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A DRIVE-BY ESTIMATION METHOD OF LOOSE BEARING BASED ON TRACK GEOMETRY USING A MEASUREMENT OF UNLOADED TRACK GEOMETRY

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Abstract. *In railway steel bridges, loose bearings are a recognized maintenance concern. This support defect involves gaps that develop between bearing components, causing the girder to displace abruptly as a train passes. In recent years, drive-by methods utilizing the longitudinal level of track geometry from track inspection cars have attracted considerable attention. In field measurements, unloaded track geometry was obtained, and the difference between the loaded and unloaded 5-m symmetric chord offset track geometries (5-m DLU) served as the evaluation metric. Field validation was conducted on an in-service railway line comprising multiple consecutive deck-girder bridges with direct fixation to the track, each 13.2 m long (span: 12.4 m). The results showed that an increased amplitude at locations with a bearing gap of 0.8 mm was consistent with numerical analysis. A method for estimating loose bearings based on the 5-m DLU amplitude near the support, using a predefined threshold, was validated on five bridge bearings, yielding three true positives. To further improve accuracy, theoretical analysis demonstrated that positional misalignment between the two track geometry measurements used to calculate the 5-m DLU introduces an error proportional to the spatial derivative of the track geometry and the magnitude of the misalignment. These results indicate that the 5-m DLU contains noise from positional misalignment, which may affect loose bearing estimation.*

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1 INTRODUCTION

Detecting loose bearings is an important inspection task in the maintenance and management of steel railway bridges [1]. A loose bearing is a defect in which gaps form between the sole plate and the lower bearing, or between the lower bearing and the bearing seat, due to damage to the bearing seat mortar, bearing settlement, or corrosion and wear. These gaps are compressed and cause uplifting when a train passes. Loose bearings are a concern because they increase stress on bearing parts and surrounding components, which can lead to fatigue cracks and loose bolts. The occurrence and condition of loose bearings must therefore be reliably detected and monitored, and corrective measures taken as needed. Although ground-based monitoring methods for detecting loose bearings have been proposed [1], they present significant cost challenges in sensor installation and management.

In recent years, onboard measurement methods using track inspection vehicles have advanced considerably [2–8]. Hattori et al. [7,8] demonstrated that the presence of a loose bearing induces localized variations in the 5-m symmetric chord offset track geometry near the support. Because the influence of unloaded track geometry, which is embedded in the loaded geometry obtained by track inspection vehicles, cannot be neglected on actual railway lines, they proposed using the difference between the loaded and unloaded track geometries, defined as DLU. They also proposed a method for estimating loose bearings based on a predefined DLU threshold [8]. However, this validation was limited to comparisons with visual inspection records, leaving questions about the method's accuracy. Furthermore, the non-negligible false detection rate warrants deeper analysis of noise components in the DLU.

This study, therefore, revisits the findings of Hattori et al. [8], validates the proposed loose bearing estimation method against bearing displacement measurements from displacement sensors, and analyzes positional misalignment errors in the DLU calculation to improve estimation accuracy.

2 NUMERICAL METHOD

2.1 The FEM-based calculation program

This study uses an existing girder deflection–track geometry conversion program [6] that calculates track geometry from structural deformation. Figure 1 shows the calculation flow of this program. It consists of a structural analysis module using a two-dimensional finite element method (2D FEM) and a signal processing module using the track maintenance management database system LABOCS [9]. The 5-m SCTG (5-m symmetric chord offset track geometry) is obtained through the signal processing module.

The structural analysis models the structure using 2D elements (springs and beams) and calculates the structural response to a loading sequence matching the wheel arrangement and wheel loads of the track inspection vehicle. Because the dynamic response of the structure is negligible at low speeds, the structural analysis module computes the static response at each load position.

2.2 Loose bearing model

A nonlinear spring was introduced into the structural analysis module. Throughout this paper, the vertical gaps in the loose bearing are collectively referred to as the "uplift gap," with its magnitude denoted by g.

