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A parametric study on the influence of track irregularities upon train induced ground vibration

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ABSTRACT

Track irregularity is an important factor of train induced ground vibration, and sometimes causes strong ground vibration. For example, track irregularity due to corrugated rail increased 16 to 31.5 Hz components of ground vibration more than ten decibels on a shallow freight train line tunnel. To estimate the influence of track irregularity, we performed a parametric study using a program for solving coupled vibration of moving-vehicle and structure. We at first confirmed the accuracy of the program by comparing measured and calculated vibration of an in-situ measurement site. In the parametric study, we calculated the acceleration of roadbed caused by sine wave form track irregularity with various wavelength and amplitude. As a result, track irregularity amplitude was found to have certain threshold value. If track irregularity amplitude is larger than the threshold, roadbed acceleration increases as the track irregularity amplitude increases. However, if track irregularity amplitude is smaller than the threshold, roadbed acceleration is almost independent to the amplitude of track irregularity. The threshold amplitude corresponds to the balance point of static axle load and inertial force excited by the track irregularity.

Keywords: Ground Vibration, Simulation, Railway   I-INCE Classification of Subjects Number(s): 41.3

1. INTRODUCTION

Track irregularity is an important factor of train induced ground vibration, and sometimes causes strong ground vibration. Recently, remarkable increase of ground vibration caused by track irregularity was reported on a shallow freight train line tunnel (1) and a Shinkansen tunnel (2). To estimate the influence of track irregularity, we performed a parametric study using a program for solving coupled vibration of moving-vehicle and structure.

2. Background of the Study

2.1 Ground Vibration Problem on a Freight Train Line Tunnel (1)

On a relatively shallow freight train line double track tunnel, problems of train-induced ground vibrations occurred. The depth of overburden is about 13 meters at the site. The track type is slab track, and installed continuous welded rails. Though train speed and other train conditions were almost equal, ground vibration from down track train was more than 10 dB bigger than vibration from up track train, and caused the problem. In this chapter, we used weighted vibration acceleration level for evaluation. Frequency weighting is JIS vertical weighting curve (equivalent to the whole body weighting of ISO 8041$_{-1990}$ for z axis), and time constant is 0.63 s.

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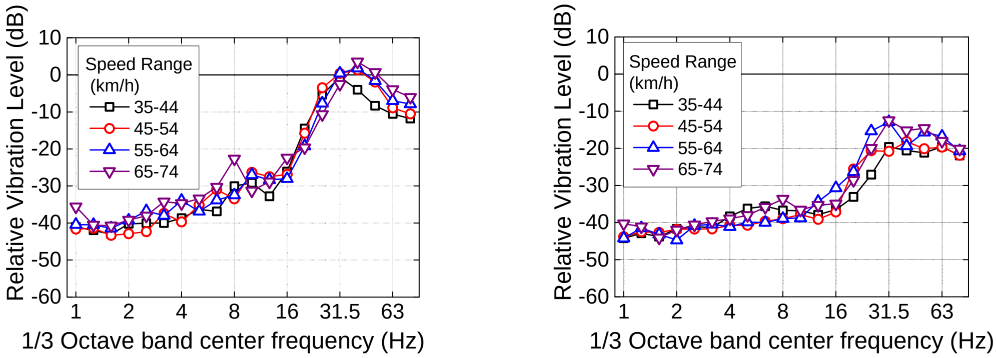
2.2 Investigation of cause and countermeasure

To find out the cause of the difference, we compared one third octave band spectra in the tunnel shown in Figure 1. In consideration of dispersion, speed of trains are classified four ranges that are 35 to 44 (km/h), 45 to 54 (km/h), 55 to 64 (km/h) and 65 to 74 (km/h). In this chapter, we express the maximum value of measured ground vibration level as 0 dB. As seen in Figure 1, major difference appears in the frequency range of 20 to 40 Hz. Figure 2 shows the subtraction of up track train spectrum from down track spectrum. Peak frequency band shifts to higher frequency band as train speed becomes higher. This feature is conspicuous in the ranges of frequency bands 25 to 40 Hz.



