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Study on Abnormal Condition Detection Technology for Railway Bogies Using Trackside Sensor

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Abstract

In recent years, condition monitoring technology has been actively developed aiming at safer operation and maintenance cost reduction. In this study, condition monitoring device attached on trackside is used for the monitoring of railway bogies in terms of the diagonal wheel load imbalance ratio Rd. In general, the ratio Rd widely varies even though the same train pass on the trackside device. Therefore, the factors that cause the variation of Rd should be investigated to improve the measurement accuracy. In this paper, the correction method to reduce the variation of Rd is mentioned. Further examination is conducted on specific bogie abnormalities that can be detected.

Keywords: railway, condition monitoring, wheel-rail contact, lubrication, wheel load, MBD simulation.

1 Introduction

Thanks to the recent development of low cost yet reliable sensors, condition monitoring systems of railway utilizing from both on-board and on-ground sensors have been widely studied [1]. The condition monitoring system leads to Condition Based Maintenance (CBM) and is expected as labor saving inspections. In particular, the condition monitoring technology for railway bogie is directly related to the running safety.

In this study, condition monitoring technology utilizing trackside device that monitors diagonal wheel load imbalance ratio R_d calculated by four wheels vertical forces is considered for the purpose of the detection of abnormalities of bogie's wheel load imbalance ratio R_d. R_d is a value determined at the time of bogie assembly, and the value is thought to be small. However, collected data on service operation widely varies even though the same railway vehicle run under almost same conditions. This research aims to suppress R_d variation and improve the detection sensitivity of bogie abnormalities. Specifically, countermeasures from both hardware and software perspectives are considered. Furthermore, the detection sensitivity for bogie abnormalities is examined with reference to past research, and the results are reported.

2 Trackside condition monitoring device

2.1 Detail and installation of devices

As shown in Figure 1, Tokyo Metro uses trackside condition monitoring devices that can measure vertical forces and lateral forces using attached strain gauges to the rails. Tokyo Metro holds nine lines in Tokyo metropolitan area and the trackside devices are installed at least four locations on each line. The trackside monitoring devices are equipped in 42 locations and most of the devices are attached at circular curves for the aim of monitoring lubrication condition between wheel and rail. Measured data is managed in central via an internet connection [2]. This study investigates the detection of bogie abnormalities using data measured through condition monitoring.

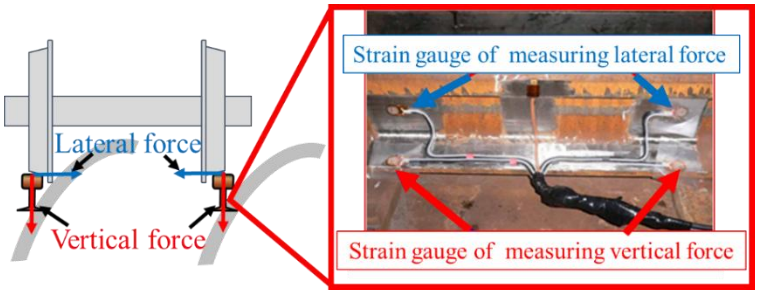


Fig. 1 Overview of condition monitoring devices.

2.2 Diagonal wheel load imbalance ratio

In this study, a condition monitoring using diagonal wheel load imbalance ratio in a bogie is discussed [3]. The value is defined as below.

$$R_{\mathrm{d}} = \frac{100\{(P_{1\mathrm{o}} + P_{2\mathrm{i}}) - (P_{1\mathrm{i}} + P_{2\mathrm{o}})\}}{P_{1\mathrm{o}} + P_{1\mathrm{i}} + P_{2\mathrm{o}} + P_{2\mathrm{i}}} \quad (1)$$

In above equation, "P" is the vertical force, the subscript "1" indicates the leading axle, "2" indicates the trailing axle, "o" indicates the outside wheel, and "i" indicates the inside wheel. Generally, the value of R_d does not change significantly and is thought to change only when an abnormality occurs. Therefore, monitoring the R_d value enables detection of bogie abnormalities.

Figure 2 shows the results of one month measurement of R_d at the service line. The number of data is totally 211 for a specific bogie in a month. As shown in the figure, the standard deviation is 2.2%, indicating that data varied with each run. Even though the value of R_d seems to be irrespective of the boarding rate of the vehicle, it widely varies as shown in the figure.

To improve the detection sensitivity of bogie abnormalities, it is necessary to minimize changes in this data. Hardware and software countermeasures to suppress this variation will be discussed in the following chapters.

