Fault detection of railway track by multi-resolution analysis

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Abstract

Conditions of track have conventionally been measured by using exclusive inspection vehicles. If the conditions of the track can be detected by attaching simple sensors such as accelerometers on board of commercial vehicles, more efficient maintenance of tracks would be possible. This paper describes rail corrugation detection from the vertical acceleration of a vehicle body by time-frequency analysis. An actual vehicle running tests on a commercial line was conducted, in which vertical acceleration of axle-boxes and a vehicle body were measured. In this paper we show the rail corrugation can be detected from the vertical acceleration of a vehicle body by multi-resolution analysis (MRA) using wavelet transform.
Keywords: railway, spectrum analysis, diagnostics, rail corrugation, fault detection, wavelet, multi-resolution analysis.

1 Introduction

Faults of railway tracks not only cause deterioration in ride quality but also generate noise and have the potential to cause serious accidents. The track faults have conventionally been measured using exclusive track inspection vehicles. However, this method is costly and is therefore not widely employed on local and sub-main lines. It also has a problem in that very frequent inspections cannot be made if schedules are overcrowded, even on priority lines.

If faults can be detected by attaching simple sensors such as accelerometers to commercial vehicles, more efficient maintenance of tracks would be possible. Such vehicles are called "probe-vehicles". In order to put "probe-vehicles" to

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practical use, estimation of the vehicle's state, by pulling out the necessary information from among the information on track irregularities and the measurement noises of the sensors, is required.

This paper proposes the methods to detect a rail corrugation by using a wavelet transform from the acceleration measured in a vehicle body on board.

2 Measurement test with actual vehicle

2.1 Rail corrugation

Rail corrugation is minor wear and has a wave height of 0.1 mm and a wavelength of 5–10 cm occurring on the rails; it generates both damage to rails and noise [3–6]. It occurs mainly in the inner rails in steep curves such as shown in fig. 1

Figure 1: Example of rail corrugation.

2.2 Measurement test

Vertical and lateral accelerations of the vehicle body and the axle-box were measured with accelerometers, and exterior noise was also measured with microphone at the one of the main line in Japan (fig. 2). Focusing on the vehicle body acceleration as the object of the analysis, we attempted to extract the corrugation information.

2.3 Test results

Fig. 3 shows the measurement result of the curved section with significant corrugation. This is the measurement result for traveling a curve with a radius of 202 m at a constant speed of 38 km/h. A comparison of vertical acceleration of the right and left axle-boxes, shown in figs. 3(a) and figs. 3(b), respectively, shows that the left axle-box, i.e. the inner-rail side, vibrates more strongly. This is a characteristic of corrugation in steep curves and confirms the occurrence of corrugation on an inner-side rail.

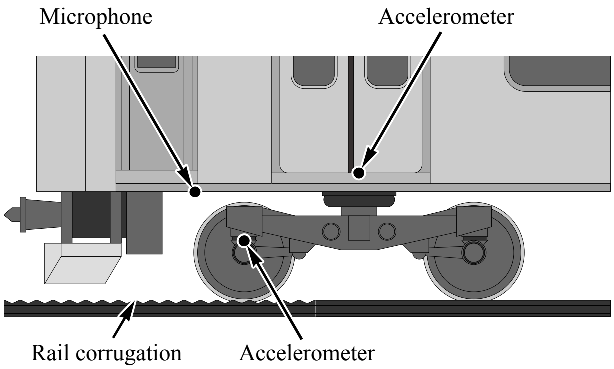


Figure 2: Position of sensors attached.

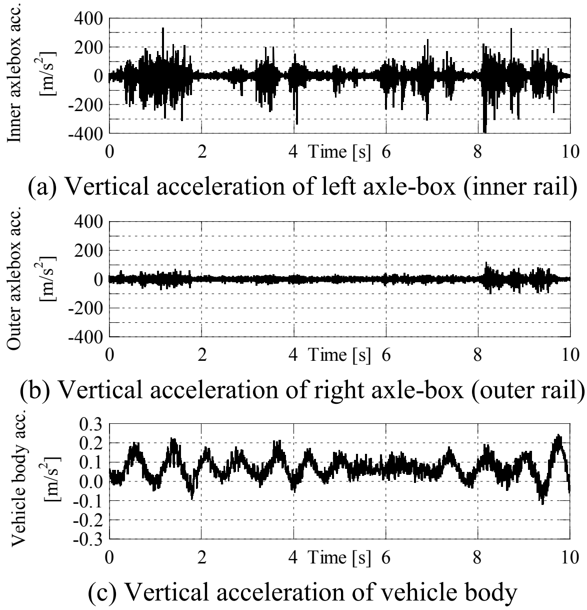


Figure 3: Measurement results of curved section with corrugation.

