Chapter 5

Development of Track Condition Monitoring System Using On-board Sensing Device

Hitoshi Tsunashima, Hirotaka Mori, Masayuki Ogino and Akira Asano

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61077

Abstract

Monitoring the conditions of railway tracks is essential for ensuring the railway safety. In-service vehicles equipped with sensors and GPS systems can act as probes to detect and analyse real-time vehicle vibration. Recently, a compact on-board sensing device has been developed. This chapter describes the track condition monitoring system that uses a compact on-board sensing device and diagnosis software. The diagnosis software provides the function of detecting track faults using the root mean square (RMS) of the car-body acceleration. It also allows analysis in the time-frequency domain using wavelet transform. A monitoring experiment in a local railway line showed that the system is effective for practical application.

Keywords: Safety, Track, Condition monitoring, Fault detection, Vibration, Wavelet, Multiresolution analysis

1. Introduction

Preventive maintenance, in which responsible persons recognise unsafe or risky conditions and instigate repairs before accidents occur, has become an important issue for railways [1,2]. To facilitate preventive maintenance, it is desirable to monitor track conditions either continuously or at high frequency levels. Currently, the methods utilised for track monitoring include observations by trackmen, as well as the use of specialised track inspection and rail flaw detection cars. However, while these methods allow highly accurate track monitoring, the operational frequency at which they can be deployed to monitor tracks is extremely limited due to considerations such as cost and sustainability controls. Additionally, local railways suffer not only from significant age-related facility deterioration but also from difficulties in securing funding and maintaining technological advancements, which means that many railway operators are unable to perform adequate monitoring.

In-service vehicles equipped with simple sensors and GPS may serve as probes to detect and analyse real-time vehicle vibration and signalling systems while running. Probe vehicles [3,4] may dramatically change the current style of rail maintenance and thus contribute to establishing safe transport systems.

The probe vehicles can change the current maintenance style to focus on locations regarded as essential maintenance areas, utilising data acquired by real-time monitoring of actual vibration together with positional information obtained by GPS. Monitoring based on information obtained by in-service vehicles may enable the detection of maintenance problem at an early stage [4], thus contributing to the revitalisation of local railways by making maintenance tasks more efficient.

In response to these challenges, the use of probe vehicles, which consist of in-service vehicles to which simple sensors have been added, can be considered as a plausible technique for monitoring track conditions during the course of commercial operations. Previously, portable on-board devices have been developed to allow diagnostic track monitoring [5-8]. A number of long-term experimental studies conducted in cooperation with railway operators have demonstrated the feasibility of pinpointing the locations of track faults and the reproducibility of measured data.

In this chapter, we describe a compact on-board sensing device that represents an improvement on portable probe devices [8,9] along with a track condition monitoring system that utilises track condition monitoring software[10]. We then present an example of the diagnostic results obtained using this monitoring software. The root mean square (RMS) value of the vibrational acceleration was used as an assessment index in diagnosing rail condition. In addition to the RMS value of the vibrational acceleration, wavelet transforms are used in order to develop a system capable of more accurate diagnoses.

2. Track condition monitoring system

2.1. System overview

Several kinds of track faults can be detected by measuring the acceleration of bogies [11-13]. However, if track faults can be detected in-cabin, condition monitoring of track irregularities will be much easier. As the distinctive signal of track faults is hidden in natural frequency of car-body vibration, signal processing is necessary for the acceleration measured in-cabin to detect track faults.

Figure 1 shows a schematic overview of the track condition monitoring system. This system is divided into a vibration measurement unit and an analysis unit. The vibration measurement unit utilises a compact on-board sensing device to measure the vehicle vibration from within the car itself during ordinary commercial operation. The analysis unit uses track condition monitoring software to extract the requisite information from the measured data and then computes assessment values to diagnose the track condition. The compact on-board sensing device is described in Section 2.2, while the monitoring software is described in Section 2.3.

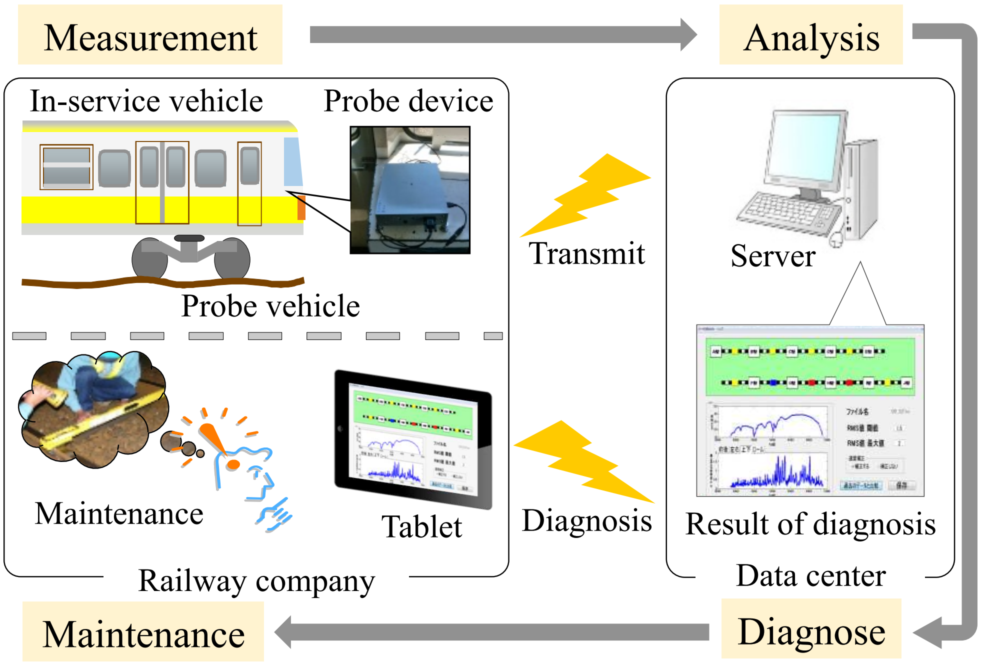

Figure 1. Track condition monitoring system [10]

The measured data obtained from the measurement unit are transmitted to the analysis unit either by a cellular telephone channel or by writing to external media. The diagnostic results produced by the track monitoring software are used to provide feedback to railway operators through online channels via smartphones or tablet computers. Railway operators can use this information to establish the track maintenance priorities, thus facilitating the maintenance planning and work.

In addition, the real-time measurement of railcar vibrations during commercial operation allows for rapid response, such as emergency track inspection and maintenance, in situations when railcar vibration observations detect irregularly large deviations from standard control values. Thus, the use of this monitoring system to perform continuous monitoring of railcar vibrations allows early detection of deterioration or other track irregularities, thus enabling railway operators to conduct effective maintenance work [9].

2.2. Compact on-board sensing device

Figure 2 shows the compact on-board sensing device used in the track condition monitoring system. This device comprises three-axis acceleration sensors, a rate gyroscope, a Global Positioning System (GPS) receiver that is used to determine the train position and travel speed and sensor interfaces that input sensor signals to a computer.

