Drive-by Bridge Deflection Estimating Method Based on Track Irregularities Measured on a Train: Extension to Multiple Bridge Sections

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Abstract. Although bridge deflection during train passage is a typical index for measuring a bridge's structural performance, determining this parameter on-site requires considerable effort and cost. Therefore, the drive-by method based on track irregularity differences between the first and last vehicles of a train was proposed. However, measuring trains' track irregularities on first and last vehicles are limited. Thus, extension to the use of asymmetrical chord offset track irregularity (ACTI) measured by typical track inspection trains (two-bogie track inspection vehicle) is desired. However, since the other axle displacements affects the measured ACTI by the difference based method, even if adjacent bridges are structurally separated, the adjacent bridge deflection can affect the measured ACTI of the target bridge. This study extended the past drive-by bridge deflection estimation method to ACTI measured by two-bogie track inspection vehicle by considering adjacent bridges. Then, authors conducted numerical simulations to understand the impact of the proposed method and the adjacent bridges' deflection. The results revealed that bridge deflections could be estimated after correcting the phase by multiplying the difference between the two ACTIs by the conversion factor. This estimation method based on the ACTIs also resulted in high girder deflection measurement sensitivity at 10–15 m bridge span, confirming the superiority of this study's method.

Keywords: Drive-by Bridge Inspection · Bridge Deflection · Track Irregularity

1 Introduction

With minimum human and economic resources, the methodology for efficiently managing many railway structures, such as bridges, has become an important social issue in many countries [1]. Hence, structural health monitoring (SHM), a bridge deflection tool under train passages serving as a typical index of the bridge's structural performance that can be measured from the ground with considerable effort and expense, has been proposed [2]. An example of a method under SHM is the novel drive-by method based on the difference between track irregularities of in-service trains that has been proposed as an efficient bridge deflection measurement for simply supported bridges [3]. Remarkably,

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investigations have revealed that since many track inspection vehicles are operating, the application range of drive-by bridge deflection estimations can be expanded once the maximum bridge deflections can be determined from the track irregularities obtained from track inspection vehicles [4]. However, a method for estimating bridge deflections from track irregularities using a two-bogie, four-axle track inspection vehicle (hereafter simply referred to as a track inspection vehicle) that has been used in Japan and China [4] is yet to be studied. Furthermore, although this vehicle instrumentation is notably based on a code-based system, where the deflection of adjacent bridges without structural connection physically affects the measured values of a target bridge, little is known about the influence of these adjacent bridges [3, 5]. Therefore, the authors in this study developed a method for estimating the maximum deflection of a bridge using two-track irregularities obtained from a track inspection vehicle. Then, we conducted numerical analyses to clarify the effect of adjacent bridges on a target bridge's deflection estimation accuracy.

2 Methods

2.1 Bridge Deflection Estimation *via* Inspection Trains

Figure 1 shows the outline of this study's track inspection vehicle, comprising two bogies and four axles, used to measure the understudied rails' relative displacement. Notably, our investigation adopted asymmetrical chord offset track irregularity (ACTI), the relative displacement of three of the four axes, to evaluate track irregularity. Hence, Fig. 1 also depicts the relationship between the 124 and 134 ATCIs, which are the relative displacements of the 2nd and 3rd axles, including those of the track irregularity when the displacements of the 1st and 4th axles were 0 [4].

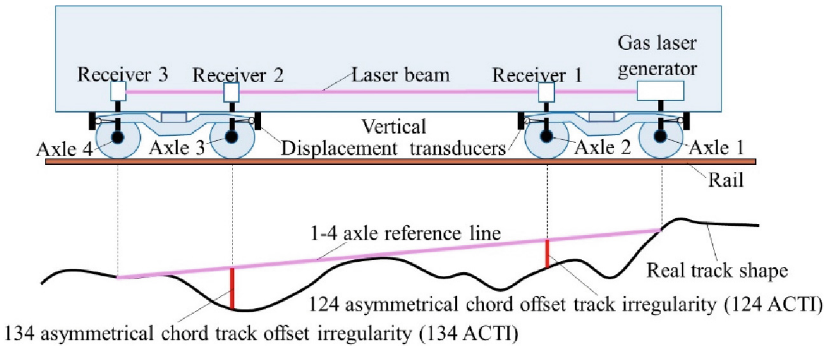

Fig. 1. Schematic showing a two-bogie track inspection vehicle with asymmetric chord offset track irregularities.