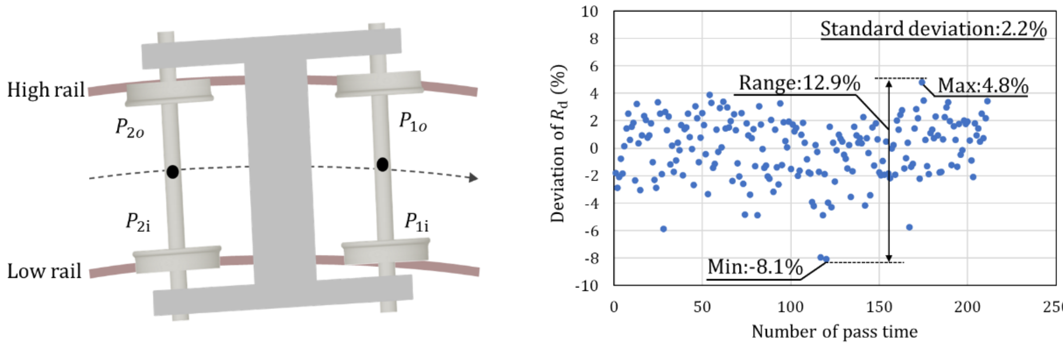


Fig. 2 Measurement results of R_d (R=202mm, C=65mm, S=4mm).

3 Correction of vertical force using lateral force

3.1 Theory of correction method

In order to investigate the factors that cause R_d to be varied, the balance of forces and moment of rotation applied for a wheelset as shown in Figure 3 are considered. The vertical balance of forces and the balance of moment at the center of wheelset can be expressed as follows.

$$P_o + P_i = mg\cos\theta + F_c \sin\theta + k_z z_o + k_z z_i \tag{2}$$

$$P_o b_0 + k_z z_o (b_0 + b_1) + rQ_i = P_i b_0 + k_z z_o (b_0 + b_1) + rQ_o \tag{3}$$

From these equations, the vertical forces, coincide with wheel load, can be expressed as follows.

$$P_o = \frac{1}{2}(mg\cos\theta + F_c\sin\theta) + \frac{b_0 + b_1}{2b_0}k_z z_o + \frac{b_0 - b_1}{2b_0}k_z z_i + \frac{r}{2b_0}(Q_o - Q_i) \tag{4}$$

$$P_i = \frac{1}{2}(mg\cos\theta + F_c\sin\theta) + \frac{b_0 - b_1}{2b_0}k_z z_o + \frac{b_0 + b_1}{2b_0}k_z z_i - \frac{r}{2b_0}(Q_o - Q_i) \tag{5}$$

These equations show that the vertical forces vary depending on the relative displacement between axle box and bogie frame and lateral forces. In particular, the lateral forces of a bogie running on a sharp curve varies depending on the lubrication condition. Therefore, the effect of lateral forces is eliminated using Equations (5) and (6).

$$\hat{P}_{\mathrm{o}} \equiv P_{\mathrm{o}} - \frac{r}{2b_0}(Q_{\mathrm{o}} - Q_{\mathrm{i}}) \tag{6}$$

$$\hat{P}_{\mathrm{i}} \equiv P_{\mathrm{i}} + \frac{r}{2b_0}(Q_{\mathrm{o}} - Q_{\mathrm{i}}) \tag{7}$$

In these equations, the terms of lateral forces in equation (3) and (4) are moved to the left side and are corrected vertical forces $\hat{P}_o$ and $\hat{P}_i$ mean corrected value regardless of lubrication conditions. Then the corrected value of wheel load imbalance ratio $\hat{R}_d$ is defined as follows.

$$\hat{R}_{\mathrm{d}} \equiv \frac{100\{(\hat{P}_{1\mathrm{o}} + \hat{P}_{2\mathrm{i}}) - (\hat{P}_{1\mathrm{i}} + \hat{P}_{2\mathrm{o}})\}}{\hat{P}_{1\mathrm{o}} + \hat{P}_{1\mathrm{i}} + \hat{P}_{2\mathrm{o}} + \hat{P}_{2\mathrm{i}}} \tag{8}$$