This device is battery-powered and capable of up to 6 h of sustained operation. Thus, the device need only be placed inside a cabin to enable vehicle vibration measurements and does not require human supervision. If the vehicle is equipped with an on-board power supply, the

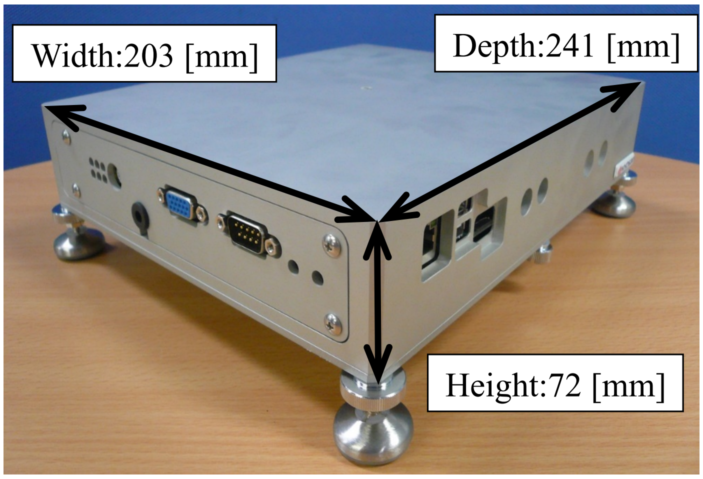

Figure 2. Compact on-board sensing device [10]

device is capable of continuous measurement. Furthermore, the device is equipped with function for automatically transmitting measured data to a server via cellular phone channels and writing data to a microSD card or other recording media. By further equipping the device with a noise meter, it is also possible to diagnose corrugation conditions from cabin noises.

2.3. Monitoring software

Using the compact on-board sensing device to diagnose track conditions required the development of an interface on the software side that is capable of establishing communication with the on-board devices and that offers features such as efficient handling of the large volumes of measured data that accumulate from the devices. It was also necessary to create visualisations to display the monitoring results and reduce the time interval required between measurement and diagnosis. Accordingly, we chose to implement a graphical user interface (GUI) for signal-processing operations on measured data and result visualisation in MATLAB (MathWorks). The following section discusses these operations in more detail.

3. Track monitoring software

3.1. Assessment indexes

Track irregularities not only cause vehicle vibrations that degrade rider comfort, they also increase the risk of derailments. For this reason, they are among the most important items to be monitored. Vehicle vibrations are strongly correlated with track irregularities, so the magnitude of vehicle vibrations is an effective means of assessing general track condition trends [2]. For this reason, sections of track over which high rates of vehicle vibrational acceleration are detected may be understood as indicative of degraded track conditions.

This monitoring software takes the amplitude of the vibrational acceleration as an index of track faults. The RMS value of this amplitude is then extracted and used to assess track conditions. However, because this assessment value alone does not convey frequency information, we augment it by performing time-frequency analysis using continuous and discrete wavelet transforms to obtain more detailed diagnostic information.

3.2. RMS values

We need to obtain localised RMS values over short time intervals to obtain the relationship between track condition and position. The RMS value may be obtained from measured values over a short time segment (the number of the data: N) at the time t according to

$$x_{rms}(t) = \sqrt{\frac{1}{N}\sum_{\tau=t}^{t+N-1} x(\tau)^2}. \tag{1}$$

Track irregularities include longitudinal level irregularities, alignment irregularities and cross level irregularities. To assess the longitudinal level irregularities, we determine the RMS values of the vertical acceleration measured by the compact-size on-board sensing device. Here we compute RMS values using N = 26 and a sampling time of 0.012 s.

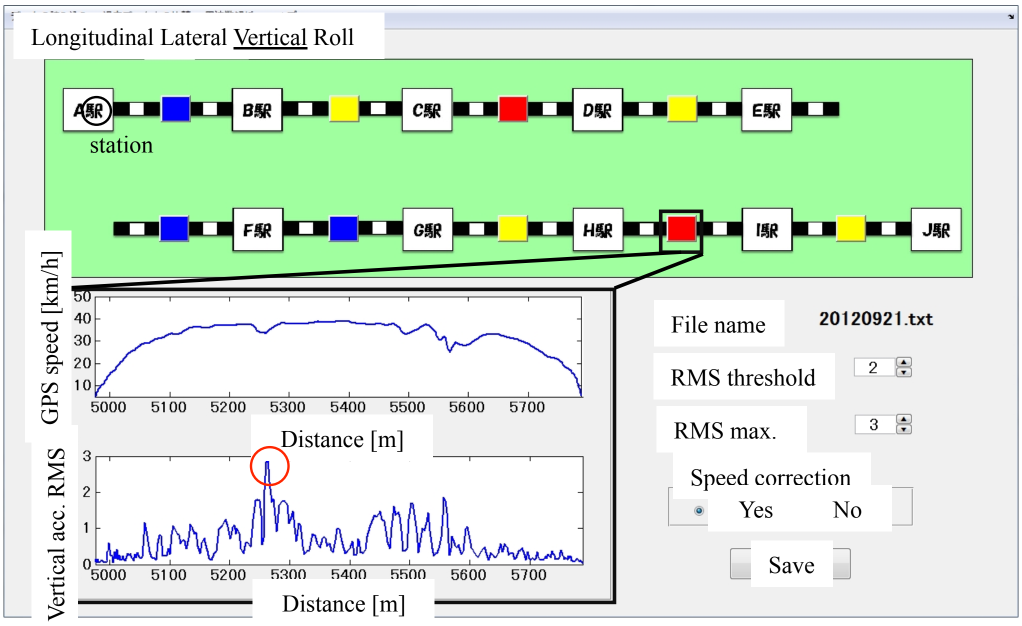

Figure 3. The main window of the track monitoring software [10]

Figure 3 shows the main window of the track monitoring software. The display here is an example of the analysis of actual measured data from a regional railway, as discussed in Section 5 below. The main window indicates an assessment of track condition based on the RMS value of the vibrational acceleration computed using Eq. (1). The track diagrams in the upper portion of Figure 3 indicate colour-coded assessments of track conditions for each station-to-station segment. The different colours (red, yellow and green) indicate the RMS value of the vibrational acceleration referenced to the threshold value determined for the system.

The lower part of Figure 3 shows the RMS value of the actual measured value and the travel speed for a selected station-to-station segment. By inspecting regions with large RMS values, it is possible to clarify the position at which track faults arise.

The upper portion of Figure 4 compares travel data for multiple journeys on specific station-to-station segments. Points at which the preset threshold value (2.0 m/s^2) was exceeded are plotted. The point at 5260 m was plotted a large number of times, suggesting the possibility of a track fault at that location. The lower portion of Figure 4 displays the RMS values (maximum values) of the points circled by the dashed-line curves in the upper portion for each of several dates. The decrease in the RMS value reflects the effect of repair work carried out between September 2012 and February 2013. This shows that the system enables specific points to be identified as segments requiring inspection, thereby facilitating long-term monitoring of track maintenance.

Consequently, whereas assessments of travel data from a single journey (Figure 3) fail to yield accurate assessments in some cases, assessments of travel data from multiple journeys (Figure 4) can allow accurate diagnoses based on the frequency with which track faults arise.

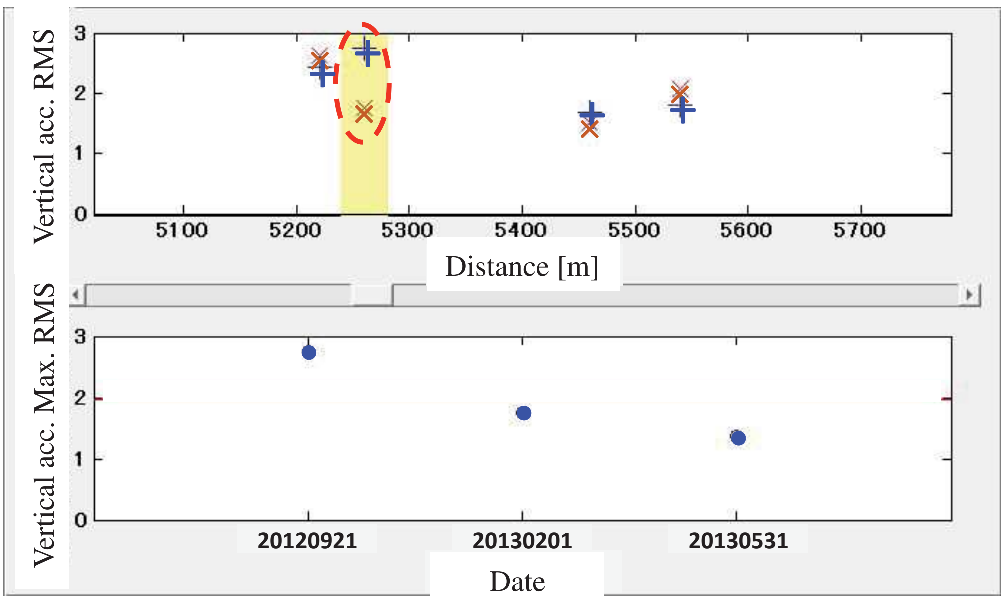

Figure 4. Assessments of travel data from multiple journeys [10]

3.3. Assessment using a continuous wavelet transform

In the previous subsection, we discussed the use of RMS values for simple monitoring of track conditions. However, assessments based on RMS values do not furnish frequency information and are thus poorly suited for characterising many varieties of track faults. To remedy this deficiency, in this subsection, we discuss an analysis based on the continuous wavelet transform, which is a method of time-frequency analysis, as a technique for yielding more detailed diagnostics.

The continuous wavelet transform proceeds by multiplying a target waveform $x(t)$ by a mother wavelet $\psi(t)$. This is a transformation technique that has the effect of emphasising certain portions of the waveform and suppressing others. The technique, which is well suited to the analysis of unsteady signals exhibiting sudden variation, is defined by

$$(W_{\psi}x)(a,b) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{a}} \overline{\psi}\left(\frac{t-b}{a}\right) x(t)dt. \tag{2}$$

The parameters a and b are known, respectively, as the dilatation and location parameters; they have the effect of translating in time the mother wavelet $\psi(t)$ by a time shift b and $1/a$ on frequency. $\overline{\psi}(t)$ indicates the complex conjugate of $\psi(t)$.

Figure 5 shows a real-world example of the continuous wavelet transform feature implemented by the monitoring software. Users may select a station-to-station segment to display target vibrational acceleration waveforms, and their wavelet transforms, for that segment. The signal plane of the continuous wavelet transform is expressed by contour lines; colours closer to white correspond to larger amplitudes and contain large numbers of corresponding frequency components. The vertical axis of the signal plane displays the pseudo-frequency as obtained by conversion of the scale value.

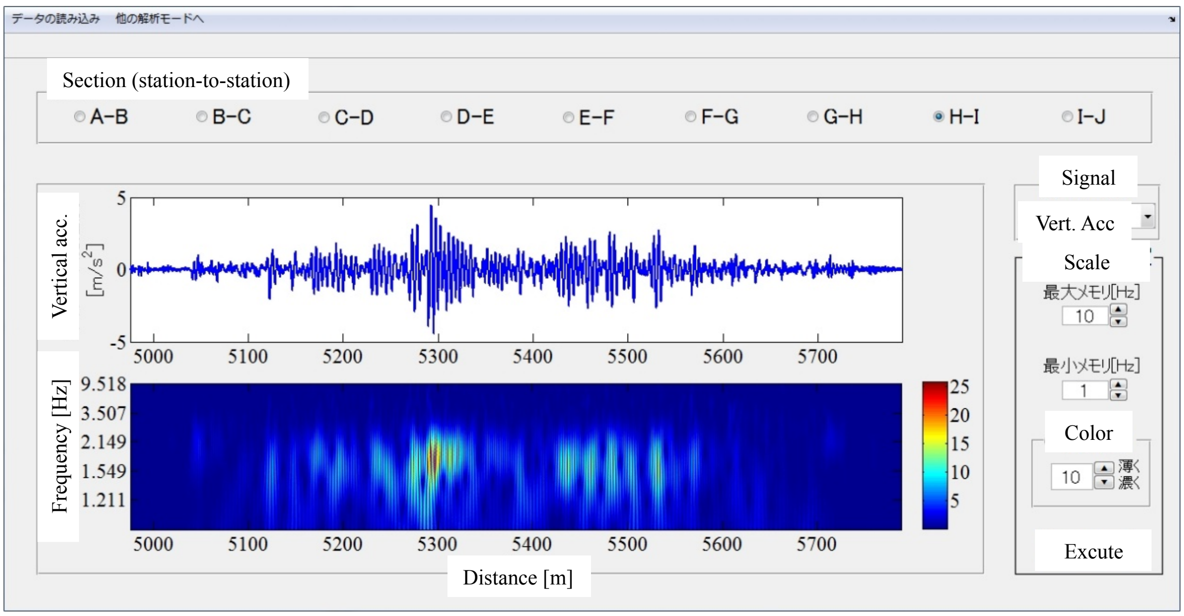

Figure 5. Real-world example of the continuous wavelet transform [10]

3.4. Discrete wavelet transform

Visualising analytical results based on continuous wavelet transform contour line maps is a convenient method of displaying for learning the properties of signals. However, for signal processing carried out by arithmetic operations, displaying information results by superposing multiple pieces of information is not always efficient. For this reason, we discretise the parameters a and b in Eq. (2) to give the following discrete wavelet transform:

$$D_{m,n} = \int_{-\infty}^{\infty} \psi_{m,n}(t)x(t)dt, \tag{3}$$

where

$$\psi_{m,n}(t) = 2^{-m/2}\psi(2^{-m}t - n). \tag{4}$$

Integer m and n are the scaling and the dilation parameters, respectively.

We now use this discrete wavelet transform to perform multiresolution analysis. In multiresolution analysis, a target signal $x(t)$ is decomposed into approximation coefficients (representing its low-frequency components) and multiple detail coefficients (representing its high-frequency components). Using the discrete wavelet transform with the decomposition level m_0, the signal $x(t)$ may be expressed as

$$x(t) = \sum_{n=-\infty}^{\infty} A_{m_0,n}\phi_{m_0,n}(t) + \sum_{m=-\infty}^{m_0}\sum_{n=-\infty}^{\infty} D_{m,n}\phi_{m,n}(t), \tag{5}$$

where $\phi_{m,n}(t)$ are scaling functions, defined by

$$\phi_{m,n} = 2^{-m/2}\phi(2^{-m}t - n). \tag{6}$$

The coefficients of the approximation component may be computed according to

$$A_{m,n} = \int_{-\infty}^{\infty} \phi_{m,n}(t)x(t)dt. \tag{7}$$

The detail coefficients of the signal at level m are given by

$$d_m = \sum_{n=-\infty}^{\infty} D_{m,n}\psi_{m,n}(t). \tag{8}$$

http://dx.doi.org/10.5772/61077

Thus, the original signal $x(t)$ may be expressed in the form

$$x(t) = a_{m_0}(t) + \sum_{m=-\infty}^{m_0} d_m(t). \tag{9}$$

Figure 6 shows the results of a multiresolution analysis via discrete wavelet transform carried out by the monitoring software. Using this feature, the car-body vibrational acceleration of each station-to-station segment may be decomposed at any desired level, and the signal may be reconstructed from the required components. Thus, by inspecting particular components, it should be possible to detect track faults corresponding to those components. The decomposition level m_0 must be chosen appropriately based on the sampling frequency and the frequency band from which one wishes to extract features.

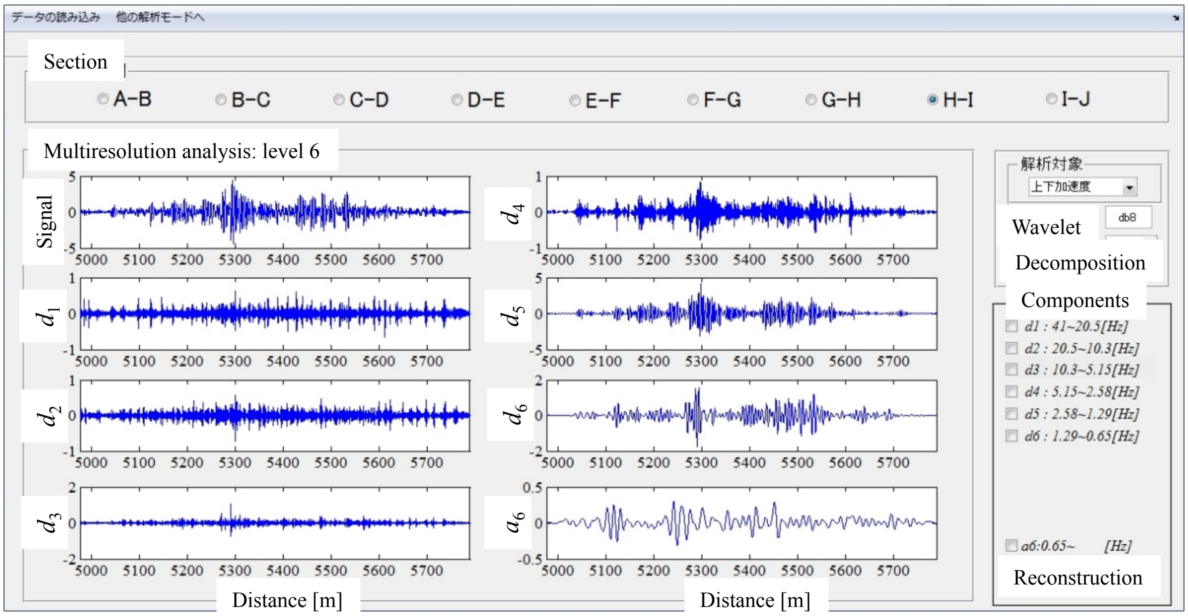

Figure 6. Multiresolution analysis via discrete wavelet transform (decomposition level m_0: 6) [10]

4. Simulation

The track condition monitoring system in this study is premised on the use of vibrational measurement devices to measure the vehicle vibrational acceleration. For this reason, we used simulations to investigate whether different types of track faults, including longitudinal level irregularities, corrugations and level differences in rail joints, may be detected from data on vehicle vibrational acceleration.

- Vehicle model

Figure 7 shows the vehicle model used in the simulation. The vehicle model is a linear model of a single car that considers two degrees of freedom (vertical motion and pitch) for the car body and two degrees of freedom (vertical motion and pitch) for each bogie, yielding a total of six degrees of freedom. The car runs at a speed of 50 km/h over a straight-line segment of track of length 300 m. Table 1 lists the parameters of the vehicle model.

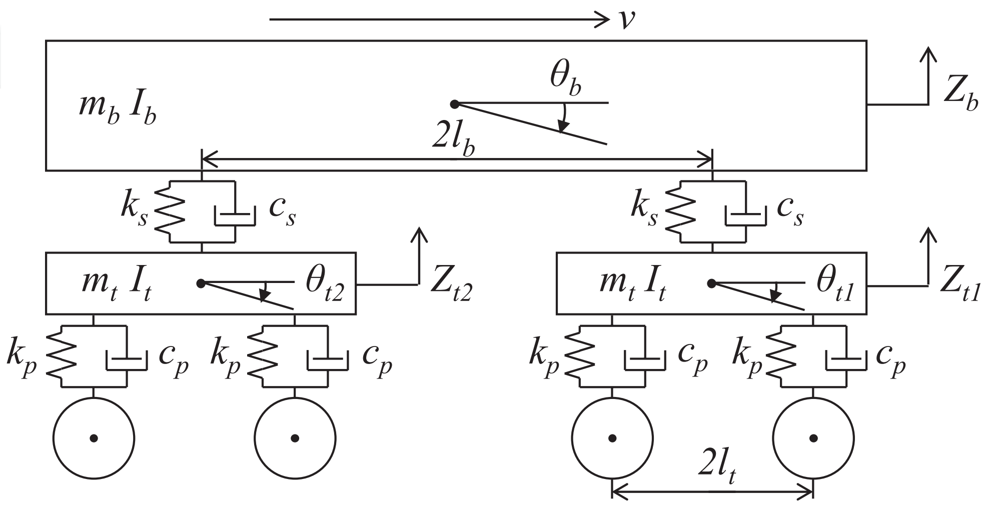

Figure 7. Vehicle model [10]

Symbol	Description	Unit	Value
m_b	Car-body mass	kg	14600
m_t	Truck mass	kg	2400
I_b	Car-body inertia	kgm^2	500452
I_t	Truck pitch inertia	kgm^2	2773.5
$2l_b$	Car-body base	m	14.1
$2l_t$	Wheel base	m	2.15
k_p	Primary suspension vertical stiffness	kN/m	1090
k_s	Secondary suspension vertical stiffness	kN/m	329
c_p	Primary suspension vertical damping	kNs/m	19.6
c_s	Secondary suspension vertical damping	kNs/m	27.2
v	Vehicle speed	km/h	50

