

A METHOD FOR THE EVALUATION OF ASYMMETRY OF HIGH-SPEED RAILWAY RAIL PROFILES

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Abstract: The rail head profile plays a crucial role in determining the wheel–rail contact geometry and the dynamics of railway vehicle systems. Existing methods for asymmetric rail profile design, as well as evaluation indices for rail profiles, mainly focus on one-sided rail deviation from the target profile. A quantitative measure of asymmetry between the left and right rails is still lacking in both design and inspection. Field tests indicate that the asymmetry of rail profiles may induce abnormal carbody vibration. To address this issue, three indices have been proposed to characterize the asymmetry of the rail lateral profiles based on their geometric characteristics. Furthermore, a method for calculating the combined index A_r and evaluating rail profile asymmetry in the longitudinal spatial domain has been introduced. This proposed method provides a theoretical basis and an analytical tool for establishing asymmetry limits in both profile design and evaluating the longitudinal asymmetry state of tracks.

Keywords: High-speed railway; Rail profile; Asymmetry; Evaluation index

1 INTRODUCTION

The rail head profile is one of the key factors in the wheel–rail system. A proper rail profile ensures that the wheelset achieves a reasonable equivalent conicity, enhances the vehicle's running stability and safety, maintains the wheel–rail contact band, and reduces both the contact stress and wear between the wheel and rail. Research by Yu indicates that the asymmetry of rail profile diminishes wheelsets' equivalent conicity and this may lead to swaying of carbody as well as side wear of the rail [1]. The development of side rail wear may evolve to severe side wear or alternate wear. Zhang's studies on EMU vibrations in the Hainan high-speed railway and Bai on alternate wear in the Hangshen high-speed railway both prove that the asymmetry of rail profile contributes to the vibration [2-3].

Rail profile optimization can be realized by various approaches and the common objectives include improving the rolling radius difference (RRD) curve, the equivalent conicity, and reducing the wheel–rail contact stress. Zeng established a design model for asymmetric rail profiles using B-spline functions with variable weight coefficients and analyzed the model by means of multi-objective optimization [4]. I. Y. Shevtsov optimized the rail profile by numerical optimization techniques, taking a properly selected RRD function as the optimization objective on the basis of the analysis of the wear index and the fatigue index [5]. Similarly, Wang adopted an RRD-based rail profile optimization design method with a reverse-engineering design concept [6]. Using CHN 50, 60, and 75 kg/m rails as examples, they demonstrated the effectiveness and efficiency of the method. Spangenberg, following the conformal profile design concept, analyzed its influence on wear and rolling contact fatigue and optimized the wheel–rail profiles accordingly [7].

Existing rail profile evaluation indices mainly focus on a one-sided rail, quantifying its quality by the deviation of the measured profile from the design profile. The Grinding Quality Index (GQI), which is commonly used to evaluate ground rail profiles, is calculated based on the deviation between measured profiles and target profiles. Based on this idea, Teever Handal created the Profile Deviation Index (PDI) [8]. Their core idea is also to evaluate the offsets of the discrete points between the measured rail profile and the target profile, but for different regions the calculation uses different weight coefficients. In addition, Ingemar proposed the Gradient Index Profile (GIP) for the comprehensive assessment of wheel–rail wear [9]. The gradient indices of the wheelset and the rail are evaluated separately and then combined by weighted averaging into a comprehensive evaluation index. The Swedish Transport Administration is now trialing and adjusting the limit of this index, with the intention of replacing the evaluation method based on equivalent conicity. This evaluation method involves the difference between left and right profiles, yet cannot reflect the asymmetry independently.

At present, the objective of track grinding maintenance is mainly to restore the standard profile. Although this guarantees the running quality of vehicles, it inevitably leads to a certain amount of over-grinding and hence higher costs. As the maximum operating speed of Chinese high-speed railways continues to rise, a high-speed passenger railway network covering different speed levels will be formed. Provided that sufficient safety margins are ensured, implementing differentiated grinding strategies and evaluation standards for passenger lines of different speed levels shall be more economically efficient. This places higher demands on the rail grinding strategies and the acceptance of track grinding. Therefore, the proposed asymmetry evaluation index adds a valuable dimension to rail design, inspection, and grinding acceptance, and provides a more complete evaluation tool for rail inspection and tailored grinding solutions.