Although direct differences could not be obtained since the 124 and 134 ACTIs had different phase characteristics [4], converting ACTI with a distance delay into symmetrical chord offset track irregularity (SCTI) with flat phase characteristics corrected the phase characteristics. Thus, possible differences between the 124 and 134 ACTIs could be created, where the 10 m SCTI was the displacement at the interest position minus the average displacement at positions 5 m in front and behind. However, we subsequently observed that when the phase characteristics of the 10 m SCTI was 0, ACTI's conversion required the amplitude ratio of the 10 m SCTI and ACTI as the gain and the positive/negative characteristics of the ACTI as the phase. Therefore, the authors designed an inverse filter (Fig. 2) with the amplitude characteristics of the target inverse filter.

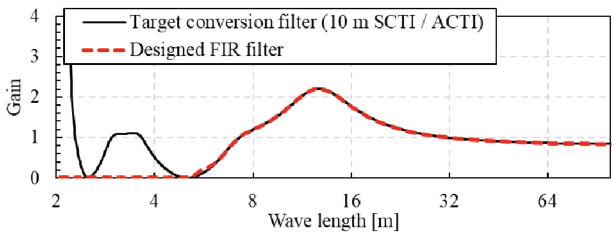

Fig. 2. Designed inverse filter amplitude characteristics.

As shown theoretically in the literature [3], the maximum value of the difference between two-track irregularities under differing load conditions is proportional to a bridge's deflection maximum value. Interestingly, this fact holds because the difference between the two-track irregularities cancels out the track displacement other than the bridge deflection, extracting only the structure's deformation component due to load differences. Hence, considering this fact, we adopted the theoretical model in calculating the maximum difference between the two-track irregularities (those 10 m SCTIs from ACTIs) and the maximum bridge deflection. Then, we stored the ratio between them as a conversion factor. The maximum bridge deflection was also notably estimated from onboard measurements by multiplying the maximum difference between the two measured track irregularities by the stored conversion factor. Figure 3 shows the theoretical model for the conversion factor calculation.

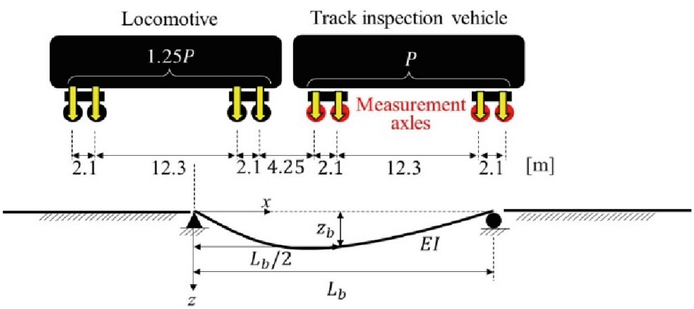

Fig. 3. Schematic showing the modeling of a bridge and the vehicles in a track inspection vehicle.

Next, we modeled the vehicle using moving loads, thus making it a two-vehicle train (the first as the track inspection vehicle and the second as the locomotive). Figure 4 shows the 10 m bridge deflection calculated using this model, including the difference between the two-track irregularities (DTI). We then calculated two 10 m SCTIs on board using the filter in Fig. 2 after calculating the 124 and 134 ACTIs from the axle displacements. When the span length was 10 m, the maximum DTI value was about 0.25 for a maximum bridge deflection of 1, and the conversion factor from maximum DTI to maximum bridge deflection was about 4. Figure 5 shows the conversion factors at various span lengths.

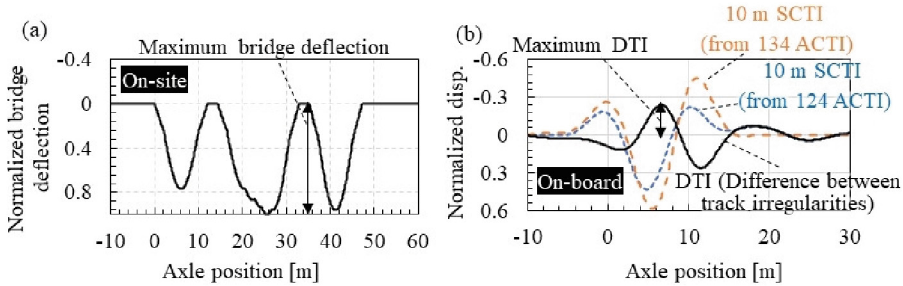

Fig. 4. Schematic showing the (a) quasi-static bridge deflection responses during the passage of the two-vehicle track inspection train and (b) the calculation results from the 10 m SCTIs and DTIs (10-m span length).