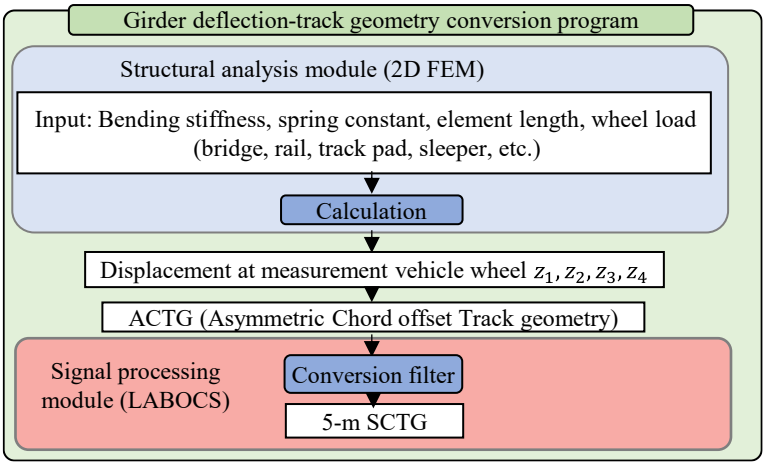


Figure 1: Calculation flow of the girder deflection–track geometry conversion program.

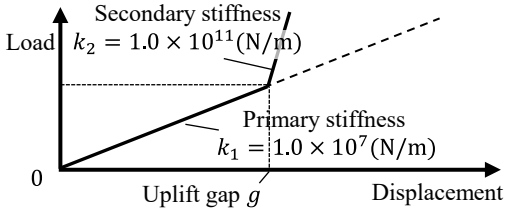


Figure 2: Load-displacement relationship of the nonlinear spring representing the loose bearing.

Figure 2 shows the load-displacement relationship of the nonlinear spring representing the loose bearing. When the bearing displacement is less than g, the bearing stiffness is low, corresponding to a primary stiffness of $k_1 = 1.0 \times 10^7 (\mathrm{N/m})$. When the displacement exceeds g under train loads, the stiffness is assumed to recover to that of a normal bridge bearing without an uplift gap, corresponding to a secondary stiffness of $k_2 = 1.0 \times 10^{11} (\mathrm{N/m})$.

2.3 Calculation case

Figure 3 shows the FEM model of a bridge section comprising seven simply supported girders, each with a bridge length of 13.2 m and a span of 12.4 m. The bridges are labeled B1 through B7 from left to right. The nonlinear spring representing the loose bearing was placed on either the train entrance or exit side of B4. Seven calculation cases were analyzed, with $g = 1.0,\ 0.8,\ 0.6,\ 0.4,\ 0.2,\ 0.1,$ and 0 mm, reflecting values commonly observed in railway practice.

In the FEM model, the track inspection vehicle is represented as a two-car train: the first car is a two-bogie inspection vehicle, and the second is a diesel car. Only one side of the rail and bridge was modeled; wheel loads were based on measurements from a separate field test [8]. The bridge and rail were modeled using beam elements; the track pad and bridge bearings were modeled using spring elements. The model captures only the vertical component, so horizontal bearing displacement was not modeled. Table 1 lists the bridge and rail specifications used.

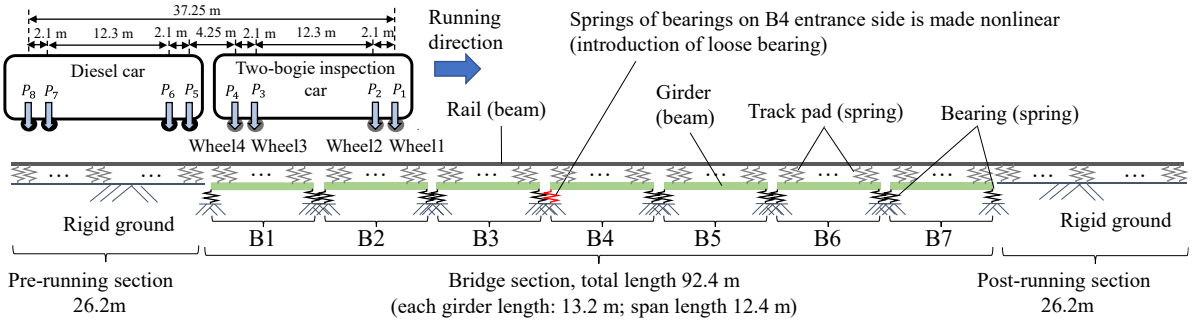


Figure 3: FEM model of the bridge section comprising seven simply supported girders.