2 DEFINITION OF RAIL PROFILE ASYMMETRY INDICES

2.1 Definition of Lateral Asymmetry Indices of Rail Profiles

2.1.1 Datum of the local coordinate systems of the left and right rail heads

Figure 1 shows the relative positions of the local coordinate systems of the left and right rail heads with respect to the track coordinate system. The origin of the track coordinate system, denoted as $Oxyz$, is located at the midpoint between the gauge measuring points of the left and right rails. The lateral axis Oy is parallel to the common tangent of the rail crowns of the left and right rails, with the horizontally right direction taken as positive. The vertical axis Oz is perpendicular to the lateral axis and intersects it at the origin, with the vertically downward direction taken as positive. According to the right-hand rule, the longitudinal axis is perpendicular to the Oyz plane, with the direction pointing into the plane taken as positive.

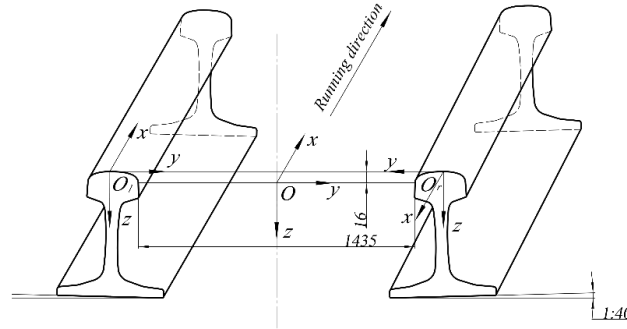


Figure 1 Positions of the Local Coordinate Systems of the Rail Heads and the Track Coordinate System

The local coordinate systems of the left and right rail heads, designated as O_lxyz and O_rxyz , are then aligned laterally so that the distances from the gauge measuring points of each rail to the origin of the track coordinate system are both 717.5 mm. The left and right rails are then completely symmetric about the origin O at their respective gauge measuring points. After the alignment, the cross-sectional views of the left and right rail profiles in a plane perpendicular to the rail are shown in Figure 2.

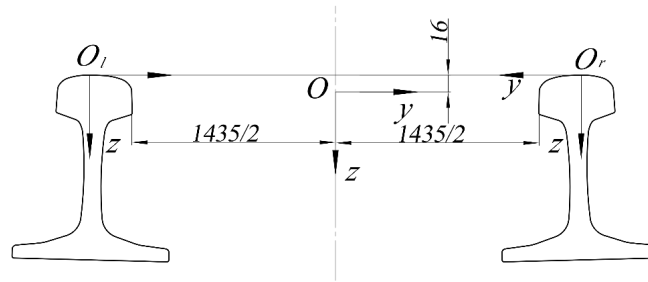


Figure 2 Positions of the Left and Right Rails and the Track Coordinate System after Lateral Alignment

The left and right profiles are thereby positioned vertically by their respective highest points and laterally by their respective gauge measuring points. This alignment procedure allows any pair of left and right rail profiles to be situated in the same track coordinate system. By establishing a unified alignment between the local rail head coordinate systems and the track coordinate system, the errors caused by lateral position offsets in field measurement are eliminated, and a unified datum is determined for the computation of the geometric asymmetry indices.

2.1.2 Geometric definition of the asymmetry indices

The first rail asymmetric index, denoted as DY , is used to describe the lateral asymmetry of the distribution of the highest points of the rail profiles. After the left and right rail profiles are laterally aligned in the track coordinate system, DY is the difference of lateral distance of the highest points of the left and right profiles. The region near the rail crown is the principal range in contact with the wheel tread. Therefore, the lateral asymmetry of the highest-point distribution reflects the offset of wheel–rail contact and the asymmetry of wear. This in turn affects the distribution of the wheel–rail vertical gap and the variation of the rolling radius difference of the wheelset. Figure 3 illustrates the lateral distances y_l and y_r of the highest points of the left and right rails.

