Detection method for rail corrugation adopting on-board monitoring

H. TANAKA, Y. SARUKI, Akihiro HAGA, Motoyasu FUKUYAMA
Railway Technical Research Institute, Tokyo, JAPAN
Kyushu Railway Company, Fukuoka, JAPAN

Abstract

Rail corrugation should be maintained, because that leads to noise and vibration along railway track. However, rail corrugations have been inspected so far basically by visual inspection during the track patrol. Since the rail corrugation has taken place in many sharp curves, more efficient inspection technique than track patrol is requested. In this study, we examined an efficient detection technique for rail corrugations using on-board measured data which are axle-box acceleration, internal noise and car-body acceleration. At first, we proposed the detection technique for the rail corrugation by processing these data in spatial frequency domain. Next, we investigated on corrugated section that had been detected by proposed technique. As a result, we showed that our technique can not only identify the corrugated section but also can estimate the amplitude of the rail corrugation.

Introduction

The rail that is a vital component of railway track is worn out or damaged by the load from the repeatedly running train. As one example of results by such wear and damage, there is a phenomenon that is called "corrugation," which is ruggedness on top of rail surface, caused by periodical wear. The "low rail corrugation" especially generated on the top of surface of low rail in sharp curves, as shown in Fig.1. This corrugation is reported to be generated most frequently, and it is very undesirable from a viewpoint of noise and vibration. Moreover, the ballast is loosened due to increase of load variation spread from the wheel to the rail then the track irregularity growth quickens. Furthermore, load variation caused by rail corrugations leads to deterioration of track materials such as rail fastening system. Fig. 2 shows the presence of the corrugation and the example of the relation of the track irregularity growth. It is understood that the track irregularity advancement cannot be controlled by the corrugation even if the track is maintained by tamping machine, and the track deteriorates at once. Therefore, rail corrugations are preferably removed by rail replacement or rail grinding.

These corrugations are inspected generally by visually inspection or simple measurement during track patrol. However, it takes long time to inspect the whole line by the visual inspection. In addition, since the corrugation grows due to repeated train loads every day, a technique to efficiently monitor the corrugation is requested.
On-board monitoring on commercial trains has been recently getting popular to detect some damage in railway infrastructure. So we are focusing on such a technique to be applied to rail corrugation. The conventional technique that uses the axle-box acceleration has been known as a detection method of the rail surface irregularity on a vehicle [1 and 2]. The axle-box acceleration is a vibration acceleration measured on the axle-box that supports the wheel set of bogie. As for this acceleration, it is known that it has a high correlation with rail surface irregularity and high correlation with wheel load variation [3]. In addition, there are other detection techniques based on the internal noise or the car-body acceleration. However, it is considered these techniques are more difficult to apply than the technique with the axle-box acceleration, because of these data including various frequency components except the corrugation.

In this study, we discussed a technique to detect the rail corrugation using on-board measured data of axle-box acceleration, internal noise and car-body acceleration. Further, we executed a field
investigation in the corrugation section in detail, and verified the accuracy of our technique using on-board measured data, comparing with detection result on field inspection.

Outline of on-board measurement

We carried out running tests of an express train on a narrow gauge line as shown in Fig. 3. We measured the axle-box acceleration on both side of the leading axle of the first bogie as shown in Fig. 4 (a). In addition, we measured the internal noise and the car-body acceleration to detect the corrugation in a cabin as shown in Fig. 4(b).

The sensor for measuring axle-box acceleration whose rated capacity is 50G and response frequency range is DC-1500Hz was used. Also, the sensor for measuring car-body acceleration whose rated capacity is 10G and response frequency range is DC-500Hz was used. The sensor for measuring internal noise used sound level meter. The microphone set to downward in a wooden box, which an internal echo was small to intercept the noise in the vehicle, and to collect the sound that originated in the corrugation from the floor selectively.

Simultaneously we recorded tachometer pulse to convert these data from time sampling into distance sampling accurately and the location detection pulse to calculate more accurate kilometer with data recorder.