(a) Down track train (b) Up track train

Figure 1 – One third octave band spectra on the roadbed concrete

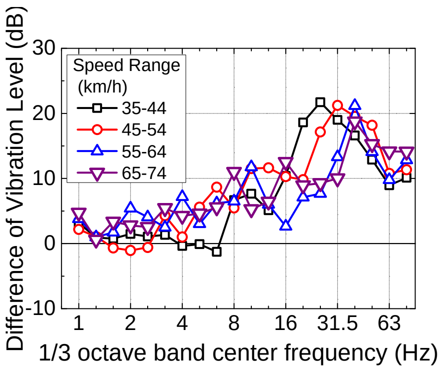


Figure 2 – Spectrum difference between down track train and up track train

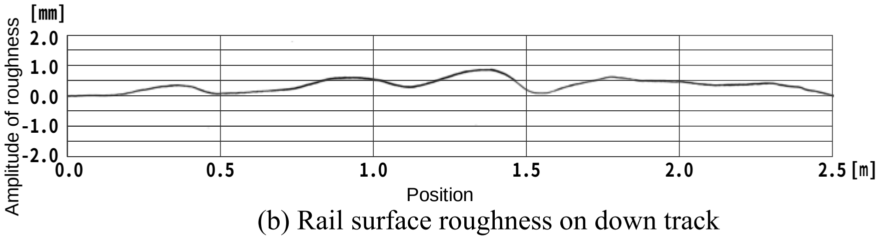
Table 1 lists relationship between averaged trains speed and dominant frequency band. We calculated the length of effect factor to divide average trains speed by dominant frequency bands. This table presents that the length of effect factor is about 0.35 to 0.5 m. In addition, we obtained this tendency only down track. Therefore, we supposed that some factors on the down track with this wavelength caused remarkable ground vibration.

Figure 3 and 4 show the rail surface condition of the outer rail of down track and up track, respectively. We found remarkable corrugation on the down track rail, and its wavelength was around 0.45 m (Fig. 3). On the other hand, there was no such corrugation on the up track rail (Fig. 4). Therefore, we deduced that the corrugation of down track rail increased ground vibration, and the operation company of this line changed the corrugated rail to new one and reduced 10 dB.

Table 1 – Relationship between averaged trains speed and dominant frequency band

Speed Range (km/h)	Averaged Trains Speed (km/h)	Averaged Trains Speed (m/sec)	Dominant Frequency Band (Hz)	The Length of Effect Facter (m)
35-44	40.7	11.3	31.5	0.36
45-54	53.0	14.7	40.0	0.37
55-64	61.7	17.1	40.0	0.43
65-74	72.0	20.0	40.0	0.50

(a) Rail of down track



(b) Rail surface roughness on down track

Figure 3 – Rail surface condition of down track

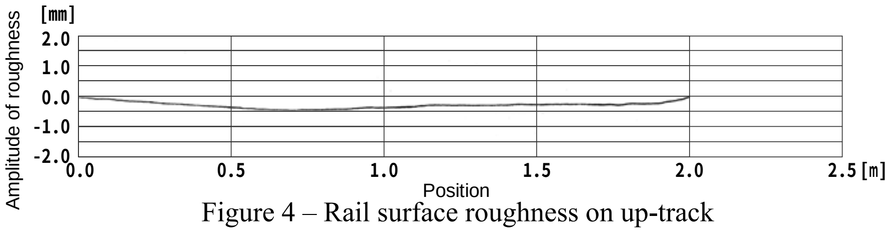


Figure 4 – Rail surface roughness on up-track

3. PARAMETRIC STUDY

As discussed in previous chapter, track irregularity sometimes cause ground vibration much larger than we expected. To estimate the influence of track irregularity, we performed a parametric study using a program named DALIA (KKE Inc.) (3) for solving coupled vibration of moving-vehicle and structure. We at first confirmed the accuracy of the program by comparing measured and calculated vibration of an in-situ measurement site. Then, we calculated the acceleration or the excitation force of ground vibration caused by track irregularity with various wavelength and amplitude. In this chapter, we use unweighted vibration acceleration level (time constant = 0.63 s) for evaluation.

3.1 Preliminary Analysis

3.1.1 Freight Line Tunnel

Figure 5 shows the image of the model for freight line tunnel. We modeled car body and bogies with rigid beam elements, and axles with mass elements. As for track and structure model, we modeled rails, track slabs, and tunnel with beam elements. Two rails were modeled with single beam element with equivalent weight and stiffness. The weight and the stiffness of tunnel was contracted to concrete roadbed, and modeled by single beam element under the track. Since there is no further information than shown in Figures 3 and 4, we modeled track irregularity by sine wave. The wavelength is 0.45 m, and the amplitude is 0.5 mm (down track) and 0.1 mm (up track) respectively. Table 2 shows major model parameters.