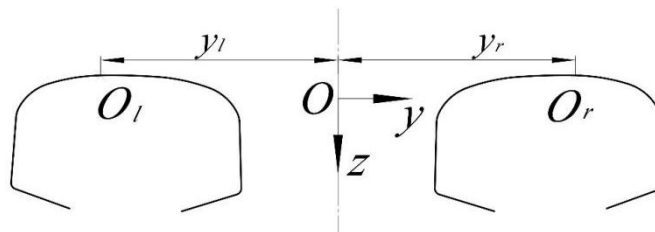


Figure 3 Schematic of the Lateral Distance Difference DY between the Highest Points of the Left and Right Rails

For a given pair of left and right rail profiles, DY is calculated according to equation (1):

$$DY = y_l - y_r \quad (1)$$

where y_l and y_r are the lateral distances from the crown points of the left and right rails to the origin of the track coordinate system respectively, both taken as positive values. A positive DY indicates that the crown of the right rail deviates further toward the field side of the track than that of the left rail, and vice versa.

The second rail asymmetric index, denoted as DS , is used to describe the asymmetry of the slope of the profiles in the crown region between the left and right rails, and is defined as the difference between the slopes of the left and right rail profiles within a certain crown width L . The slope of the rail profile in the contact region affects the distribution of wheel–rail contact points, whereas the asymmetry of the inclination of the left and right rails causes an asymmetry of the contact-point distribution. This results in an influence on the wheelset offset and the equivalent conicity. The calculation of the slope contains the first-order variation characteristic of the profile. This index therefore reflects the asymmetry through the difference of the first-order features of the profiles. Figure 4 illustrates the slopes k_l and k_r of the left and right rails.

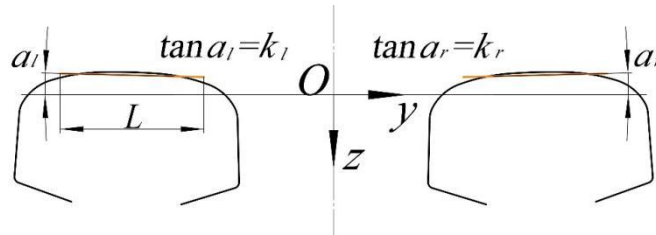


Figure 4 Schematic of the Slope Difference DS between the Left and Right Rails

For a given pair of left and right rail profiles, DS is calculated according to equation (2):

$$DS = k_l - k_r \quad (2)$$

where k_l and k_r are the slopes of the left and right rail profiles, within a certain interval width L .

The third rail asymmetric index, denoted as DC , is used to describe the asymmetry of curvature in the crown region between the left and right rails, and is defined as the difference between the fitted curvatures of the left and right rail profiles within a certain range near the rail crown. The curvature of the rail head profile reflects the concavity or convexity and contains the second-order variation characteristic of the profile, which has an influence on the conformal wheel–rail contact. The asymmetric coupling of the curvatures of the left and right rails affects the dynamic contact of the wheelset. Figure 5 illustrates the curvatures c_l and c_r of the left and right rails.

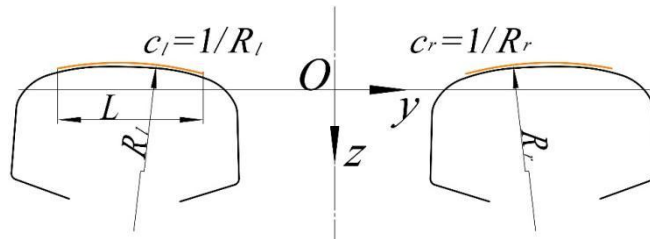


Figure 5 Schematic of the Curvature Difference DC between the Left and Right Rails

For a given pair of left and right rail profiles, DC is calculated according to equation (3):

$$DC = c_l - c_r \quad (3)$$

where c_l and c_r are the curvatures of the left and right rail profiles, within a certain interval width L .