![Fig.3 Test vehicle (express train on conventional line)](image-url)
Detection method of rail corrugation using on-board measured data

The signal of on-board measured data that contains various frequency components is recorded by time sampling. At first, the frequency components that originate in the corrugation are specified by the frequency analysis in this chapter. Secondly, only necessary frequency components are extracted by the band-pass filter processing. Thirdly, the filtered waveforms are converted into the level waveforms, and the degree of the corrugation is expressed numerically. Fig.5 shows the processing flow of on-board measured data to detect rail corrugation.

![Fig.5 Processing flow for detection of rail corrugation using on-board measured data](image)
Pre-processing

In order to use on-board measured data for the track maintenance that recorded in time sampling, they should be converted to distance sampling data to identify the location of the time sampling data on the track. We converted those data to distance sampling by using the tachometer pulse after two step filtering shown in the Fig.5.

The first pre-processing is a low-pass filtering to prevent aliasing at re-sampling. This filter called an anti-aliasing filter. The second pre-processing is a high-pass filtering to zero calibration. This filter called a drift correcting filter.

Frequency analysis

Fig. 6 shows power spectra of axle-box acceleration at both side axles measured in three sections: A, B and C. Similarly, power spectra of internal noise and car-body acceleration measured are shown in Fig. 7. The section A is a curve of 250m in radius where left rails are low rails. The section B is a curve of 250m in radius where right rails are low rails. The section C is a straight line without corrugations. In each section, the running speed of vehicle is about 60 km/h.

As shown in Fig. 6, a peak of PSD is visible at spatial frequency of approximately 6-7 [1/m] (wavelength about 0.15 m) in power spectra of the sections A and B. On the contrary, a remarkable peak is invisible in the section C. Therefore, it is considered that wavelength of corrugations about 0.15m exists on the sections A and B. Also, some other peaks can be seen, which are caused by different factors from low rail corrugations.

As shown in Fig.7, similarly a peak is seen at spatial frequency of approximately 6-7 [1/m] (wavelength about 0.15 m) in power spectra of the sections A and B. However, another peak is seen at spatial frequency of about 20 [1/m] in all sections in power spectra of internal noise. Similarly, other peaks are seen at spatial frequency of about 2 [1/m] and 20 [1/m] in all sections in power spectra of car-body acceleration. These are peaks caused by some factors different from corrugations.
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In many previous studies, the extraction of rail corrugations was through the filtering on the time frequency axis [1 and 2]. However, corrugations are periodic ruggedness on the spatial axis formed on the rail. Therefore, there is a possibility of cutting off the component of the rail corrugation in this processing depending on the running speed of vehicle. In order to avoid such possibility, the cut-off frequency should be set widely. Then in that case, there is a possibility that some other components than rail corrugations are included. In order to avoid these problems, we adopted a technique to execute the band-pass filtering in spatial frequency. This filter called a corrugation extraction filter.

In this study, band-pass filtering was executed by wavelength of 0.10-0.25m to extract only the signal related to rail corrugations. One example of the band-pass filtered waveform of on-board measured data, the axle-box acceleration is shown in Fig.8. We find that the frequency elements other than rail
corrugations are removed by this processing, and the accuracy of detecting corrugations has been improved. After this filtering, "Kilometer" used by track maintenance is further added to the data on the spatial axis by using the signal from ground coils installed on the railway track almost every 1km. A misregistration of position of the processed data on the ground is corrected by this processing.

![Fig.8 Example waveform of axle-box acceleration before and after with band-pass filtering](image)

Detection of corrugated section by leveling

Further in this study, we propose the leveling as a technique to detect corrugation generation sections. The leveling is a technique commonly used in the field of sound and vibration analysis, and there is already an example having been applied to axle-box acceleration. Since the leveling is carried out on time axis, this processing is usually called "Time weighted level." Data compression is possible by the low-pass filtering, which is an advantage of the leveling.

We applied the concept of this time-weighted level to data on spatial axis. "Space-weighted level" is defined by the equation below. Space factor $\kappa$ is a constant for weighting on spatial axis. We have understood that $\kappa=1.0$ is appropriate for indicating the corrugated section, as a result of having examined $\kappa$ value by changing some parameters. This processing corresponds to the low-pass filtering by wavelength of 1m.

$$L(x) = 10\log_{10} \left\{ \frac{1}{\kappa} \int_{-\infty}^{\infty} a^2(\zeta)e^{-\frac{(x-\zeta)^2}{\kappa^2}} d\zeta \right\}$$

Here, $L(x)$ : space weighted level at observation point $x$ [dB]
The example of a detected result of corrugated section by leveling is shown in Fig.9. By leveling, the level value at curved section is increased, and we can detect the corrugated section, even if you using measured data.

