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Condition Monitoring of Railway Transition Zones Using Acceleration Measurements on Multiple Axle Boxes: Case Studies in the Netherlands, Sweden, and Norway

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Abstract. Railway transition zones connecting conventional embankments and rigid structures, such as bridges and tunnels, usually degrade much faster than other railway sections. Efficient health condition monitoring of transition zones is important for preventative track maintenance. In this paper, a methodology for monitoring railway transition zones using acceleration measurements on multiple axle boxes (multi-ABA) of a passing train is presented. To showcase its capability, the measurements in the Netherlands, Sweden, and Norway are analyzed and discussed. It is found that different bridges and transition zones exhibit unique characteristics including dominant wavelengths and energy distribution. Based on these unique characteristics, the geometry and support conditions at different locations of a transition zone can be evaluated. Higher train speed makes the characteristics more pronounced. The results demonstrate that the multi-ABA measurement has the potential to evaluate and thus monitor the health conditions of various transition zones.

Keywords: Railway Transition Zones · Condition Monitoring · Axle Box Acceleration · Onboard Measurement · Wavelet Analysis

1 Introduction

Railway transition zones are track segments connecting conventional embankments and other civil structures, such as bridges, tunnels, and culverts. Track conditions usually degrade much faster at transition zones than those at other locations due to significant variation in track support properties. For example, in the Netherlands, the maintenance frequency at transition zones can be more than two times higher than that at other track sections [1]. Such frequent maintenance is not only very costly but also largely reduces track availability. Therefore, effective monitoring of transition zones is important for preventative and efficient track maintenance.

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In the literature, to monitor the health conditions of railway transition zones, trackside measurement techniques are commonly used. Coelho, et al. [2] measured the passenger train-induced dynamic responses of a typical Dutch transition zone linking a conventional track and a concrete culvert. The track settlements and pore water pressures were monitored over one year. Stark, et al. [3] reported an instrumentation program which included the measurements of wheel and tie loads, and the permanent and transient vertical displacements as a function of depth at three bridge approach sites in a high-speed line in the United States. More measurements on transition zones can be found in [4–6]. In general, the track-side measurements can capture many details of the transition zones, thus giving specific solutions to the problems. However, such techniques are expensive when multiple transition zones at the network level need to be monitored.

Alternatively, onboard measurement methods, such as axle box acceleration (ABA) measurements, have the potential to enable more efficient condition monitoring of transition zones. The ABA measurement method was developed to detect track defects, such as squats [7] and joint bolt tightness [8]. These defects are generally with short wavelengths. In the present work, the ABA measurement method is extended to be applied to transition zones with relatively longer wavelengths. However, since the design and construction of different transition zones vary significantly, it is challenging to develop a robust method that is applicable to monitoring different transition zones. To achieve this, an in-depth understanding of ABA measurements at different transition zones is essential.

In this paper, we present a methodology for monitoring transition zones of railway bridges using acceleration measurements on multiple axle boxes (multi-ABA) of a passing train. The measurements in the Netherlands, Sweden and Norway are presented as case studies to show the potential of multi-ABA for evaluating the health conditions of railway transition zones.

2 ABA Measurement System and Data Analysis Method

The ABA measurement system consists of accelerometers on multiple axle boxes, a GPS antenna and a tachometer, as shown in Fig. 1. The GPS antenna is on the train roof to record the train's location. The tachometer records the train speed and also helps identify the train's position especially in mountainous areas.

Fig. 1. Multi-ABA measurement system (source of photos: TU Delft OpenCourse Ware)

The sampling frequency of the accelerations is set to 25.6 kHz to acquire sufficient information over a broad range of train speeds. In this paper, focus is on the sleepers, ballast layer and substructures at the transition zones in the low frequency range, usually below 200 Hz. The responses at a transition zone are highly location-dependent. Therefore, the continuous wavelet transform (CWT) method is employed to analyze the axle box accelerations. In CWT, the convolutions of an acceleration are calculated with a group of scaled and shifted wavelet functions. The wavelet coefficient of the acceleration signal $a_{w,r}$ from wheel w and rail r at location x and wavelet scale s ($s > 0$) is [7]:

$$CWT_{w,r}(x,s) = \sum\nolimits_{n=0}^{N-1} a_{w,r}(n)\varphi^{*}\left(\frac{(n-n')\delta_t}{s}\right) \tag{1}$$

where φ is the mother wavelet and the Morlet function is employed here. * denotes a complex conjugate and φ^* is a family of wavelets derived from the mother wavelet by various translation and scaling steps. N is the number of points in the time series, $n = 0, 1, \ldots, N-1$. n' is the continuous variable for the translation, δ_t is the time step.