2.2 Definition of the Combined Rail Profile Asymmetry Index

DY , DS , and DC represent the differences in the lateral position of the rail crown, the local slope, and the local curvature. Their dimensions and magnitudes differ from one another. According to the actual geometric parameters of the three indices, each absolute quantity is divided by the corresponding reference quantity to obtain the relative variations η_y , η_s , and η_c of the three asymmetry indices, as shown in equations (4), (5), and (6).

$$\eta_y = DY/L \quad (4)$$

$$\eta_s = DS/S \quad (5)$$

$$\eta_c = DC/C \quad (6)$$

where L is the width of the analysis zone of the rail head, S is the slope of the rail cant, and C is the curvature of the standard rail crown profile. The above definitions retain the signs of the indices so as to preserve the directional information of the relative differences between the left and right rails. Assigning different weights to η_y , η_s , and η_c and combining them with the weights, the combined index A_r can be written as:

$$A_r = w_y \eta_y + w_s \eta_s + w_c \eta_c \quad (7)$$

where w_y , w_s , and w_c are the weight coefficients of the terms η_y , η_s , and η_c respectively. The determination of the weight coefficients is related to the influence strength of the three indices on the target variable. In the next section, based on the concept of the pure rolling offset of a wheelset in steady state, which characterizes the influence of rail asymmetry on the wheelset offset, a set of measured rail data is used to calculate the corresponding weighting coefficients as a case study.

3 LONGITUDINAL EVALUATION METHOD FOR RAIL PROFILE ASYMMETRY

The pure rolling offset of a wheelset reflects, under the condition of given wheel and rail profiles, the steady-state lateral offset of the wheelset when the difference between the left and right rolling radii is zero, and it is capable of reflecting the offset effect produced by the asymmetry of the wheel–rail profiles [10]. In this section, 100 pairs of rail profiles measured on the Beijing–Shanghai high-speed railway and the wheel profiles measured nine times within a wheel reprofiling cycle are used. First, the three indices DY , DS , and DC of the 100 rail pairs are calculated. Then the pure rolling offsets of all wheels in rigid contact with the rails are computed. By establishing a reasonable regression model, the influence weights of the asymmetry indices are obtained. Finally, according to the proportions of the coefficients of the three indices in the regression model, the weight coefficient allocation of each asymmetry index in the combined asymmetry index is determined.

3.1 Weight Allocation Method Based on the Pure Rolling Offset of a Wheelset

Let y_w be the lateral offset of the wheelset center relative to the lateral axis Oy of the track coordinate system. At this offset, the rolling radii corresponding to the contact points between the left wheel and the left rail and between the right wheel and the right rail are $r_l(y_w)$ and $r_r(y_w)$. The rolling radius difference $\Delta r(y_w)$ of the left and right wheels is defined as in equation (8).

$$\Delta r(y_w) = r_l(y_w) - r_r(y_w) \quad (8)$$

The pure rolling offset y_0 of the wheelset is the lateral offset satisfying equation (9), as shown in Figure 6.

$$\Delta r(y_0) = r_l(y_0) - r_r(y_0) = 0 \quad (9)$$

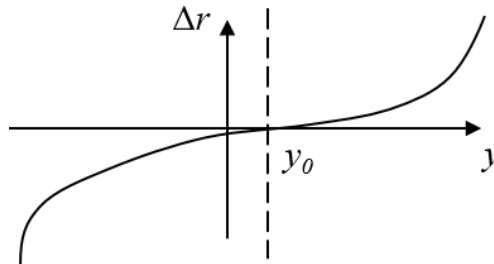


Figure 6 Schematic of the Pure Rolling Offset y_0 of a Wheelset

For a set of rail profile data and multiple sets of wheel profile data, in addition to calculating the offset with the measured combinations of the left and right profiles, the offsets can also be computed with symmetric wheelsets derived from the left and right wheels, so as to obtain the offset data including both the symmetric and asymmetric wheelset effects. A linear mixed-effects model with random intercepts for wheels is adopted, and the regression model is defined as equation (10).