VERIFICATION OF ACCURACY BY FIELD INVESTIGATION

Outline of rail surface irregularity measurement of corrugation

We carried out a detailed field investigation to verify the accuracy of our proposed detection technique. In the field investigation, the measurement of sequential data of longitudinal rail surface irregularity was carried out to identified wavelength and the wave height of the corrugation. The device called as CAT (Corrugation Analysis Trolley) shown in Fig.10 was used for the measurement [4]. The CAT device is of a trolley type and can measure the rail surface irregularity on track. The principle of the inertia measurement is used, and the output of the acceleration sensor of the servo
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type is integrated twice and the waveform of the rail surface irregularity is obtained.

![Image](image_url)

Fig.10 Measurement scenery of corrugation using CAT

**Rail surface irregularity of corrugation**

Fig.11 (a) shows the example of waveform of measured data of corrugation on low rail by CAT. The waveform is processed by the band-pass filter that extracts wavelength of 0.10–0.25m in the same way as the on-board measured data. The wave amplitude is increasing as the measurement is shifting from the tangent section to curved section via transition curve. Large values commonly observed at 25m intervals are caused by the impact excited when the device passes rail joints.

Fig.11 (b) shows the example of power spectrum of measured waveform of rail corrugation by CAT. The peak is seen at spatial frequency of about 6.5 [1/m] (wavelength of about 0.15 m) in the same way as power spectrum of axle-box acceleration. This peak corresponds to the surface irregularity of low rail corrugation.

![Graphs](image_url)

**Fig.11 Measurement result of low rail corrugation at sharp curve**
Comparison of wave heights between on-board measurement and ground one

The relation between the wave height of corrugation measured by CAT and the spatial weighted level of on-board measured data are shown in Fig.12. We find that the level value has a high correlation with the wave height of corrugation. Thus we have obtained the prospect that the wave height of corrugation is able to be estimated from the spatial weighted level value of the on-board measured data.

Focusing on the correlation coefficient among axle-box acceleration, internal noise and car-body acceleration, axle-box acceleration is the highest. Next, we found that there was a correlation in the wave height of corrugation and internal noise though the correlation is somewhat lower than axle-box acceleration. In addition, we found that there was a correlation also in the wave height of corrugation and the car-body acceleration though accuracy is inferior to these.

As shown in Fig. 13, internal noise is the airborne sound or the structure borne sound of car-body. On the contrary, car-body acceleration is a vibration through primary and secondary suspensions. Therefore, we considered that correlation of internal noise with corrugation is higher than that of car-body acceleration.
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(b) Internal noise
(c) Car-body acceleration

Fig.12 Relation between height of corrugation and space weighted level

Fig.13 Schematic propagation of sound and vibration caused by rail corrugation

Conclusions

In this paper, we discussed the detection technique of the low rail corrugation using on-board measured data, and obtained results are as follows:

1. We carried out frequency analysis on the on-board measured data. As a result, in all data, we found the frequency component excited by corrugation. Next, corrugation is rail surface
irregularity on the spatial axis. Therefore, we showed that the corrugated section was able to be detected with the band-pass filtering extracting some specific wavelength on the spatial axis.

2. We obtained relationship between the wave height of rail corrugation and some parameters such as axle-box acceleration.

3. We showed that rail corrugations can be detected practically by the internal noise and the car-body acceleration. These parameters can be measured on a vehicle without so much difficulty.

If we change a wavelength of band-pass filter according to the wavelength of targeted corrugation, our technique can detect other type of rail corrugations too. We have already known that can detect high rail corrugation or straight rail corrugation which wavelength is longer than low rail corrugation. We plan to examine the possibility of detection technique for other type of rail failures in addition to rail corrugations, for instance, head checks or rail surface shellings.

References: