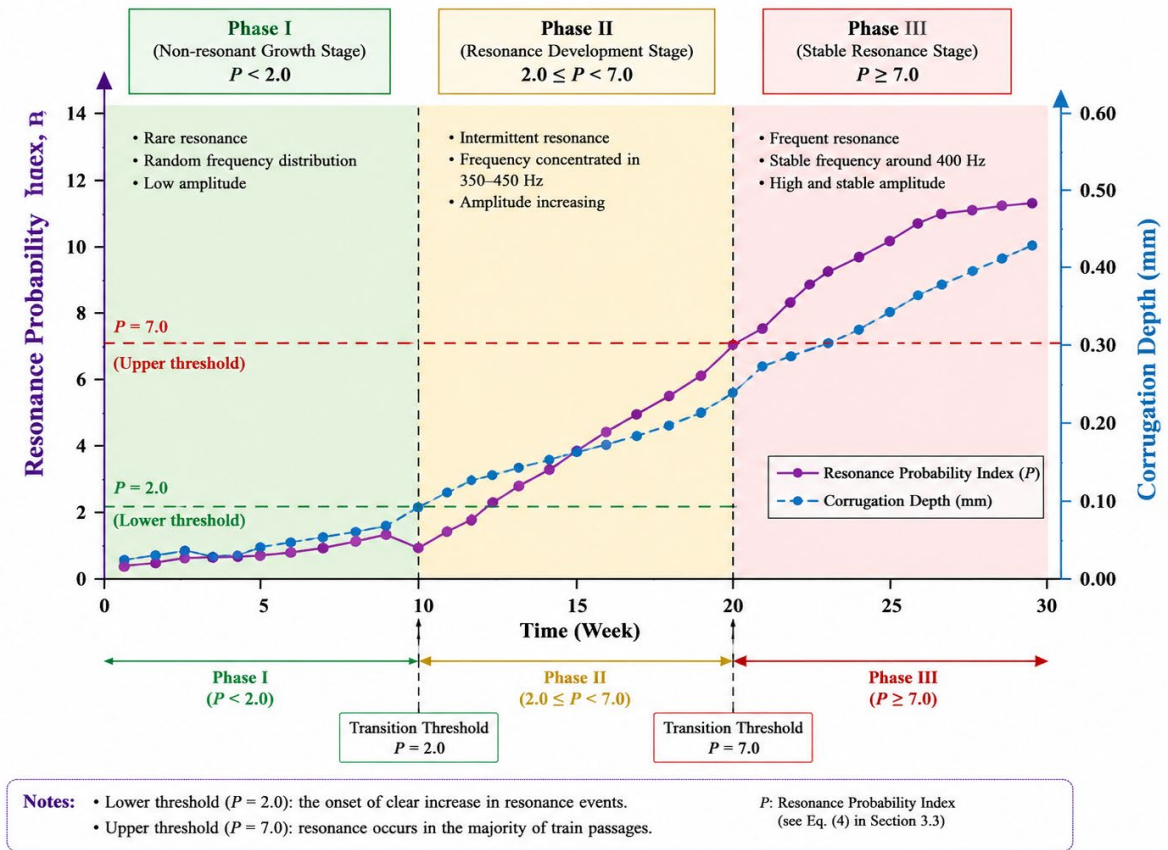


Fig. 8. Schematic diagram of the development stage of wheel-rail resonance caused by corrugation

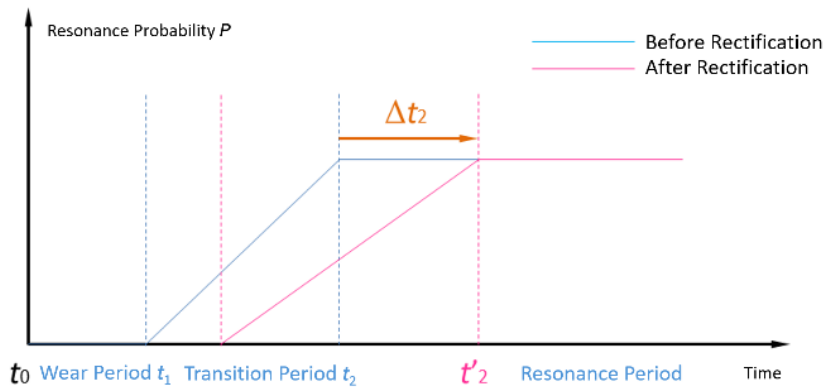


Fig. 9. Trend chart of disease deterioration under the criterion of wheel-rail dynamic

As shown conceptually in Fig. 9, the objective of any rail corrugation remediation strategy should be to maximize the duration of Dynamic Phase II and to postpone the onset of Dynamic Phase III. By extending the interval between resonance initiation and the establishment of a stable resonance, maintenance interventions can reduce wheel-rail noise, mitigate fatigue damage, decrease grinding frequency, and improve the overall lifecycle performance of railway infrastructure. Therefore, the proposed dynamic-phase model not only provides a mechanistic interpretation of the evolution of rail corrugation but also establishes a practical, wheel-rail dynamics-based criterion for evaluating maintenance effectiveness and optimizing preventive maintenance schedules in urban rail transit systems. From an engineering perspective, the proposed maintenance effectiveness criterion can be readily integrated into routine railway maintenance planning. During normal operation, rail vibration data can be continuously collected from fixed trackside accelerometers or onboard monitoring systems. The resonance probability index (P) is periodically calculated from the monitored train passages and used to identify the current deterioration phase. When the monitored rail section enters Dynamic Phase II, maintenance personnel may schedule preventive rail grinding before the rail reaches the severe-resonance condition of Dynamic Phase III. The duration of Dynamic Phase II, therefore, provides maintenance engineers with a practical time window for planning grinding operations while considering maintenance resources, traffic availability, and operational constraints. Rather than triggering maintenance based solely on fixed inspection intervals, the proposed framework supports condition-based maintenance by continuously evaluating the dynamic condition of the wheel-rail system. Consequently, preventive grinding

decisions can be made based on the observed deterioration trend, potentially reducing unnecessary grinding operations while preventing excessive corrugation.

5. Conclusion

Rail corrugation-induced wheel–rail resonance remains one of the most challenging maintenance and noise-related problems in modern urban rail transit systems. Conventional maintenance strategies primarily rely on geometric measurements of corrugation depth and wavelength, which often fail to accurately determine the optimal timing for preventive rail grinding. Consequently, maintenance activities may be performed either too early, resulting in unnecessary costs, or too late, leading to excessive wheel–rail noise, accelerated deterioration, and increased fatigue damage. Therefore, the integration of dynamic monitoring technologies into maintenance decision-making has become increasingly important for achieving efficient and sustainable railway asset management. In this study, a rail dynamic response-based wheel–rail resonance monitoring framework was developed and validated using long-term field measurements across multiple metro track sections with varying corrugation characteristics. Rail vibration signals collected by trackside accelerometers were analyzed using time-domain and frequency-domain processing techniques, including FFT-based spectral analysis, resonance identification, vibration amplitude evaluation, and resonance probability assessment. Furthermore, a novel wheel–rail resonance probability index (P) was introduced to quantitatively characterize the occurrence and severity of resonance phenomena during the evolution of rail corrugation. The results demonstrated a strong correlation between the development of rail corrugation and wheel–rail resonance behavior. For all monitored sections, resonance probability increased with increasing corrugation depth. Compared with Type I corrugation, Type II corrugation exhibited significantly faster resonance development and stronger dynamic coupling with the wheel–rail system. Resonance frequencies associated with Type II corrugation were predominantly concentrated around 400 Hz, while vibration amplitudes increased substantially as corrugation progressed. These findings confirm that wheel–rail resonance characteristics provide a more sensitive indicator of rail deterioration than geometric measurements alone.

One of the most important contributions of this study is the development of a proposed three-stage dynamic deterioration model comprising Dynamic Phase I (Non-Resonant Growth Stage), Dynamic Phase II (Resonance Development Stage), and Dynamic Phase III (Stable Resonance Stage). The proposed model successfully describes the complete evolution of the system from the initial formation of corrugation to the onset of stable wheel–rail resonance. Based on this model, Dynamic Phase II was identified as the optimal preventive maintenance window, during which rail grinding can effectively suppress resonance growth before severe deterioration occurs. In addition, a resonance-based maintenance-effectiveness criterion, expressed as the extension of the Dynamic Phase II duration (Δt_2), was proposed. Unlike conventional evaluation methods that rely solely on post-maintenance geometric measurements, the proposed criterion directly reflects wheel–rail dynamic behavior and provides a practical tool for assessing the effectiveness of rail grinding, friction management, lubrication systems, vibration mitigation technologies, and other maintenance strategies. Although the proposed framework was developed and validated using metro railway data, the methodology may also be applicable to other railway systems, such as high-speed and heavy-haul railways, after appropriate calibration and validation under their specific operating conditions. The proposed monitoring framework enables railway operators to transition from reactive maintenance practices toward predictive and condition-based maintenance strategies. Such an approach can reduce wheel–rail noise, decrease unnecessary grinding operations, extend rail service life, improve passenger comfort, and lower infrastructure maintenance costs. From a societal perspective, the proposed methodology helps reduce environmental noise pollution in urban areas, particularly in densely populated regions near railway corridors. By minimizing wheel–rail resonance and associated noise emissions, the approach may improve residents' quality of life while enhancing the sustainability of urban transportation systems.

Despite its promising results, several limitations should be acknowledged. Monitoring was conducted on four metro sections: two with Type I corrugation and two with Type II corrugation. Although these sections represent the most common corrugation conditions encountered in the Beijing Metro, they cannot fully capture the variability associated with different railway systems, vehicle types, operational speeds, rail profiles, and track structures. Therefore, the proposed resonance thresholds should be interpreted as data-driven guidelines rather than universally applicable values. Second, the proposed monitoring framework relies exclusively on rail vibration measurements. While rail acceleration signals proved effective for identifying wheel–rail resonance, the absence of complementary information such as axle-box acceleration, wheel condition, acoustic emission, and vehicle dynamic responses may reduce the robustness of resonance identification under varying operational conditions. Integrating multi-sensor information is expected to improve the reliability and generalizability of the proposed approach. The deterioration model was validated only for corrugation-induced wheel-rail resonance in metro systems. Additional validation across different railway infrastructure types, including heavy-haul and high-speed railway networks, is required before the proposed thresholds can be generalized to broader railway applications. Accordingly, the conclusions of this study should be interpreted within the scope of the monitored metro sections, and additional validation under different operational conditions is recommended before broader implementation.

Future research should focus on expanding the monitoring database across different railway systems and operational environments to establish universally applicable resonance thresholds. The integration of machine learning and artificial intelligence techniques with resonance monitoring data may enable automated prediction of corrugation growth and maintenance requirements. Furthermore, digital twin technologies, real-time cloud-based monitoring platforms, and multi-sensor fusion approaches that integrate vibration, acoustic, and vehicle-condition data could significantly enhance the capabilities of predictive railway maintenance systems. In conclusion, this study demonstrates that wheel–rail resonance monitoring provides a reliable and sensitive approach for evaluating rail corrugation deterioration. The proposed resonance probability index, three-stage dynamic deterioration model, and resonance-based maintenance criterion collectively establish a new framework for dynamic-condition assessment and preventive rail grinding optimization. These contributions have the potential to transform existing maintenance practices from geometry-based inspection toward intelligent, data-driven, and

predictive railway asset management, thereby improving operational efficiency, reducing lifecycle costs, and enhancing the safety and sustainability of urban rail transit systems. The proposed quantitative phase classification criteria enable reproducible identification of deterioration stages and provide practical guidance for condition-based maintenance planning.

Author Contributions

Aimin Xu contributed to conceptualization and project administration. Ke Liu contributed to methodology and data collection. Miao Wu contributed to software, validation, and analysis. Yuefeng Duan contributed to analysis, investigation, and data collection. Shimeng Liu contributed to draft preparation, methodology and software. Junting Zhu contributed to manuscript editing and analysis.

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Declaration of Artificial Intelligence (AI) Tools

The authors used ChatGPT solely for language editing and to improve readability. The authors reviewed and verified all content and take full responsibility for the accuracy and integrity of the manuscript.

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