$$\bar{y}_o = p_o + p_y \eta_y + p_s \eta_s + p_c \eta_c + p_w + \varepsilon \quad (10)$$

where $\bar{y}_o$ is the mean value, taken over the vehicles, of the pure rolling offset of the wheelset under a given condition combination, p_o is the intercept, η_y , η_s and η_c are the dimensionless relative variations of the indices respectively, p_w is the random wheel effect, and ε is the residual error. For a given number N of conditions, the regression model can be written as equation (11):

$$Y_o = \eta P + W + \varepsilon \quad (11)$$

where Y_o is an $N \times 1$ matrix consisting of the mean offsets under each condition, η is the matrix of dimensionless index values corresponding to each condition; P is a 4×1 matrix of the regression coefficients p_o , p_y , p_s and p_c ; W is an $N \times 1$ matrix of the random deviations caused by different wheel–rail combinations; and ε is the residual error. By adjusting the parameters so as to minimize the residual error, the multiple regression model actually solves the least-squares solution of the system of linear equations, and the corresponding p_y , p_s and p_c then represent the influence of rail asymmetry in the model. Since the weighting coefficients of A_r are intended to reflect the relative contributions of the three rail asymmetry indices, they can be calculated according to equation (12):

$$w_i = \frac{p_i}{|p_y| + |p_s| + |p_c|} \quad (12)$$

where p_i takes p_y , p_s and p_c .

3.2 Distribution Characteristics of the Combined Rail Profile Asymmetry Index

For the Beijing–Shanghai high-speed railway dataset, the coefficients of the regression model obtained by the above algorithm are: $p_o = -0.226$, $p_y = 1.619$, $p_s = 1.259$ and $p_c = 1.133$. The mean errors and the root mean square errors between the regression predictions and the observations for wheels of different wear states under the nine measurements are shown in Figure 7 and Figure 8. For both the wheelsets with measured asymmetric wheel profiles and those with symmetric wheel profiles, the variation curves of the mean pure rolling offset errors are basically consistent, which indicates on the one hand, that the influence of rail asymmetry exists stably and on the other hand, that the asymmetry of the measured wheel profiles is relatively insignificant. For wheels with different degrees of wear, the absolute mean errors between the values predicted by equation (10) and the actual values are basically within 0.1 mm, and the root mean square errors are approximately in the range of 0.6–0.9 mm.

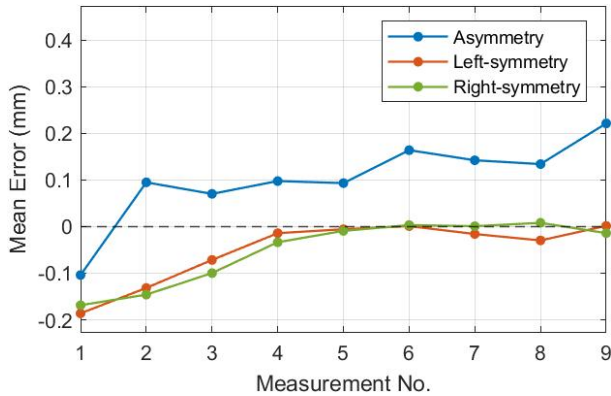


Figure 7 Mean Errors of the Regression Values of the Wheelset Offsets Averaged over the Nine Measurements

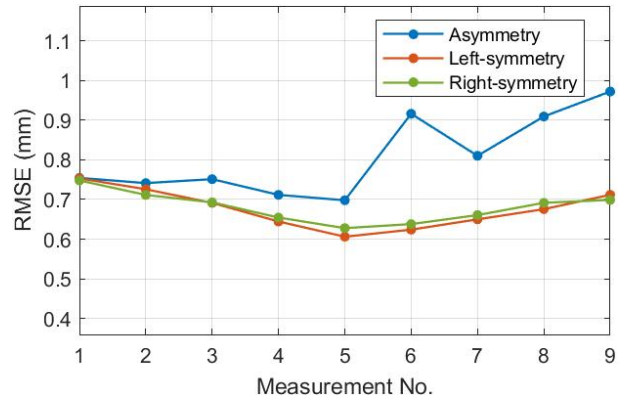


Figure 8 Root Mean Square Errors of the Regression Values of the Wheelset Offsets Averaged over the Nine Measurements