In order to show a comparison with a case where there is no corrugation, the measurement result of the straight section is shown in fig. 4. The travel speed was 38 km/h, as in the case for the curved section. The vertical accelerations of the both right and left axle-boxes are extremely small in comparison with those measured in the curved section shown in fig. 3. A difference in the accelerations due to presence of corrugation is noticeable on the axle-boxes, particularly on the inner-rail side. The corrugation of this example could possibly be detected comparatively easily by methods such as threshold-value treatment.

However, when converting a commercial vehicle into a "probe-vehicle" by attaching sensors, the introduction can be made more easily by attaching sensors at locations as easily accessible as possible. This means that if track faults can be detected by accelerometers equipped in a vehicle cabin, fault detection of rails can be made without modifying a vehicle, leading to easier introduction.

The results for the curved section (fig. 3(c)) and the straight section (fig. 4 (c)) show that the vertical accelerations of the vehicle body measured on the floor of a cabin are greatly influenced by first resonance frequency of the vehicle body and thus, vibration due to the corrugation decays. These results indicate that detection of corrugation from the vehicle body accelerations requires special signal processing to extract the signal due to the corrugation.

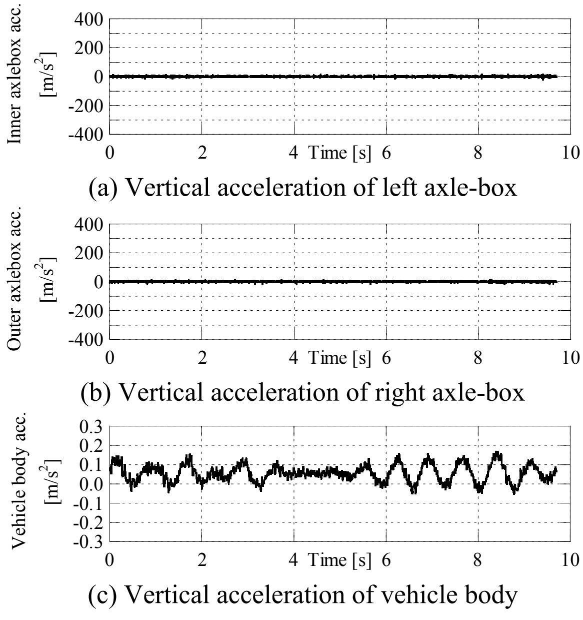
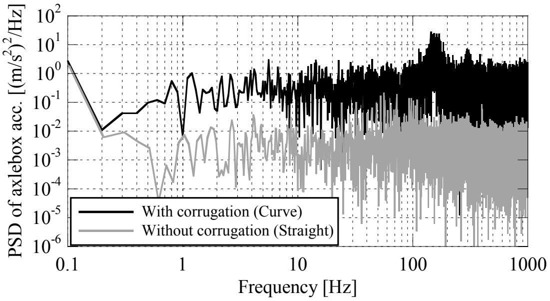


Figure 4: Measurement results of straight section without corrugation.

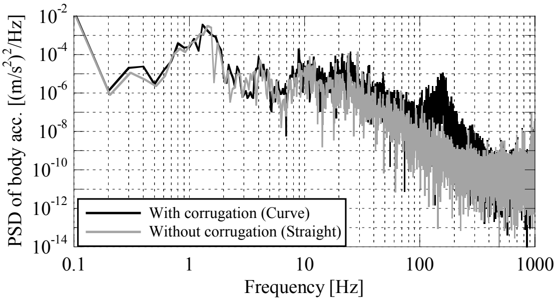
3 Detection of rail corrugation

3.1 Comparison through frequency analysis

Since corrugation is a periodic on the rail surface, it was possible that the use of a frequency analysis would be able to extract its characteristics. PSDs were obtained from the data on the sections with and without corrugation (fig. 3 and fig. 4, respectively), and the results are shown in fig. 5. Fig. 5(a) shows the PSD of the vertical acceleration of the axle-box of the inner-rail side. The curved section with corrugation has a higher level than the straight section over the entire frequency range and has a peak at approximately 160 Hz. Since the travel speed was 38 km/h, a wavelength of 6.9 m can be obtained from the peak frequency. This agrees with the general wavelength range of corrugation, and therefore the peak is considered to be caused by corrugation.



(a) PSD of acceleration of inner axle-box



(b) PSD of acceleration of vehicle body

Figure 5: PSD with and without corrugation.

Fig. 5(b) shows the PSD of the vertical acceleration of the vehicle body. The peak at 1–2 Hz is considered to represent the natural frequency of pitch of the vehicle body. In the curved section with corrugation, a peak is observed at approximately 160 Hz, as was found on the axle-box, indicating that vibration caused by corrugation is included in the vehicle body vibration. The presence of corrugation can be recognized through a frequency analysis. However, identification of the actual location of its occurrence requires a time-frequency analysis.

3.2 Time-frequency analysis using wavelet transform

3.2.1 Wavelet transform

Fourier transform is frequently employed for extracting frequency information from time history. However, it has the problem of losing time information that is important for determining the locations of faults. Although a windowed Fourier transform can solve this issue, it is not fit for detecting unknown signals. The result depends on size of the window. Small window cannot see low frequency. Large window blurs the rapid changes to the whole of the window.

Wavelet transform [2] is the expansion of Fourier transform. In wavelet transform, a signal $S(t)$ is described by shifting and scaling a small wave, $\psi(t)$, called a mother wavelet. The signal is analyzed on the basis of the mother wavelet transform. A continuous wavelet transform (CWT) is given by:

$$\left(W_{\psi}S\right)\left(a,b\right)=\int_{-\infty}^{\infty}\frac{1}{\sqrt{a}}\overline{\psi\left(\frac{t-b}{a}\right)}S(t)dt \tag{1}$$

$\psi((t-a)/b)$ shifts the time (phase) by b and makes the frequency $1/a$. This continuous wavelet transform, however, requires a considerable amount of computation, and information is redundant. Therefore, by making $a=2^{m}$ and $b=2^{m}n$ in eqn (1), we obtain:

$$D_{m,n}=\int_{-\infty}^{\infty}S(t)\psi_{m,n}(t)dt \tag{2}$$

where:

$$\psi_{m,n}(t)=2^{-m/2}\psi\left(2^{-m}t-n\right) \tag{3}$$

which is called a discrete wavelet transform (DWT). This discrete wavelet transform is characterized by more efficient translation of signals.

3.2.2 Multi-resolution analysis

Multi-resolution analysis (MRA) decomposes a signal into a number of components at different resolution by using the discrete wavelet transform. A time history $S(t)$ is decomposed into some detailed (high-frequency) components and an approximated (low-frequency) component. The original signal $S(t)$ given by:

$$S(t)=S_{m0}(t)+\sum_{m=-\infty}^{m0}d_{m}(t) \tag{4}$$

where d_m are detailed components:

$$d_{m}(t)=\sum_{n=-\infty}^{\infty}D_{m,n}\psi_{m,n}(t) \tag{5}$$

In the wavelet transform, the choice of a mother wavelet $\psi(t)$ is important. We employed *Daubechies* wavelet [1], which is orthonormal base and compactly supported wavelet. The vanishing moments of *Daubechies* wavelet can be changed by index N. We decided to use a relatively high-order generating index, $N = 7$ (fig. 6).

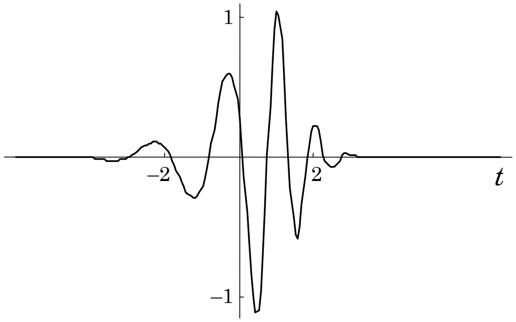


Figure 6: Daubechies wavelet (N=7).

3.2.3 Detection of corrugation through multi-resolution analysis

We propose a multi-resolution analysis to the vertical acceleration of a vehicle body, as measured on the vehicle cabin, in order to introduce a corrugation detection method in existing commercial vehicles.

The results of the multi-resolution analysis of the vertical accelerations in the curved and the straight section (fig. 3(c) and fig. 4(c), respectively) are respectively shown in fig. 7 and fig. 8. Because the sampling frequency was 2 kHz, d_1, d_2, d_3, d_4, and a_4 correspond to approximately 500–1 k, 250–500, 125–250, 62.5–125 Hz, and frequencies not greater than 62.5 Hz, respectively. A comparison between fig. 7 and fig. 8 shows that the components d_2 through d_4 for the case with corrugation, fig. 7, have larger amplitudes. Component d_3, in particular, which includes the frequency, 160 Hz, for corrugation, shows conspicuous acceleration, which is of a waveform similar to that for the axle-box shown in fig. 3(a). This result indicates that the vibration component due to corrugation can be extracted from the acceleration of a vehicle body by using a multi-resolution analysis.

The result of the analysis with a *Daubechies*' generating index N of 7 is shown here. As a result of analyses with varied N's, we attained good detectability with $N \geq 4$ for corrugation.