Table 1. Vehicle parameters

- Track geometry

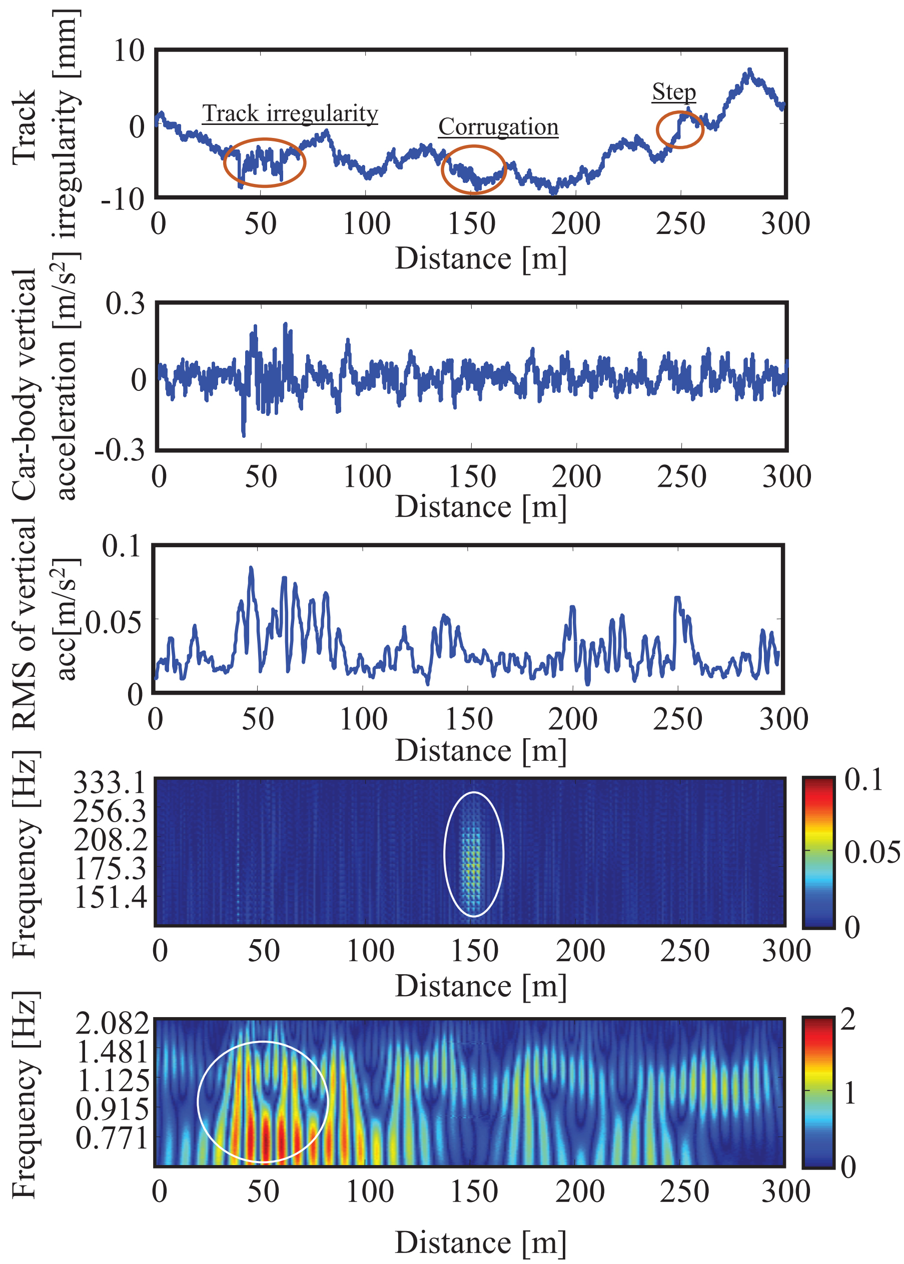

Figure 8. Assessments of the simulated data [10]

We created track geometry data whose frequency characteristic was inversely proportional to the spatial frequency; that is, the amplitude was larger at long wavelengths and smaller at short wavelengths.

Irregularities such as longitudinal level irregularities, corrugations and level differences in rail joints were artificially added to the basic track geometry waveforms constructed. The amplitude of the longitudinal level irregularities for positions between 40 and 60 m was set equal to two times the reference track irregularity. Corrugations were added over a 10 m stretch of track between positions 145 and 155 m; the corrugations were sinusoidal with total amplitude of 1 mm and a frequency of 175 Hz. The wavelength in this case is 0.08 m. At the 250 m position, we created a step-shaped level difference of 2 mm. These track irregularities are shown in the top part of Figure 8.

- Car-body vertical acceleration

We input the track geometry data, including the constructed irregularities, to the vehicle model of a single railcar shown in Figure 8 and then computed the car-body acceleration (in the vertical direction) above the centre of the front bogie. The sampling frequency was set to 820 Hz, the same as that of the vibrational measurement device. To the acceleration data computed in this way, we added white noise to represent observation noise and then output these data as the acceleration data (the second part from the top in Figure 9). The standard deviation of the measurement noise was 10^{-3} m/s^2.

- RMS values for the car-body vertical vibration acceleration

Using Eq. (1), we determined the RMS value of the computed car-body vertical acceleration (the third part from the top in Figure 8).

- Continuous wavelet transform of the car-body vertical acceleration

We applied a continuous wavelet transform to the computed car-body vertical acceleration (fourth and fifth part from the top in Figure 8). For the mother wavelet, we used *Morlet* wavelets.

- Discrete wavelet transform of the car-body vertical acceleration

We used the discrete wavelet transform to conduct a multiresolution analysis of vibrational acceleration. Using the *Daubechies* wavelets (generation index: eight), we set the decomposition level to be m_0=6 (Figure 9).

The effect of track irregularities may be partially discerned from the original waveform of the vibrational acceleration in Figure 8. However, discrepancies associated with other faults may not be discerned. The increased RMS value in the vicinity of 50 m reflects the effect of longitudinal level irregularities. On the other hand, the RMS value increases slightly in the vicinity of 250 m, but the level difference between this and the longitudinal level irregularity cannot be distinguished from the waveform. Thus, we conclude that the use of RMS values is poorly suited to distinguishing the different track faults.

Next, we consider results obtained with the continuous wavelet transform. Looking at the signal plane (151–333 Hz) of the continuous wavelet transform, we see a strong signal near 150 m around a frequency of 174 Hz. When corrugations of wavelength 0.08 m are run at a speed of 50 km/h, the frequency of the corrugations is 174 Hz. The appearance in the signal plane of features at this frequency and at the position in question may thus be understood as originating from corrugations. In addition, in the signal plane of the 0.7 to 2 Hz band, the signal strength grows extremely large in the vicinity of the natural frequency of the car body. This effect, which is particularly pronounced near 50 m, is thought to result from longitudinal level irregularities. Thus by using the continuous wavelet transform, we