Rail bending stiffness	6.47×10^{6} (N·m^2)
Track pad stiffness	4.00×10^{7} (N/m)
Girder bending stiffness	1.41×10^{9} (N·m^2)
Normal bearing stiffness	1.00×10^{11} (N/m)

Table 1: Bridge and rail specifications used in the FEM model.

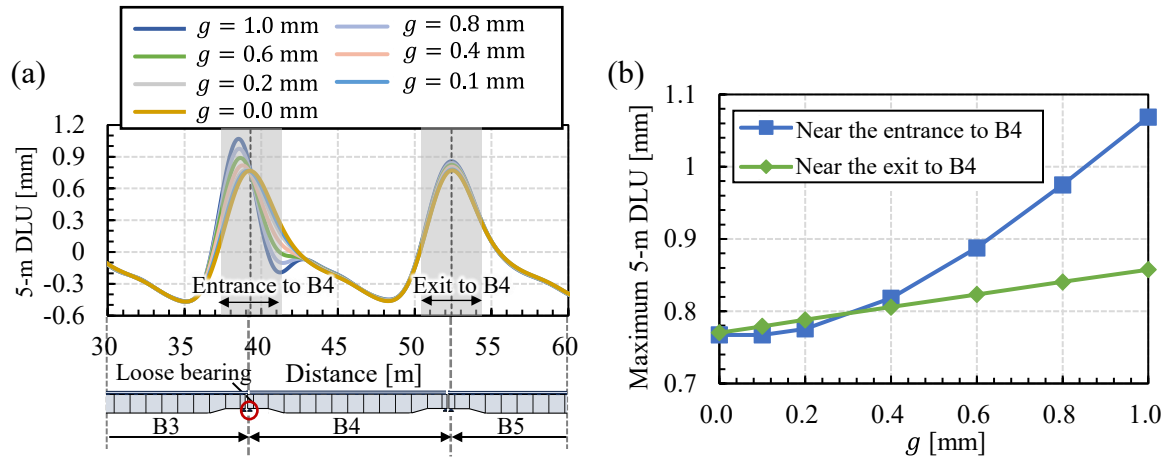


Figure.4 5-m DLU obtained using the FEM-based calculation method.

Girder and rail specifications were taken from design drawings; track pad stiffness was determined from material test results [10]. Because no unloaded track geometry is applied to the rail, the calculated 5-m SCTG is equivalent to the DLU, referred to hereafter as 5-m DLU.

2.4 Calculation result

Figure 4(a) shows the calculated 5-m DLU. For $g = 0.0$ mm, the waveform corresponds to girder deflection, exhibiting an upward peak with a half amplitude of 0.75 mm at the girder support. As g increases, the upward peak shifts approximately 1 m toward the entrance side and the peak amplitude increases.

Figure 4(b) shows the maximum 5-m DLU at the entrance and exit sides of B4, evaluated within ±2 m of each side. Near the entrance, the maximum amplitude remains approximately constant up to $g = 0.2$ mm, after which it increases linearly and monotonically (bilinear behavior), with a slope of 0.37 in the linear region. Near the exit, a linear and monotonic increase is also observed, but with a substantially smaller slope of 0.09.

3 LOOSE BEARING ESTIMATION METHOD

3.1 Verification of the numerical method

The validity of the numerical analysis method is verified using the 5-m SCTG (loaded) obtained from a track inspection vehicle and the 5-m SCTG (unloaded) obtained from a simple track inspection device. The target section comprises six consecutive spans of steel direct-fixation type III deck-girder bridges, each with a girder length of 13.2 m and a span of 12.4 m.

The deck girders are designated T1–T6 in the direction of travel of the track inspection vehicle. The bearings are line bearings, with movable bearings on the entrance side and fixed bearings on the exit side. The entrance-side bearings of T2 through T6 are designated S2–S6. Based on displacement measurements on the upper flange during train passage, loose bearings were confirmed at S2, S3, S5, and S6, but not at S4. The measured bearing gaps g_{meas} are shown in the upper portion of Figure 5.

Figure 5 (a) shows a comparison between the 5-m SCTG (unloaded) and the 5-m SCTG (loaded). The 5-m SCTG (loaded) contains a substantial unloaded track geometry component whose influence cannot be neglected. The difference between the two — the 5-m DLU (loaded minus unloaded) — is therefore calculated. Because the two 5-m SCTG datasets have different distance axes [11], a cross-correlation-based alignment method was applied when computing the difference [12].