Consequently, the weight coefficient w_y of DY for the Beijing–Shanghai high-speed railway dataset is 0.404, that of DS , w_s is 0.314, and that of DC , w_c is 0.283. These weighting coefficients are dependent on the railway line and the profile samples. For data from other lines, the weight allocation should be obtained from the measured rail data of the line and the wheel profile data of the actual operating vehicles.

After A_r is calculated from the measured left and right rail profiles, its spatial series along the measurement mileage can be obtained, as shown in Figure 9. The orange points are the original values with a sampling interval of 0.5 km. Since the mileage marks in the original data are not fully continuous, in order to facilitate the display of the variation between measurement points with large mileage gaps, the mileages without measurement data are compressed in the figure, and the measurement positions are represented by equivalent mileages starting from zero.

The discrete asymmetry index A_r sequence along mileage can be transformed from the spatial domain to the spatial frequency domain using the discrete Fourier transform (DFT). For a large amount of data, DFT is usually achieved via the fast Fourier transform (FFT). The transformed A_r in the spatial frequency domain is illustrated in Figure 10. The grey curve stands for the original A_r spectrum and the orange line stands for the filtered spectrum, focusing on frequencies under 0.5 cycles/km as an example. The A_r spectrum in the spatial frequency domain serves as a valuable tool to identify fluctuations of rail asymmetry. While spatial frequency equals zero, the A_r amplitude can be seen as a direct current component, which in this case, can reflect the shift of the wheelset caused by the measured rail series. For railway vehicles, it is essential to capture the asymmetry in the rail of low spatial frequencies, as this may lead to periodic low-frequency swaying of the carbody.

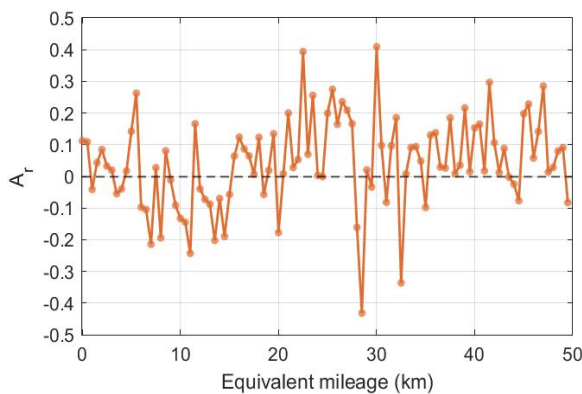


Figure 9 Longitudinal Spatial Series of the Index A_r of the Beijing–Shanghai High-Speed Railway

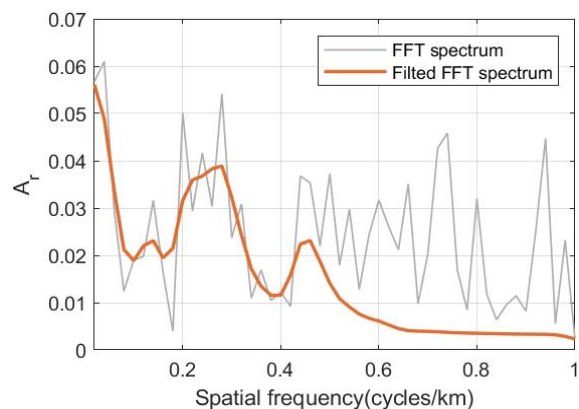


Figure 10 Spatial Spectrum of the Index A_r of the Beijing–Shanghai High-Speed Railway

4 SENSITIVITY ANALYSIS OF THE RAIL ASYMMETRY EVALUATION METHOD UNDER RANDOM DISTURBANCES

4.1 Sources of Measurement Error

Commonly used rail profile measuring instruments include contact and non-contact types, as shown in Figure 11 and Figure 12. During the measurement process with a contact-type instrument, the roughness variation between the roller and the contact surface, the operators' skill level, and the inherent error of the sensor can all cause a certain amount of error in the measurement results. A non-contact profile measuring instrument employs a laser displacement sensor for scanning, and the output profile is likewise affected by the sensor positioning and the mechanical vibrations during measurement, resulting in potential noise within the signal.