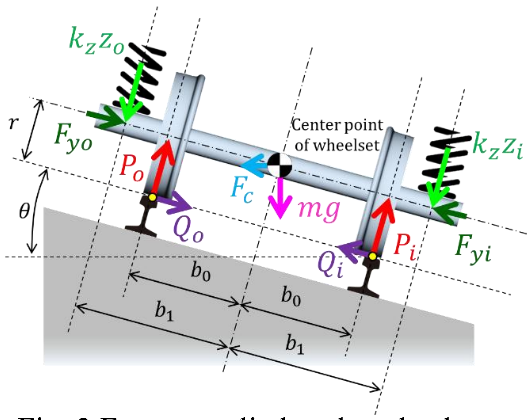


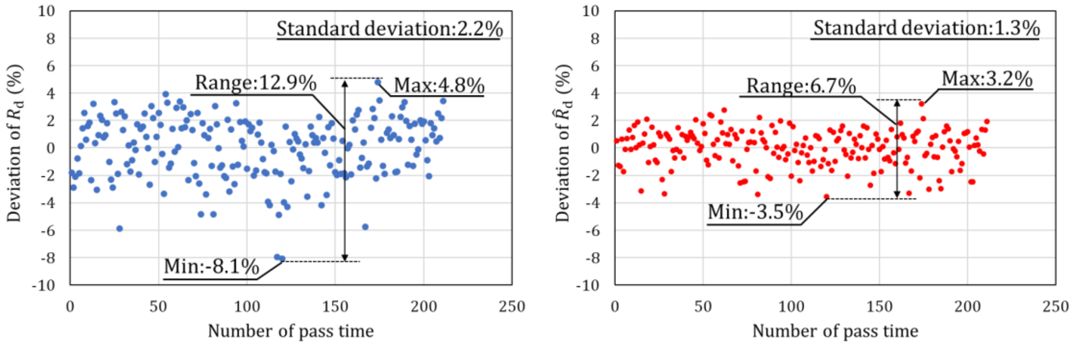
Fig. 3 Forces applied to the wheelset.

Table 1 Constants used in vertical force.

Symbol	Description
$P_{\mathrm{o}}, P_{\mathrm{i}}$	Vertical force acting on wheel-rail contact point
$Q_{\mathrm{o}}, Q_{\mathrm{i}}$	Lateral force acting on wheel-rail contact point
F_{c}	Centrifugal force of wheelset
$F_{\mathrm{yo}}, F_{\mathrm{yi}}$	Lateral force from primary suspension
θ	Angle of super-elevation
k_{z}	Vertical spring constant of primary suspension
b_0	Distance between center of wheelset and wheel-rail contact position
b_1	Distance between center of wheelset and primary suspension
$z_{\mathrm{o}}, z_{\mathrm{i}}$	Vertical displacement of primary suspension
r	Radius of wheel
m	Mass of wheelset
g	Gravitational acceleration

3.2 Data analysis for service line

Measured value in service line operation mentioned in chapter 2 for R_d are compare with corrected value $\hat{R}_d$ as shown in Figure 4. After applying lateral force correction, a range of $\hat{R}_d$ is 6.7% and a standard deviation of 1.3%, indicating that data dispersion has been suppressed. It means that the deviation is effectively reduced by the proposed correction method. For a more detailed analysis, Roller-rig test and numerical analysis are employed. Please refer to the previously study [4].



(a) Result of R_d (b) Result of $\hat{R}_d$

Fig. 4 Comparison between R_d and $\hat{R}_d$.

4 Improvements to the condition monitoring device

4.1 Simultaneous measurement of all four wheels on a single bogie

The condition monitoring device has been improved to enhance sensitivity for anomaly detection. Section 2.2 describes R_d as having the characteristic of being able to eliminate the effects of body sway, but this applies only when the vertical force of all four wheels is measured simultaneously. This does not necessarily hold true for current condition monitoring devices. The current condition monitoring device, as shown in Figure 1, measures vertical and lateral force for one axis (two wheels) at a time. In this case, measuring the vertical force of a single bogie with four wheels involves moving the vehicle body with a wheelbase of 2.1 meters. Examine the effects of vehicle body sway occurring during this movement. As shown in Figure 5, the air spring pressure when the first axle passes on the condition monitoring device is denoted as AS_r and AS_l, and the wheel load is denoted as P_{1i}, P_{1o}, P_{2i}, and P_{2o}. Next, during the 2.1m axle distance movement for the second axle measurement, when body sway occurs and the air spring pressure of the left and right air springs changes by B [kPa], it is assumed that the respective wheel loads change by $P_{2i} + \beta$ [N] and P_{2o} - β [N]. Reflecting these measurement results in R_d yields the following.

$$R_d = \frac{100\{(P_{1o} + P_{2i}) - (P_{1i} + P_{2o}) + 2\beta\}}{P'_{1o} + P'_{1i} + P'_{2o} + P'_{2i}} \quad (6)$$

Since the air spring pressure changes differ with each run, this leads to variations in R_d with each run. To address this challenge, this study improves the condition monitoring device to enable simultaneous measurement of all four wheels on a single bogie.

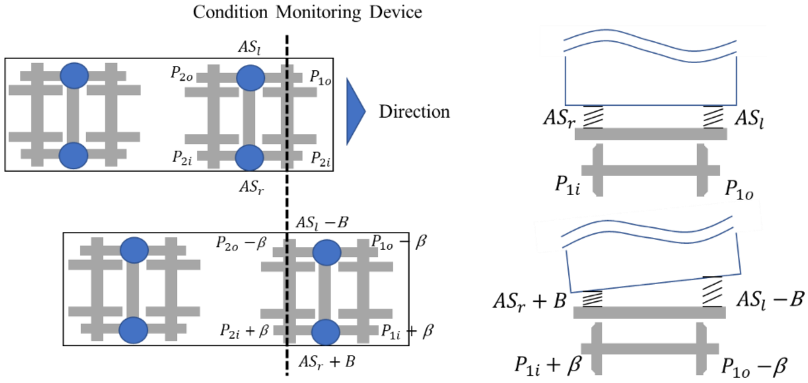
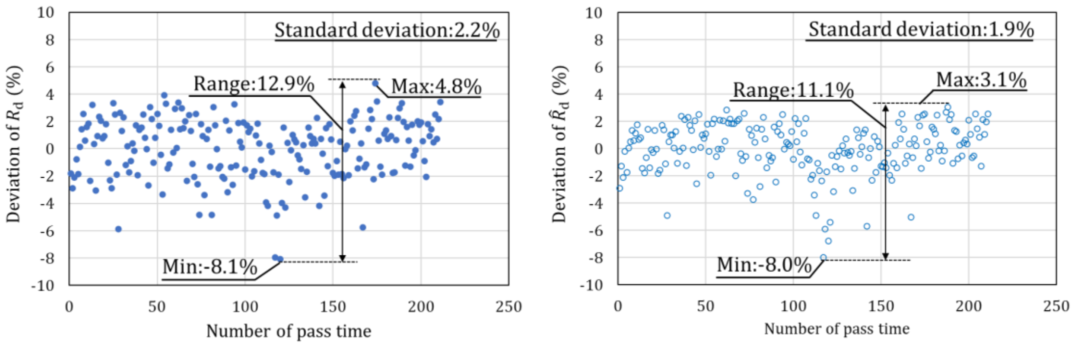


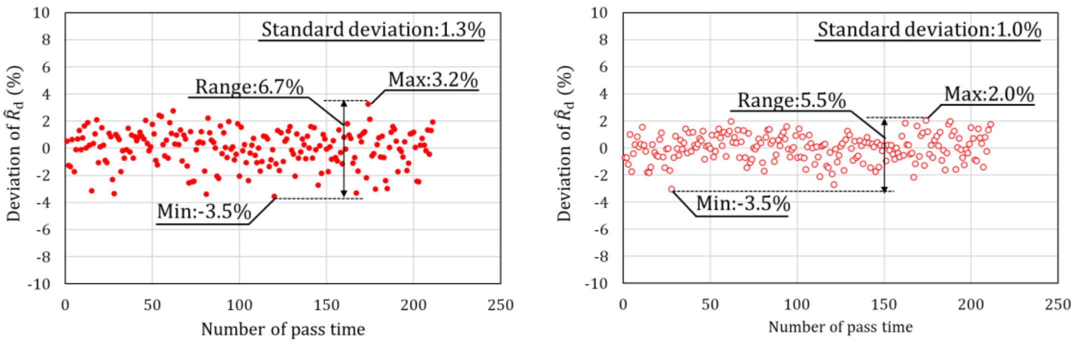
Fig. 5 Effect of Vehicle Body Sway on vertical force.

4.2 Analysis of operational line data using an improved condition monitoring device

The effectiveness of the improved condition monitoring device is evaluated by comparing the standard deviations of R_d and $\hat{R}_d$. The standard deviations of R_d and $\hat{R}_d$ before improvement are 2.2% and 1.3%, respectively. On the other hand, the improved condition monitoring device shows standard deviations of 1.9% and 1.0%, indicating that data variability is suppressed.



(a) Comparison Results for R_d



(b) Comparison Results for $\hat{R}_d$

Fig. 6 Comparison of results before and after improvement of the condition monitoring device.

Figure 7 shows the change in standard deviation resulting from the lateral force correction described in Section 3.1 and the improvements to the condition monitoring device described in Section 4.1. The data used for analysis is the average of the measurement results for three M cars and three T cars. Improvements to the lateral force compensation and condition monitoring system have suppressed the standard deviation and increased the detection sensitivity for bogie abnormalities. Specifically, lateral force compensation is performed using conventional condition monitoring device data, with a standard deviation of 2.4%. On the other hand, by measuring with the improved condition monitoring device and performing lateral force compensation, the standard deviation is suppressed to 1.2%.

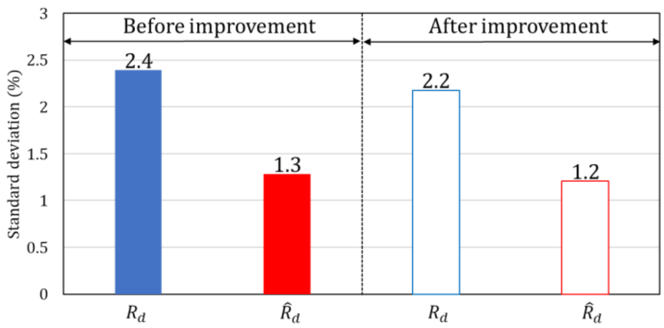


Fig. 7 Comparison results for multiple vehicles (three M cars and three T cars).

5 Detection method for bogie abnormalities

This chapter describes a bogie anomaly detection algorithm utilizing this research. Figure 8 shows the frequency distribution of $\hat{R}_d$ measured using the improved condition monitoring device and corrected for lateral force, based on data collected from 20 vehicles. The results confirm that R_d follows a nearly normal distribution. The detection method for bogie abnormalities is being investigated by reference to Hotelling's theory based on the normal distribution of R_d. Specifically, areas are divided based on each standard deviation σ, and anomalies are detected based on the probability of plots occurring within each area. An example is shown below. For example, in a normal distribution, the probability of plotting within σ to 2σ is approximately 14%. However, if the probability of plotting within this range is approximately double that 30% then an inspection after the train entered the depot. Similarly, cases involving 2σ to 3σ and 3σ or higher should be categorized, and appropriate actions should be taken in conjunction with the probability of occurrence for each category.

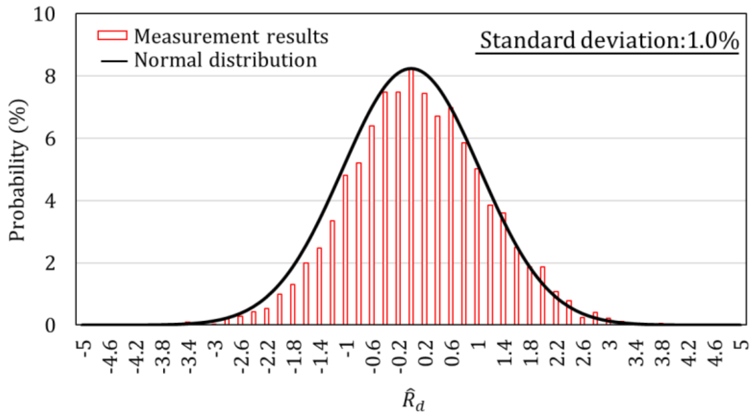


Fig. 8 The frequency distribution of $\hat{R}_\mathrm{d}$ measured using the improved condition monitoring device and corrected for lateral force (N = 4173).

6 Detection sensitivity for bogie abnormalities

The detection sensitivity for bogie abnormalities is examined based on past research examples. Specifically, it is based on previous study conducted by the Railway Technical Research Institute [5]. This previous study employs the FEM to reproduce various bogie frame cracks on bolsterless bogies. Furthermore, wheel load imbalance on the same axle is calculated in accordance with crack progression. As a result, although varying slightly at each crack location, when the crack length reaches approximately 120 mm, the change in wheel load imbalance is about 3%. Furthermore, it is stated that as the crack progresses, the wheel load imbalance changes rapidly, compromising safety. For this result, the standard deviation of R_d measured by conventional condition monitoring devices is approximately 2.5%, enabling the detection of cracks of roughly 120 mm. On the other hand, when data measurement and lateral force correction are performed using the improved condition monitoring device proposed in this study, it is found that the standard deviation at $\hat{R}_\mathrm{d}$ is approximately 1%, indicating the potential to detect cracks of approximately 90 mm.

7 Conclusions

This study aimes to enhance train operation safety and reduce inspection labor by improving the detection sensitivity of bogie abnormalities using wheel load imbalance ratio and verified the types of bogie abnormalities that can be detected. Specifically, the following three initiatives are implemented.
(1) The effect of lateral force on wheel load is clarified, a correction method is proposed, and it is confirmed that the standard deviation of R_d decreases.
(2) Improvements to the condition monitoring device are implemented, confirming a reduction in the standard deviation of R_d.
(3) Based on previous study the bogie frame cracks detectable using the anomaly detection algorithm proposed in this research are examined. As a result, it is confirmed that the detection sensitivity for bogie abnormalities had improved.

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