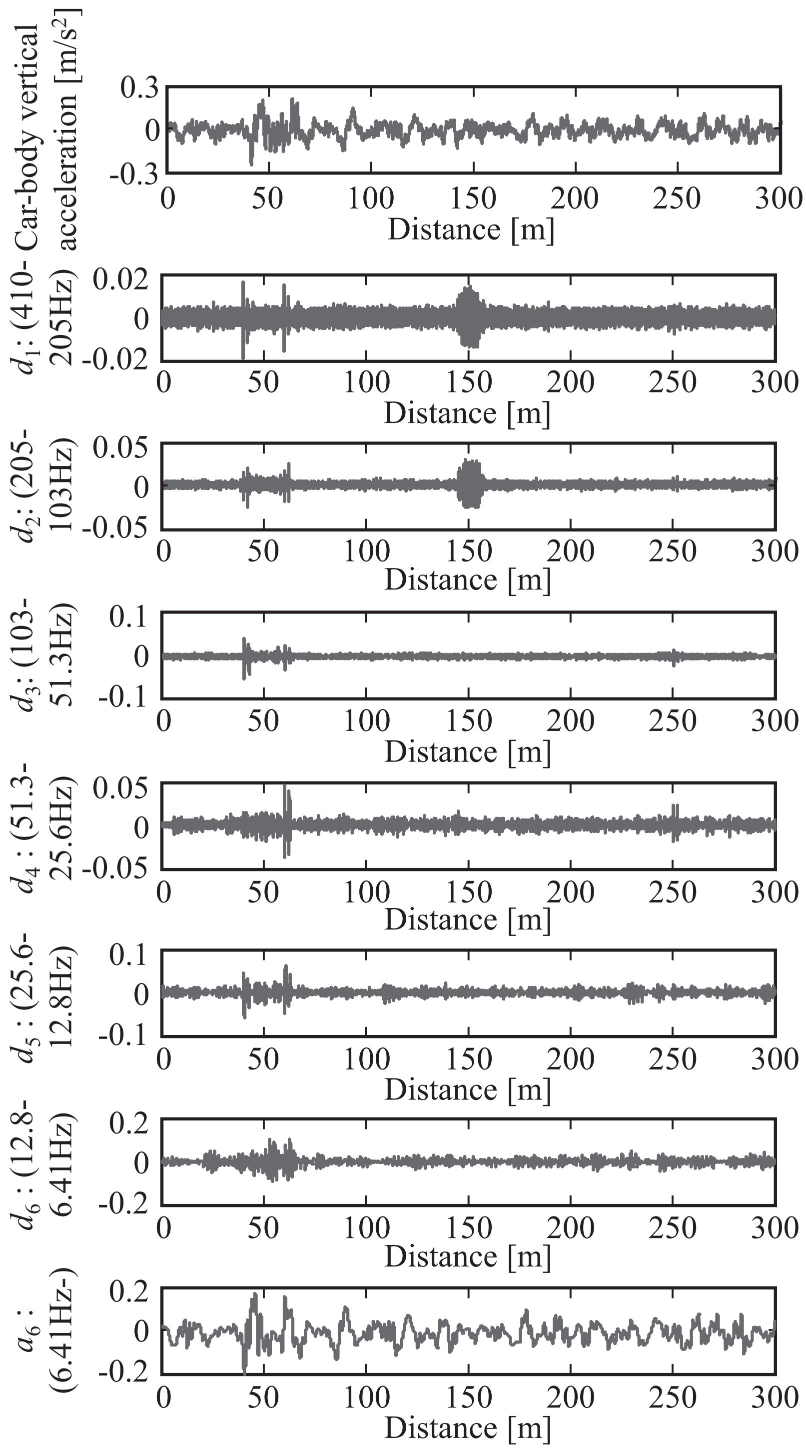

Figure 9. Multiresolution analysis of the simulated data [10]

have successfully detected information on longitudinal level irregularities and corrugations from vehicle vibrational acceleration data.

On the other hand, because the vibration response to the level difference, for example, is a step input, its properties are dispersed over a wide bandwidth. In the present case, since its strength is extremely weak, it is difficult to discern its effect from the signal plane. To remedy this difficulty, we perform multiresolution analysis using the discrete wavelet transform. Then, by inspecting the frequency components of the vehicle vibrational acceleration data (Figure 9) as decomposed into separate frequency bands, we can see that the effect of the level difference, though extremely weak, is visible in the d_4 component.

Figure 10 shows the frequency components that indicate the effect of corrugations (d_1+d_2), the components that indicate the effect of the level difference (d_4) and the low-frequency band components, in which the continuous wavelet transform indicated the effect of longitudinal level irregularities (a_6).

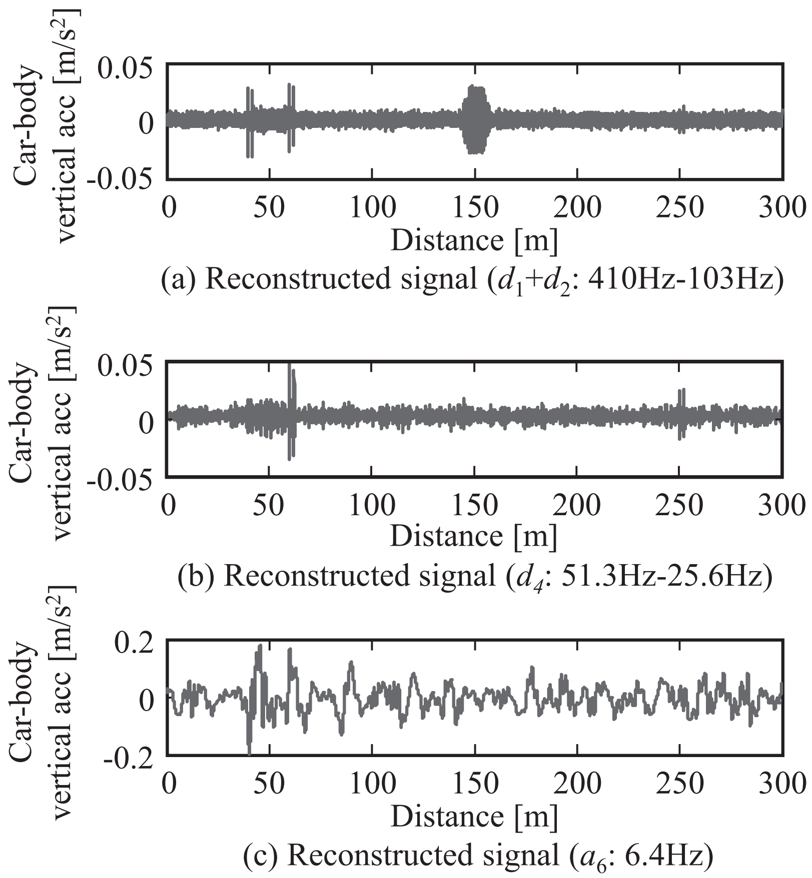

Figure 10. Reconstructed signals of Figure 10 [10]

We see that corrugations may be identified in the waveforms reconstructed from the high-frequency components (Figure 10(a)), that the level difference may be detected in the waveform of the d_4 component (Figure 10(b)) and that the longitudinal level irregularity may be identified in the waveform of the a_6 component (Figure 10(c)). Moreover, for the segment over which the magnitude of the longitudinal level irregularity was increased to twice the reference value for track irregularities, the rate of change of the connecting portion is discontinuous. Thus, we have detected discontinuities in the rate of change of the waveform (Figures 10 (a) and (b)).

This suggests the possibility that, by establishing reference values for waveforms extracted not from axle box acceleration but rather from car-body acceleration data, track faults that are difficult to detect from RMS values may be detected through the combined use of multiresolution analysis based on the discrete wavelet transform.

5. Monitoring example based on actual measured regional railway data

In the previous section, we demonstrated the efficacy of wavelet transforms for monitoring the track condition. In this section, we use actual measured value to assess the efficacy of the primary features of the monitoring software, namely, the computation of RMS values and signal analysis based on wavelet transforms. The actual measured value used for this assessment are taken from measurements made to date by the authors' research group in cooperation with a regional railway operator over an extended period time using the compact on-board sensing device [6,10].

For this railway line, we did not monitor corrugations. Therefore, in an effort to reduce the volume of handled data and increase processing speed, we reduced the volume of the measured data to 1/10 its original size. The sampling frequency of the reduced data is 82 Hz, whereupon from Nyquist's theorem, it follows that the maximum reproducible frequency is 41 Hz.

Figure 11 shows the results of analyses of the actual measured value performed by the monitoring software. The panels of the figure show, proceeding in order from the uppermost panel, the travel speed over the target station-to-station segment (as measured from GPS data), the measured waveform of the car-body vertical acceleration, the RMS value of the vibrational acceleration and the signal plane resulting from the continuous waveform transform. Based on the results of the previous section, the frequency bands of the signal plane have been divided into a low-frequency band, which captures the effect of longitudinal level irregularities, and the remainder of the frequency range. To observe the track condition, we performed visual inspections of the outer side of the track.

Looking at the RMS value waveform of Figure 11, we see a large RMS value in the vicinity of 3100 m, despite the fact that the travel speed is low at that point. In addition, the value appears large at continuous points in the vicinity of 3200 m. Another point of large RMS value appears near 3320 m. Looking at the signal plane (1.6–16 Hz) of the continuous wavelet transform, we see effects in the high-frequency band near 3100 m and 3320 m, while we see effects in the low-frequency band near 3200 m. Visual inspection of the track revealed a turnout near 3100 m; as the vehicle passes over this point, it exhibits large vibrations, whose effects are thought to be captured by the analysis.

Figure 12 presents the results of a multiresolution analysis (decomposition level $m_0 = 6$) of the car-body vertical acceleration. To assess the track condition from the decomposed signal, we reconstructed the signal into one portion containing components 1.28 Hz or below and another portion containing all other components (Figure 13). Based on analysis thus far, we

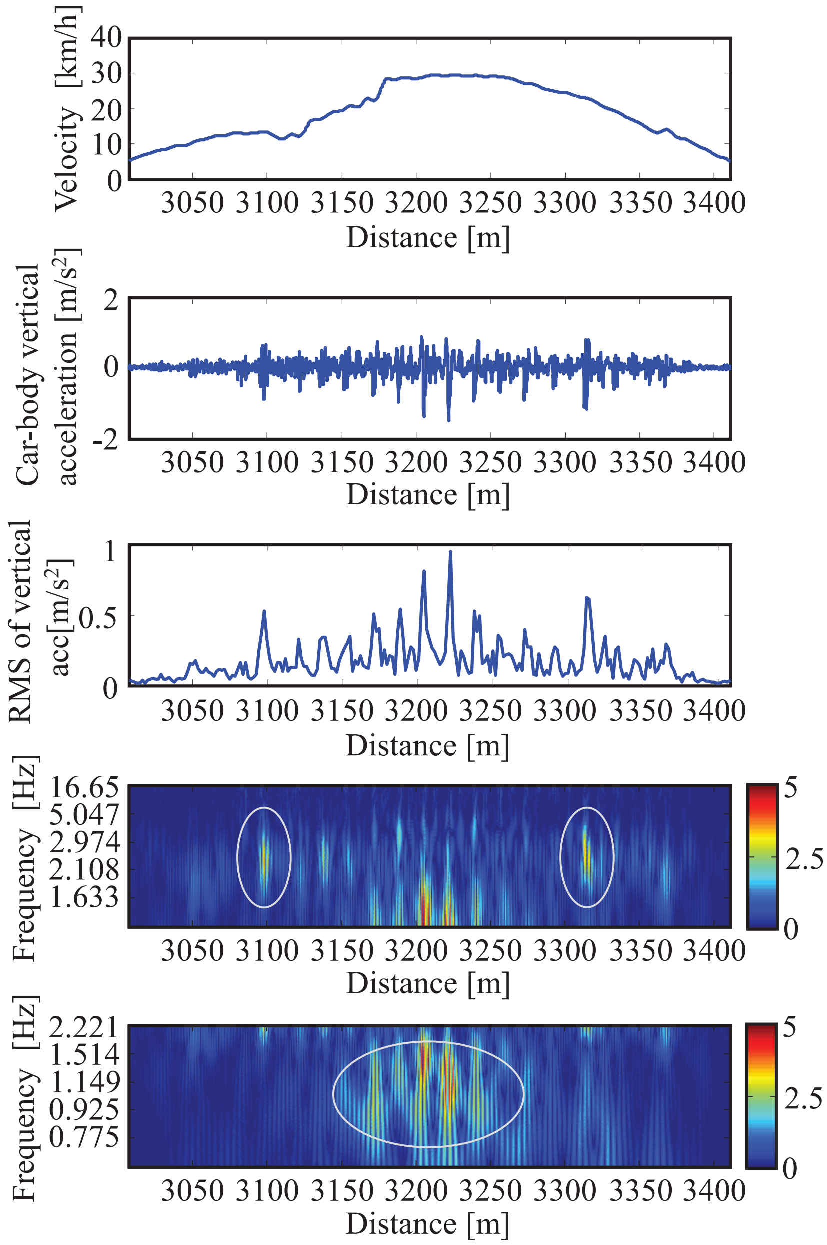

Figure 11. Assessments of the measurement data[10]

believe that the waveform (Figure 13(b)) of the low-frequency components indicates the effect of longitudinal level irregularities. Meanwhile, the waveform reconstructed from the remaining high-frequency components (Figure 13(a)) exhibits characteristic impulse-shaped peaks at fixed intervals. The lengths of the rails in this segment are 20 m, which roughly agrees with the interval of these impulse-shaped signals. This suggests the possibility that our data detected the presence of rail joints. In addition, the signal detected in the vicinity of 3320 m may indicate the effect of a loose sleeper. Accordingly, in our future work, we intend to collaborate further with the railway operator to investigate this possibility in more detail.

http://dx.doi.org/10.5772/61077

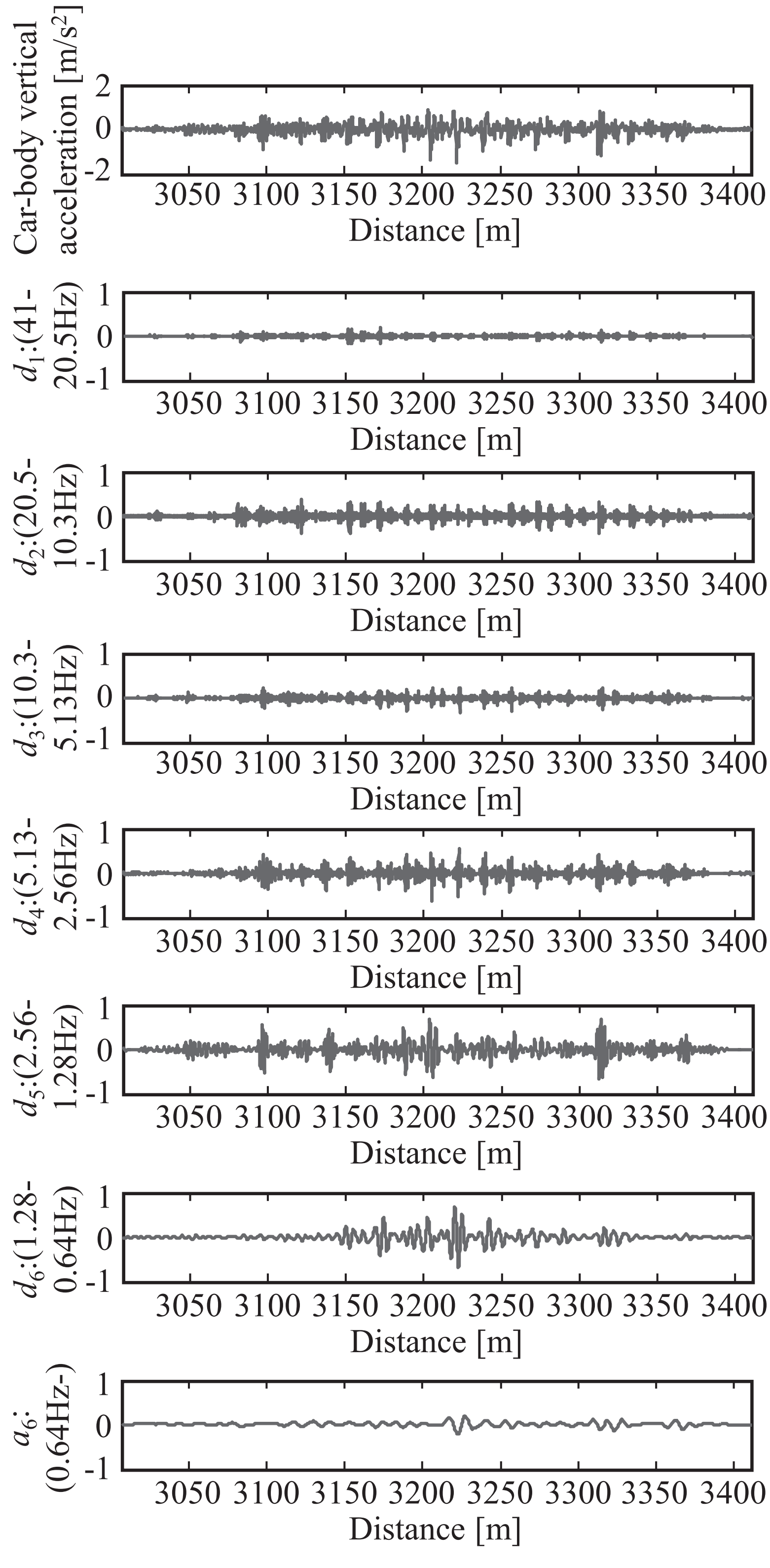

Figure 12. Multiresolution analysis of the car-body vertical acceleration [10]