Figure 11 Contact-Type Rail Profile Measuring Instrument



Figure 12 Non-Contact Rail Profile Measuring Instrument

The errors in the measured rail profile data will affect the results of the rail asymmetry indices. By adding two different levels of random errors, it is verified whether the combined asymmetry index A_r still effectively reflects the characteristics of track asymmetry under disturbance.

4.2 Sensitivity Analysis of the Indices under Random Disturbances

The index values computed from the measured rails of the Beijing–Shanghai high-speed railway, together with the wheelset offsets, are taken as the true values. Two levels of random errors, each following a Gaussian distribution with a mean of 10% and 20%, are added to three indices, after which the regression and weight coefficients are recalculated. The variation in the capability of the combined index A_r to reflect the longitudinal spatial asymmetry characteristics of the rails when the data are disturbed is then compared and analyzed. Figure 13 shows the variation of the weight coefficients under the two error levels. It can be seen that, for this dataset, the weight coefficient of the index DS is the least affected and remains almost unchanged, while the weight coefficients of the crown lateral distance difference DY and the curvature difference DC vary more noticeably and in opposite trends.

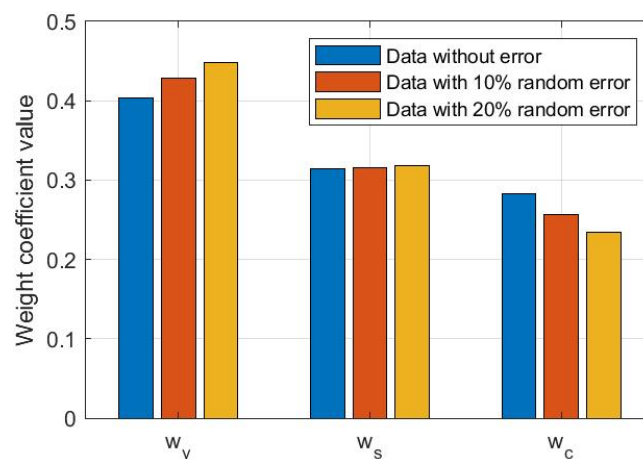


Figure 13 Variation of the Weighting Coefficients under Different Error Levels

Figure 14 and Figure 15 show the spatial distributions of the index A_r and its absolute errors with respect to the true values of A_r under different levels of random errors. Under the interference of random errors, the values of A_r fluctuate slightly with a maximum absolute error of 0.07. But the overall trend of curves is not affected.

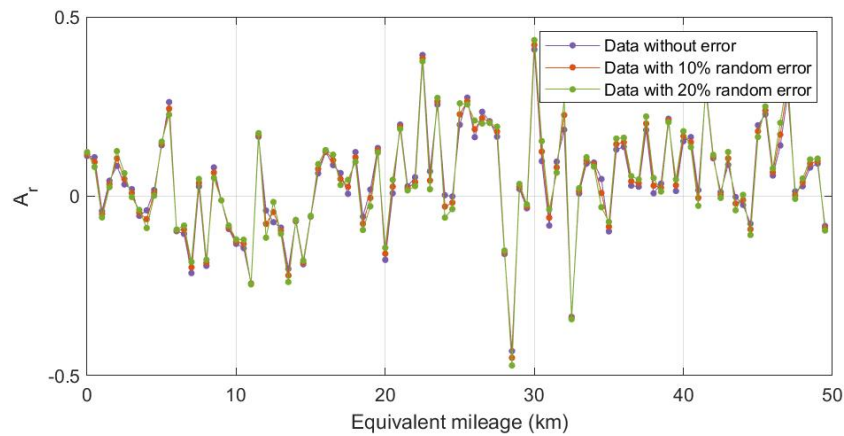


Figure 14 Longitudinal Spatial Distribution of the Rail Asymmetry Index under Different Random Errors