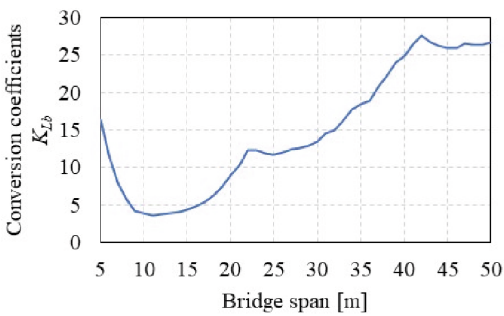

Fig. 5. Schematic showing the conversion factor from DTI to maximum bridge deflection.

2.2 Simulation Setup

Subsequently, we evaluated the adjacent span's impact on the bridge deflection estimation method for three continuous bridges with a span length of 13 m (Fig. 6). The vehicles and bridges were notably modeled using multi-body and beams. Please refer to the literature [6] for details on the vehicle-bridge interaction (VBI) simulation. While Case 0 had no adjacent bridges, Cases 1 and 2 possessed bridges B1 and B2 on both sides of the target bridge A. In Case 1, the maximum deflections of bridges B1 and B2 were half that of bridge A. However, in Case 2, the maximum deflections of the adjacent bridge were similar to that of bridge A. Table 1 shows the simulation cases. Please note that measurement noise and track irregularities other than bridge displacement are not considered here. More detailed sensitivity simulations are future issues.

Based on the simulation results, we finally calculated the 124 and 134 ACTIs, including their actual track measurements. Then, we converted them to 10 m SCTIs and further calculated their differential DTIs, setting the vehicle and bridge specifications based on a reference [7, 8].

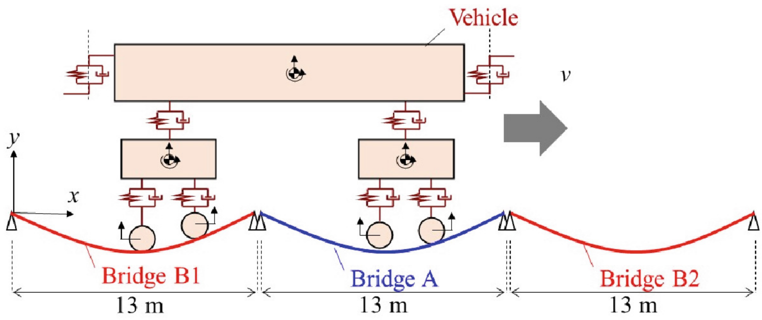

Fig. 6. Schematic showing the VBI simulation model considering the adjacent bridge deflections.

Table 1. Simulation cases.

ID	Adjacent bridge maximum deflection
Case 0	Without adjacent bridges
Case I	0.5 times the target bridge
Case II	Same as the target bridge

3 Results and Discussion

3.1 Effects of Adjacent Span Deflection

Figure 7 shows the deflection responses at the bridges A and B1 midspans obtained from this VBI simulation. We observed that while the maximum bridge A deflection was about 2 mm, the maximum bridge B1's deflection was about 1 mm in Case I and 2 mm in Case II, similar to bridge A. Likewise, the amount of bridge B2's deflection was similar to that of bridge B2.

Conversely, Fig. 8 shows the DTI calculation results for each case. We observed that the DTI in Fig. 8 (a) fluctuated due to adjacent bridge deflections, with the adjacent bridges' deflection being remarkable, especially at both ends of bridge A. However, Fig. 8 (b) shows the result of correcting the DTI at the end of the bridge to 0 to calculate the DTI's

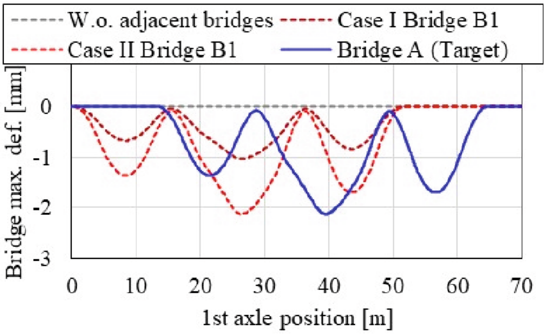

Fig. 7. Schematic showing the deflections for Bridges A and B1 in Cases I and II.

maximum amplitude. Notably, investigations revealed a difference in the maximum DTI value near bridge A's midspan due to the end correction of DTI. The results in Fig. 8 (b) also showed that the maximum DTI value increased due to the adjacent bridge's deflection: the maximum DTI tended to increase as the deflection of the adjacent bridge increased.

Figure 9 shows the error between the estimated maximum bridge displacement using the conversion factor and the maximum bridge displacement at the midspan. These values were calculated by dividing the estimated values using correct values. When an adjacent bridge was observed, the adjacent bridge's deflection increased the DTI's maximum value, overestimating the bridge's deflection compared to when no adjacent bridge existed. Even if the span length was 13 m and the maximum deflection of the adjacent bridge was half that of the target bridge, for example, this non-negligible effect reached 20%.

The conversion coefficients should be calculated after modeling the adjacent bridges to consider the overestimation effect accurately. However, the deflections of adjacent bridges should be updated according to the actual bridges being studied. Therefore, an iterative process is required in which the entire bridge section is modeled, the bridge deflection is estimated sequentially, and the results are considered in the deflection estimation of the adjacent bridges and re-estimated. Therefore, the proposed method, which is theoretical, should be generalized into a finite element (FE) method; that is, estimation using conversion coefficients based on the maximum bridge deflection should be generalized into estimation via FE model updating.

In sections with continuous bridges of almost the same span length and the same type, a simple correction method for the influence of adjacent bridges can be considered by using the conversion coefficients calculated model with adjacent bridges assuming that adjacent bridges have almost the same deflection. In actual settings, if the bridge type and span length are the same, the variation in the maximum bridge deflections of adjacent bridges will be less than 10%. Simulation findings show that the estimation errors are 1.34 and 1.39 when the maximum bridge deflections of the adjacent bridges are 0.9 and 1.1 times the bridge deflection of the target bridge, respectively. Therefore, the effect of the deflections of the adjacent bridges (approximately 4.5%) is reduced to the level of the effect of measurement noise and track irregularity other than bridge deflection by modeling adjacent bridges with the same span length and specifications as the target bridge and then calculating the conversion coefficient using the calculated maximum DTI and maximum bridge deflection.

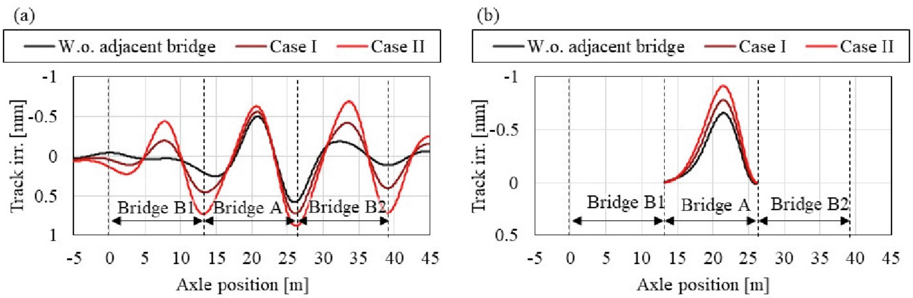

Fig. 8. Schematic showing the calculated DTIs for each case: (a) without bridge edge correction, (b) with bridge edge correction.

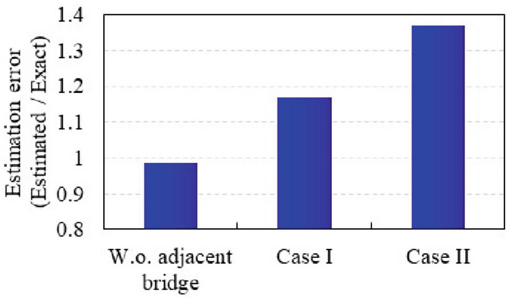

Fig. 9. Schematic showing the estimation errors caused by the adjacent bridge deflections for each case.

4 Conclusions

This study investigated a method for estimating bridge deflections based on two ACTIs for track irregularity inspection vehicles, using the two bogies and four axles frequently used in Japanese railways. Since phase corrections differentiated the two ACTIs through the conversion to two SCTIs, we clarified that the principle of the bridge deflection estimation method using the conversion coefficient proposed in the literature [3] could be applied. Furthermore, although the calculated conversion factors showed high sensitivity to the bridge deflection estimation at span lengths of 10 to 15 m during track inspections based on ACTIs, the bridge deflection of the adjacent bridge was largely affected during the ACTIs measurement, with the adjacent bridge displacements physically influencing track irregularity evaluations. A simple correction method for adjacent bridge deflection and verification on an actual bridge are left as future issues.

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