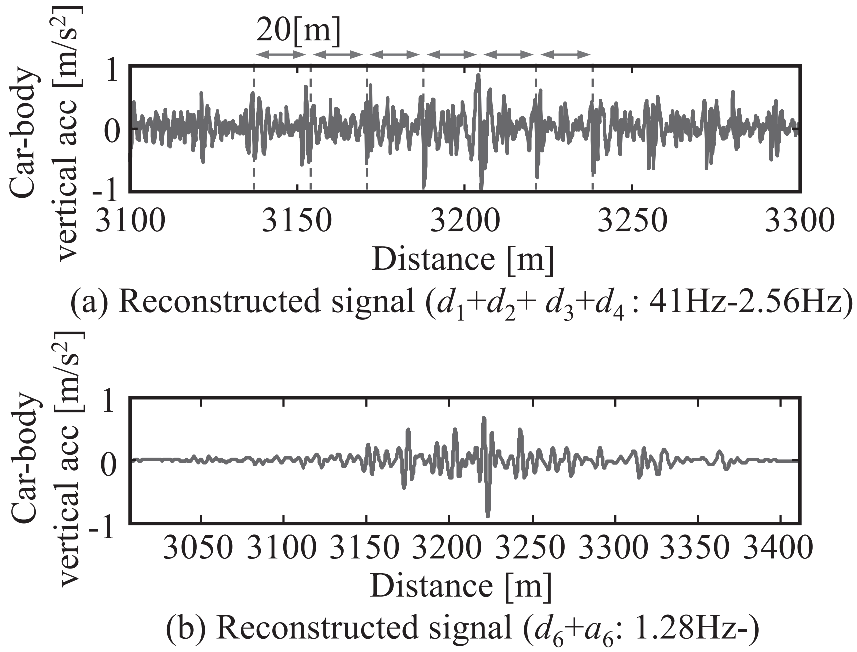

Figure 13. Reconstructed signals of Figure 13 [10]

6. Summary

In this chapter, we described a track condition monitoring system that uses track monitoring software and a compact on-board sensing device. We described the development of the track monitoring software and presented an example of the diagnostic results the monitoring software produces. To confirm the efficacy of the track condition monitoring software, we tested it using simulations and actual measured data. The results demonstrated that our system is useful for continuous track condition monitoring.

We envision the following techniques for deploying our system in practice. First, a threshold level for the RMS value will be established, and segments over which the RMS value is large will be extracted as segments requiring inspection. Next, segments requiring inspection will be subject to detailed analysis using signal planes produced by a continuous wavelet transform and multiresolution analysis based on a discrete wavelet transform. Threshold values may also be established for the components reconstructed from the multiresolution analysis and used for maintenance purposes.

The proposed system enables the timely provision of feedback regarding track maintenance, and we expect it will reduce costs and facilitate maintenance efforts to reduce overall maintenance requirements. In the authors' future work, the plan is to collaborate with the maintenance departments of railway operators to demonstrate and improve the effectiveness of the developed system.

Acknowledgements

This study was supported by the Adaptable and Seamless Technology Transfer Program through Target-driven R&D, Japan Science and Technology Agency and JSPS KAKENHI grant number 26420182.

Author details

Hitoshi Tsunashima[1*], Hirotaka Mori[2], Masayuki Ogino[3] and Akira Asano[4]

*Address all correspondence to: tsunashima.hitoshi@nihon-u.ac.jp

1 Department of Mechanical Engineering, College of Industrial Technology, Nihon University, Japan

2 National Traffic Safety and Environmental Laboratory, Japan

3 Graduate School of Nihon University, Japan

4 Kyosan Electric Manufacturing Co.,Ltd., Japan

References

[1] Goodall, R. M. and Roberts, C. Concept and techniques for railway condition monitoring. In: Railway Condition Monitoring 2006; 29–30 Nov. 2006; Birmingham: IET; 2006. 90–95.

[2] Bruni, S., Goodall, R. M., Mei, T. X. and Tsunashima, H. Control and monitoring for railway vehicle dynamics. Vehicle System Dynamics. 2007;45(7–8):765–771.

[3] Kojima, T., Tsunashima, H. and Matsumoto, A. Fault detection of railway track by multi-resolution analysis. In: Computer in Railway X. Southampton: WIT Press; 2006. 955–964.

[4] Hayashi, H., Kojima, T., Tsunashima, H. and Marumo, Y. Real time fault detection of railway vehicles and tracks. In: Railway Condition Monitoring 2006; 29–30 Nov. 2006; Birmingham: IET; 2006. 20–25.

[5] Tsunashima, H., Kojima, T., Marumo, Y., Matsumoto, A. and Mizuma, T. Condition monitoring of railway track and driver using in-service vehicle. In: Railway Condition Monitoring 2008; 18–20 June 2008; Derby: IET; 2008. 1–6.

[6] Tsunashima, H., Kojima T., Matsummoto, A. and Mizuma T. Condition monitoring of railway tracks using in-service vehicles. Japanese Railway Engineering. 2008;48(2): 6–10

[7] Tsunashima, H., Naganuma, Y., Matsumoto, A., Mizuma T. and Mori, H. Condition monitoring of railway track using in-service vehicle. In: Xavier Perpinya, editor. Reliability and Safety in Railway. InTech; 2012. 333–356. DOI: 10.5772/35205.

[8] Tsunashima, H., Mori, H., Mizuma, T. and Saito, Y. Condition monitoring of railway tracks using portable on-board sensing system. In: The 6th International Symposium on Speed-up, Safety and Service Technology for Railway and Maglev Systems (STECH2012); 2012.

[9] Mori, H., Ohno, H., Tsunashima, H. and Saito, Y. Development of compact size on-board device for condition monitoring of railway tracks. Journal of Mechanical Systems for Transportation and Logistics. 2013;6(2):142–149. DOI: 10.1299/jmtl.6.142.

[10] Ogino, M., Tsunashima, H., Yanagisawa, K., Mori, H, Asano, A. and Wakai, S. Development of track condition monitoring system based on compact onboard sensing devices (in Japanese). IEEE Transactions on Industry Applications. 2015;135(4):395–402. DOI: 10.1541/ieejias.135.395.

[11] Waston, P. F., Roberts, C., Goodman, C. J. and Ling, C. S. Condition monitoring of railway track using in-service trains. In: Railway Condition Monitoring 2006; 29–30 Nov. 2006; Birmingham: IET; 2006. 26–31.

[12] Waston, P. F., Ling, C. S., Roberts, C., Goodman, C. J., Li, P. and Goodall, R. M. Monitoring vertical track irregularity from in-service railway vehicles. Proceedings of the Institution of Mechanical Engineers, Part F, Journal of Rail and Rapid Transit. 2007;221(F1):75–88.

[13] Waston, P. F., Ling, C. S., Goodman, C. J., Roberts, C., Li, P. and Goodall, R. M. Monitoring lateral track irregularity from in-service railway vehicles. Proceedings of the Institution of Mechanical Engineers, Part F, Journal of Rail and Rapid Transit. 2007;221(F1):89–100.