4 Conclusions

With the aim of equipping a commercial vehicle with lowcost sensors and thus putting into operation a "probe-vehicle" that would enable track inspection, we studied methods of detecting rail corrugation from data measured on a vehicle. We obtained the following conclusions:

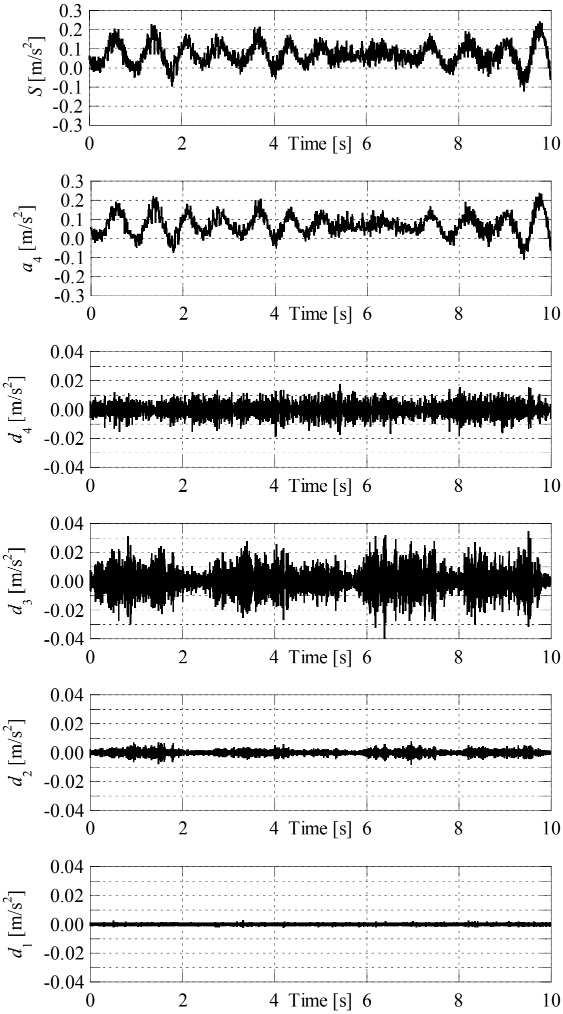


Figure 7: MRA of acceleration of vehicle body with corrugation (curved section).

(1) While the vehicle was traveling on rail corrugation during the field test clear vertical vibration occurred on the axle-box on the inner-rail side. However, detection of corrugation from the amplitude of the acceleration of the vehicle body was difficult because it includes large amount first resonance vertical vibration mode.

(2) Frequency analyses revealed peaks in all spectra of acceleration and the noises of the axle-boxes and vehicle body in the section with corrugation, and it was clear that corrugation generated periodic vibration.

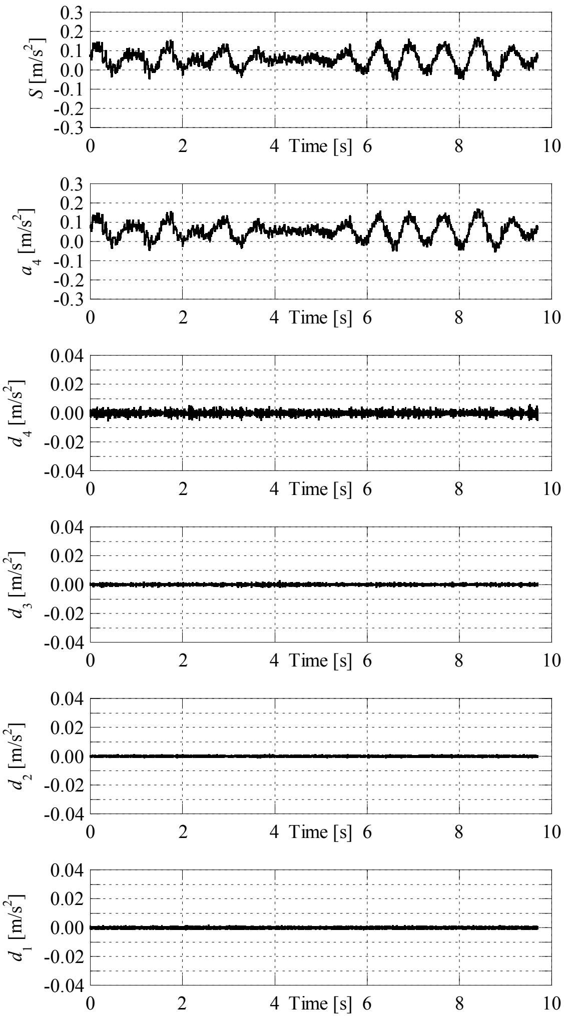


Figure 8: MRA of acceleration of vehicle body without corrugation (straight section).

(3) Multi-resolution analyses were carried out using wavelet transform, and vibration component for corrugation was extracted from detailed component (d_3) including frequency of corrugation. This verified that corrugation could be detected from the acceleration of a vehicle body.

Here, we have focused on the study of corrugation as one track fault. The application of these methods to other track irregularities is conceivable as a future expansion of this research. Since the detectability of discontinuity is part of the character of the wavelet transform, we expect that it will be possible to detect impulse-like signals such as abnormalities of rail joints.

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