Figure 5 (b) shows the 5-m DLU (loaded minus unloaded) alongside the 5-m DLU from FEM at $g = 0.8$ mm and $g = 0.0$ mm, evaluated at S2. The 5-m DLU (loaded minus unloaded) and the FEM result at $g = 0.0$ mm show good agreement in wavelength components near the span length, confirming that girder deflection is well represented. Shorter wavelength components exhibit noise, for example, in the 40–45 m section. Additionally, although some amplitude discrepancy exists, the upward peak near S2 in the 5-m DLU (loaded minus unloaded) and the FEM result at $g = 0.8$ mm show a consistent trend, and the downward peak approximately 1 m to the right of S2 agrees well in both amplitude and shape.

These results indicate that, despite noise components in the field data, the numerically derived DLU at loose bearing locations reproduces field observations well.

3.2 Amplitude-based estimation

The discussion above establishes that loose bearing characteristics can be captured using the 5-m DLU amplitude. Accounting for noise components in the field DLU not present in the numerical analysis, and for the influence of loose bearings at adjacent supports on amplitude, a method is proposed in which a loose bearing is identified when the maximum 5-m DLU within ±2 m of the support exceeds a detection threshold of 0.9 mm.

Figure 6 shows the flowchart of the proposed method. The presence of a loose bearing is denoted as positive (P) and its absence as negative (N). The method is applied to the 5-m DLU described in Section 3.1, and estimation accuracy is evaluated by comparison with g_{meas}.

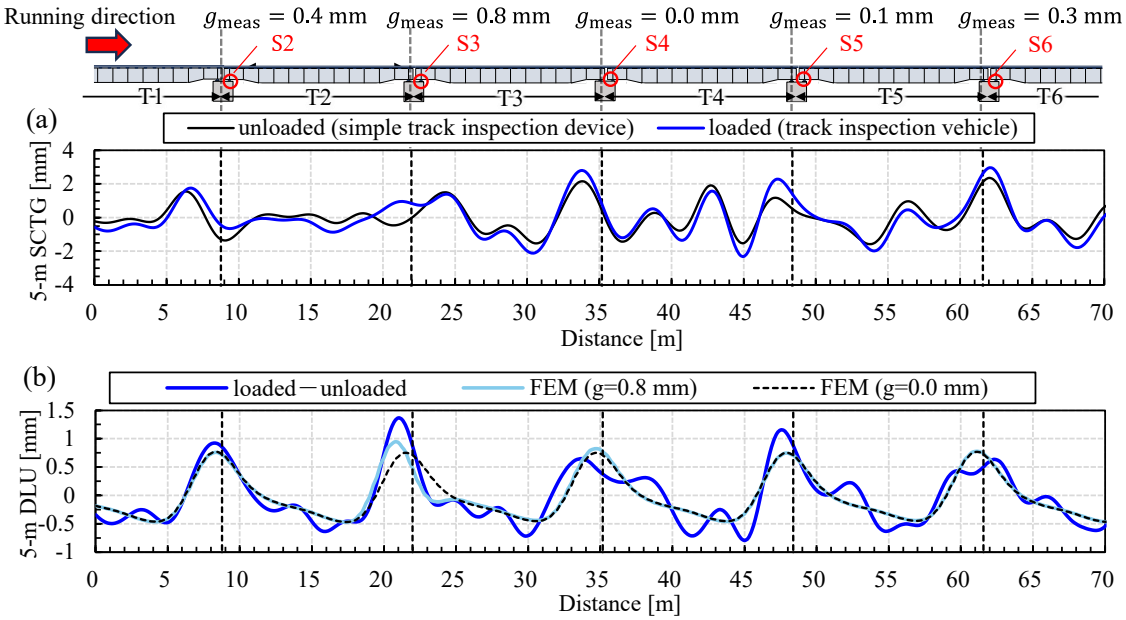


Figure 5: Comparison of track geometry : (a) 5-m SCTG (unloaded) and 5-m SCTG (loaded); (b) 5-m DLU (loaded minus unloaded) and 5-m DLU from FEM at g = 0.8 mm and g = 0.0 mm at S2.