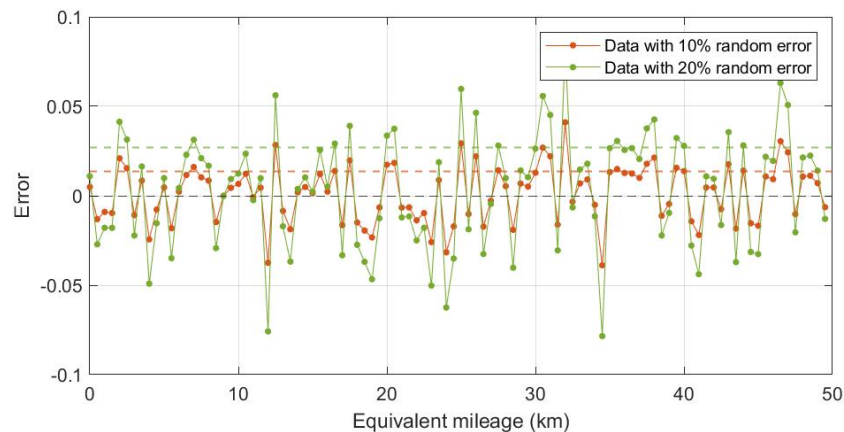


Figure 15 Absolute Errors of the Rail Asymmetry Index under Different Random Errors

Figure 16 compares the A_r spectra of the true values and under different levels of random errors. Under the interference of random errors, the peak distribution of the index A_r in the frequency domain is almost unaffected, with only a certain shift in the amplitude. This indicates that the random errors arising from measurement accuracy and calculation accuracy belong to high-frequency disturbances. These errors will likely not affect the capability of the index A_r to represent the asymmetry of the rail in the low-frequency band.

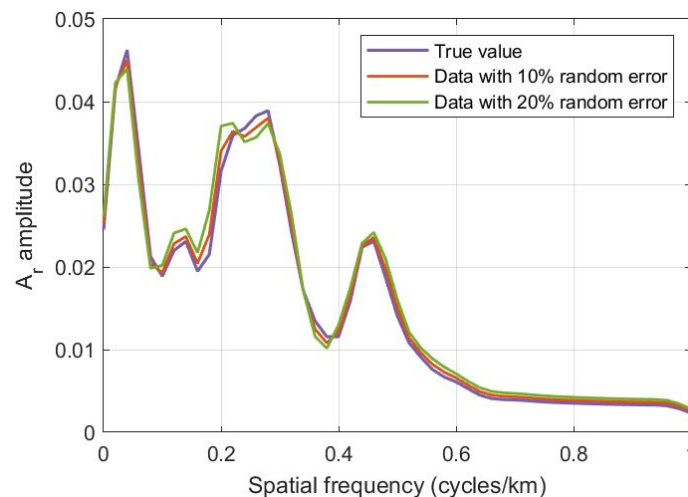


Figure 16 FFT Spectra under Different Error Levels

5 CONCLUSIONS

This paper proposes a method for evaluating the asymmetry characteristics of rail head profiles. The method is capable of characterizing the effect of rail asymmetry on the steady-state offset of a wheelset, and the numerical values possess clear physical meanings. The validity of the method has been verified with measured rail and wheel profile data, and the method retains the capability of preserving the rail asymmetry signal in the presence of random errors of different magnitudes. The evaluation method proposed in this paper enriches the rail profile evaluation system and holds significant

engineering value for the determination of asymmetry limits in rail profile design, as well as for profile inspection and grinding acceptance. Future work can further investigate the influence of rail asymmetry on vehicle dynamic performance under different degrees of rail wear and the interaction between different types of asymmetric rails and vehicles should also be researched on the basis of which a reasonable maintenance range of the index can be established.

COMPETING INTERESTS

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

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