With multiple-ABA measurements, the acceleration signal $a_{w,r}$ is obtained by averaging the ABAs from 4 wheelsets. In this way, the uncertainty is much less reduced [9]. The wavelet power spectrum (WPS) is defined as the square of the absolute wavelet coefficient:

$$WPS_{w,r}(x,s) = \left|CWT_{w,r}(x,s)\right|^{2} \tag{2}$$

A scalogram is used to visualize the WPS as a function of position and wavelength. The wavelength is obtained from the measured frequency and the train speed.

3 Case Studies

3.1 Measurements in the Netherlands

In the Netherlands, two measurement campaigns were conducted in 2019 between Dordrecht station and Lage Zwaluwe station. There are 9 bridges crossing over rivers and pavements between these two railway stations. More information can be found in the authors' previous work [9]. In the present work, the measurements at the transition zones of a typical bridge are introduced as shown in Fig. 2 below.

The bridge is about 28 m long carrying two ballasted tracks. One of the tracks, as shown with the dashed blue box in Fig. 2(a), is selected because the two measurements on this track are under different train speeds. It can be seen in Fig. 2(b) that, the ABA signals of the two measurements are generally quite similar in shape and trends, but the amplitudes are train speed dependent. The higher train speed results in the larger acceleration amplitude. The insulated joint can be identified.

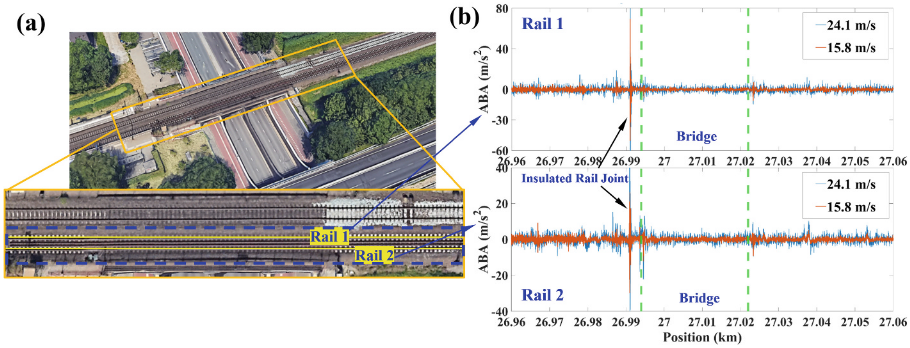

Fig. 2. Aerial photos of the transition zones and time histories of ABA measurements (source of aerial photos: Google Earth)

Figure 3 shows the corresponding WPS of the ABA measurements on the two rails at the transition zones. In Fig. 3, with wavelet analysis, the dominant wavelengths at the transition zones are visible at the high-energy areas. For example, the wavelength of about 0.6 m should be related to the sleeper interval. The sharp spike with broad short wavelength range is the impact induced by a local rail surface irregularity [10], such as an insulated rail joint in this case. The other strong responses with wavelengths longer than 1 m are probably related to the ballast layer and substructures.

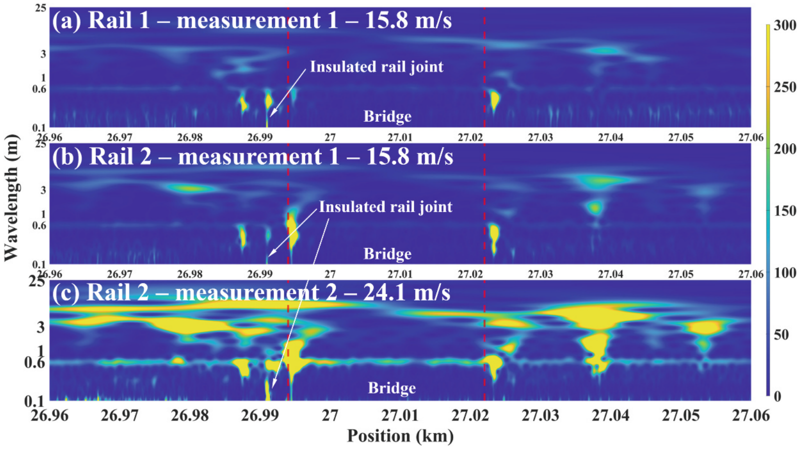

Fig. 3. WPS of the ABA measurements

It can be seen from Fig. 3(a) and (b) that, even though at the same track, the WPS of the measurements at the two rails can be slightly different in terms of the wavelength ranging from 1 to 25 m. It means that the ABA measurement is capable of identifying the slight difference of the supports at the two rails int terms of middle and long wavelength irregularities. With comparison in Fig. 3(b) and (c), it shows more clearly that train speed only affects the amplitude rather than the wavelength contents.

3.2 Measurement in Sweden

In Sweden, the ABA measurement was conducted in a mixed traffic line between Boden station and Murjek station. This railway line has only one ballasted track. As shown in Fig. 4(a), there is a culvert, with the length of 8.15 m in total, including a 4.2 m deck and two approach slabs at the two sides, each with the length of about 2 m. There were cracks found at the culvert abutment, so two steel beams were installed to help support the deck. The WPS of the ABA measurement over this culvert and the transition zones is shown in Fig. 4(b). It can be seen in Fig. 4(b) that, the effects of the welds can be easily identified. The sleeper interval related patterns are obvious. One unique characteristic is that quite strong response on the culvert is found, as shown with the large high energy areas both at rail 1 and rail 2 in wavelength range from about 3 m to 10 m. This is probably because of the dynamic characteristics of the degraded culvert structure. The origin of the dynamic characteristics can be verified by in-track tests, such as hammer tests.

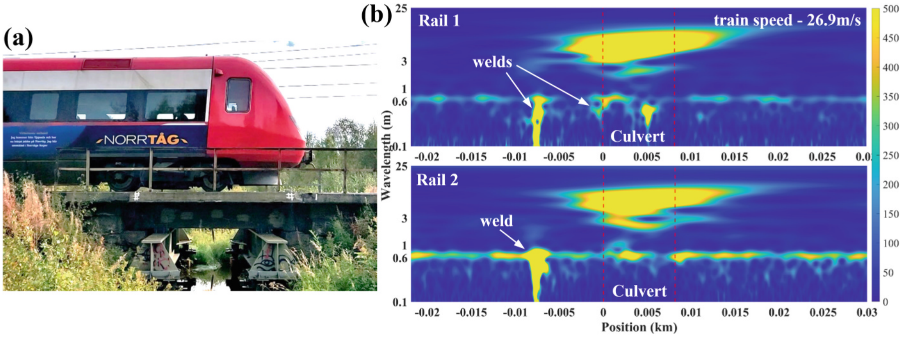

Fig. 4. ABA measurement at a culvert in Sweden

3.3 Measurement in Norway

In Norway, there is a concrete bridge with the length of about 53 m between Sosterbekk station and Katterat station, as shown in Fig. 5(a). At the transition zones, there was differential settlement due to the large variation in track support stiffness. In Fig. 5(b), at the abutments, as shown with the white dash box, high-energy areas with wavelengths about 1–10 m, are found due to the bumps caused by differential settlement. The sleeper interval-related patterns are still obvious but not so distinguishable from the patterns with shorter wavelengths, which is probably because of the short sleeper interval of 0.52 m, making the discrete rail support effect less pronounced.

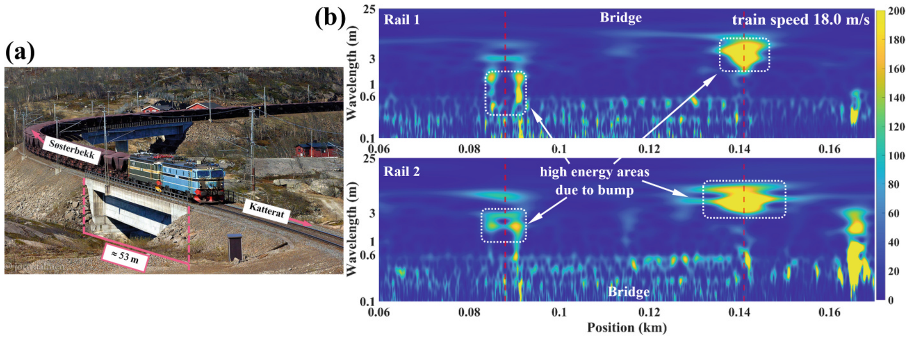

Fig. 5. ABA measurement at a bridge in Norway (source of aerial photos: https://www.arctictrains.com/Ofotbanen/i-DgW4F7N)

4 Conclusions and Future Work

In this paper, using multi-ABA measurements for health condition monitoring of transition zones is introduced and showcased with measurements in the Netherlands, Sweden and Norway. It is found that different bridges and transition zones exhibit unique characteristics including dominant wavelengths and energy distribution. Based on these unique characteristics, the geometry and support conditions at different parts of a transition zone can be evaluated. Higher train speed makes the characteristics more pronounced. These results demonstrate that the multi-ABA measurement has the potential to evaluate the health conditions of different transition zones.

In the future, local dynamic tests and numerical studies can be conducted to further interpret the ABA measurement results thus to make the multi-ABA measurements more applicable for the health condition monitoring of railway transition zones.

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