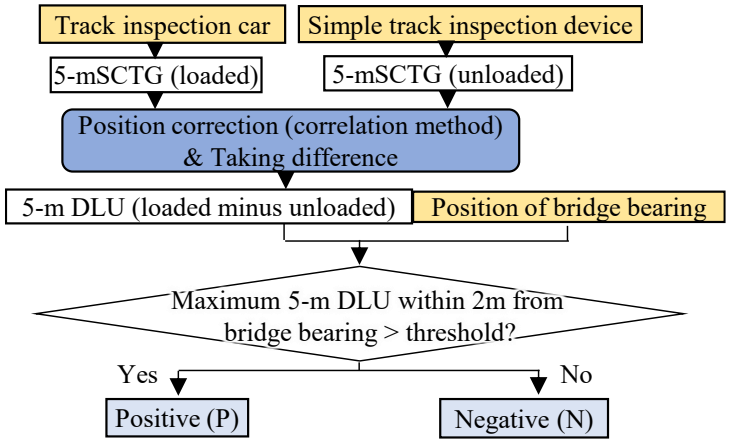


Figure 6: Flowchart of the proposed estimation method.

Table 2 presents a comparison between ground measurements and onboard estimation results. The maximum 5-m DLU is the maximum value of the 5-m DLU (loaded minus unloaded) within ±2 m of each support, S2–S6. Ground truth is classified as positive (P) when $g_{meas} >$ 0mm and negative (N) when $g_{meas} = 0$ mm. The classification row reports results using standard binary metrics: TP (true positive), TN (true negative), FP (false positive), and FN (false negative). At S4 ($g = 0.0$ mm), the result was TN, and at S6 ($g = 0.3$ mm) the result was FN; the remaining three locations were correctly classified as TP. Despite the limited number of validation cases, these results indicate the potential of the proposed method for loose bearing screening.

	S2	S3	S4	S5	S6
Maximum 5-mDLU (onboard measurement) [mm]	0.92	1.37	0.65	1.15	0.63
Estimation (P/N)	P	P	N	P	N
g_{meas} [mm]	0.4	0.8	0.0	0.1	0.3
Ground truth (P/N)	P	P	N	P	P
Classification result (TP/TN/FP/FN)	TP	TP	TN	TP	FN

Table 2: Comparison between ground measurements and onboard estimation results.

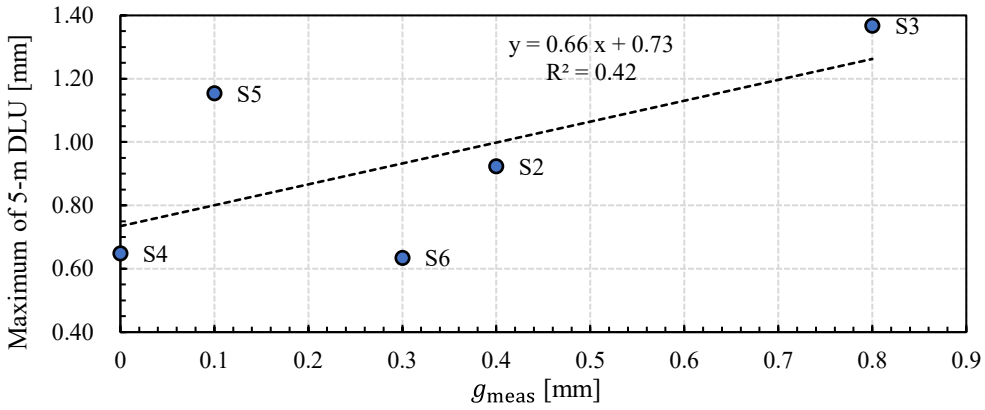


Figure 7: Relationship between $g_{\mathrm{meas}}$and the maximum 5-m DLU at S2 – S6.

Figure 7 shows the relationship between g_{meas} and the maximum 5-m DLU at S2–S6. The regression line is $y = 0.66x + 0.73$; the coefficient of determination $R^2 = 0.42$ indicates a moderate correlation and the absence of a strict one-to-one relationship.

Because noise components are present in the measured 5-m DLU shown in Figure 5 (b) but absent from the numerical analysis in Section 2, further analysis of these noise sources is necessary to improve loose bearing estimation accuracy.

3.3 Discussion

Calculating the 5-m DLU requires differencing two track geometry waveforms with different distance axes. Although cross-correlation alignment is applied, its accuracy is limited to the order of the sampling interval. Positional misalignment smaller than the sampling interval may therefore persist, introducing noise.

Let the loaded track geometry measured by the track inspection vehicle be $z_t(x)$, the unloaded track geometry be $s_t(x)$, and their DLU be $d_t(x)$, such that

$$z_t(x) = d_t(x) + s_t(x) \tag{1}$$

If the distance axis of $z_t(x)$ is correct and the distance axis of $s_t(x)$ is shifted from $z_t(x)$ by δ, then

$$s_{t,\delta}(x) = s_t(x + \delta) \tag{2}$$

The resulting DLU $d_{t,\delta}(x)$ is given by

$$\begin{aligned} d_{t,\delta}(x) &= z_t(x) - s_{t,\delta}(x) \\ &= d_t(x) + s_t(x) - s_t(x + \delta) \end{aligned} \tag{3}$$

Assuming δ is sufficiently small, a first-order Taylor expansion gives the positional misalignment error e as

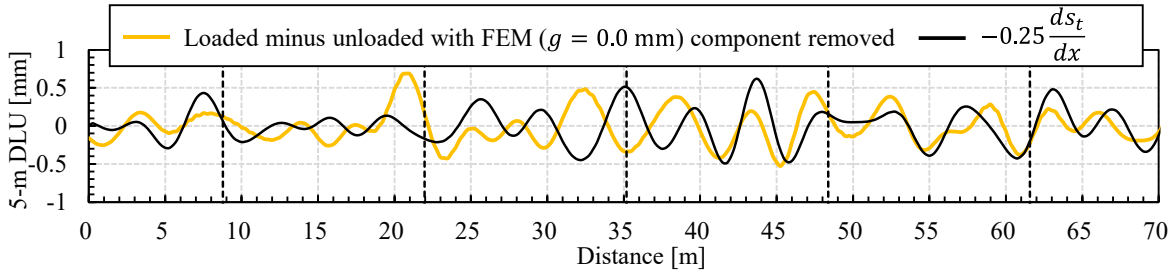


Figure 8: Comparison of 5-m DLU waveforms: loaded minus unloaded with FEM (g = 0.0 mm) component removed, and the positional misalignment error term -0.25 (ds_t/dx).

$$e = d_{t,\delta}(x) - d_t(x) = -\frac{ds_t(x)}{dx}\delta \tag{4}$$

Thus, the error caused by positional misalignment is proportional to the spatial derivative of the unloaded track geometry and to the magnitude of the misalignment δ.

Figure 8 compares the 5-m DLU (Loaded minus unloaded with FEM (g = 0.0 mm) component removed) with -0.25 (ds_t/dx). The former represents the 5-m DLU with the girder deflection component removed, retaining the loose bearing and error components. The latter represents the positional misalignment error for δ = 0.25 m from Eq. (4). The two waveforms are in antiphase in the 10–20 m and 30–40 m ranges and in phase in the 40–70 m range, with an overall moderate correlation. Within the 40–70 m range specifically, the correlation coefficient is 0.68. These results suggest that the 5-m DLU contains positional misalignment errors and that correcting these errors could improve loose bearing estimation accuracy.

4 CONCLUSIONS

This study investigated the applicability of the 5-m DLU to drive-by detection of loose bearings in railway steel bridges through field validation, threshold-based estimation, and theoretical analysis of errors caused by positional misalignment. The 5-m DLU was calculated for an in-service railway line comprising multiple consecutive deck-girder bridges (length: 13.2 m, span: 12.4 m) under direct-fixation track and compared with numerical analysis. Increased amplitude at locations with a bearing gap of 0.8 mm was consistent with the numerical results, validating the analysis method.

A loose bearing estimation method based on a predefined 5-m DLU amplitude threshold near the support was proposed and validated on five bearings at the field site using a threshold of 0.9 mm. The results yielded three TPs, one TN, and one FN. Despite the limited number of validation cases, the method shows potential for loose bearing screening.

Theoretical analysis showed that positional misalignment between the two track geometry measurements used in the differencing process generates an error proportional to the spatial derivative of the track geometry and the magnitude of the misalignment. A moderate correlation was observed between this error and the waveform obtained by removing the girder deflection component from the measured 5-m DLU. These findings indicate that the 5-m DLU contains noise from positional misalignment, which may affect loose bearing estimation.

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