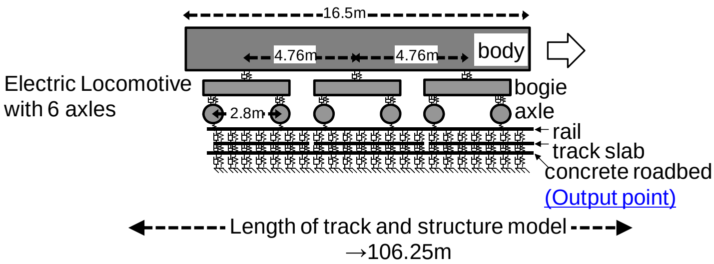


Figure 5 – Analysis model for freight line tunnel case

Table 2 – Model parameters

(a) Car

Mass (t)	Body	55.8
	Bogie	4.4
	Axle	4.5
Spring constant (kN / m)	Secondary spring	1725
	Axle spring	2105
	Wheel - rail spring	980000
Damping Coefficient (kN s / m)	Bolster damper	274
	Axle damper	78

(b) Track and structure

	Rail	Track slab	Roadbed
Mass per unit length (t / m)	0.122	1.78	47.8
Bending stiffness *EI* (MN m^2)	13.200	46.8	4800000
Axial stiffness *EA* (MN)	3320	14000	447000
	Rail pad	Slab support	Under tunnel
Spring constant (MN / m)	360	4300	1320
Damping coefficient (kN s / m)	339	259	1830

Figure 6 shows the results of the analysis with measured vibration. In this figure, reference acceleration is the maximum value of measured vibration. Peak vibration level of measured and calculated vibration agrees well. As seen in Figure 3, measured track irregularity is not a pure sine wave, and the spectra shown in Figures 1 and 6 are average value of vibration form trains running around 70 km/h. On the other hand, track irregularity used for the analysis has only one wavelength, and train is 70 km/h. Thus, calculated spectra have relatively sharp peak at 40 Hz, which agrees with the frequency determined by train speed and the wavelength of track irregularity.

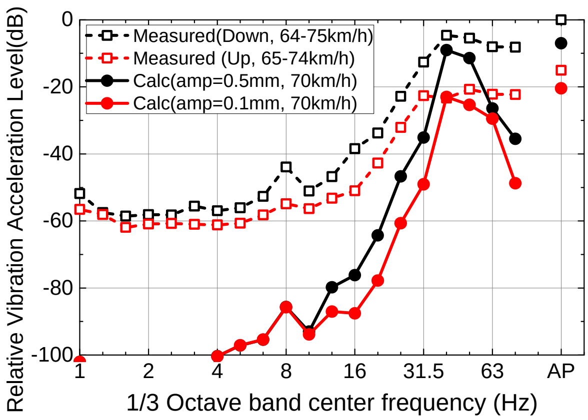


Figure 6 – Comparison of calculated and measured vibration

From this result, we could confirm the simulation model we used is adequate for the evaluation of track irregularity affection.

3.1.2 Shinkansen Over Bridge in Embankment

To confirm the applicability of this model to high-speed train like Shinkansen, we calculated the structural vibration of an abutment shown in Figure 7, and compared it with measured vibration (Figure 8). In Figure 8, we express the overall value (O.A.) of measured vibration level as 0 dB. Train model consists of 8 standard Shinkansen cars, and the speed is 270 km/h. Due to the lack of track irregularity data at this area, we used the summation of three sine waves. As shown in Figure 8, calculated vibration agrees with measured vibration, and the program we used is suitable for high-speed train analysis as well as conventional train analysis.

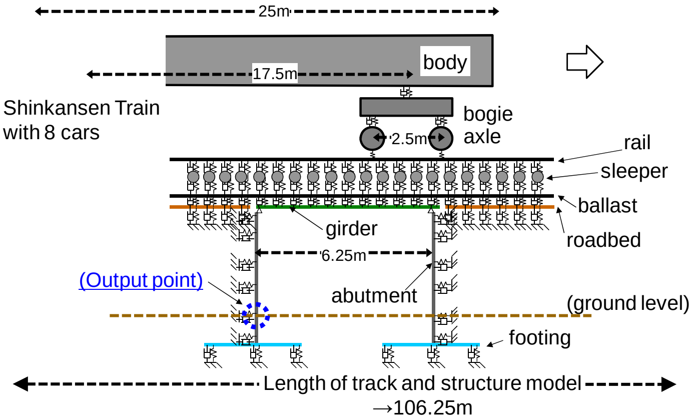


Figure 7 – Analysis model for Shinkansen running on an overbridge

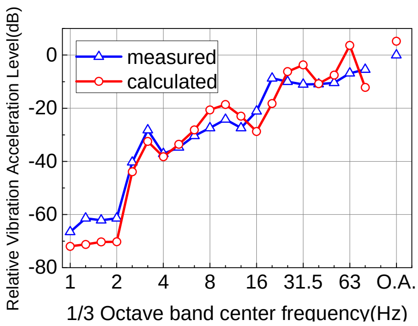


Figure 8 – Comparison of calculated and measured vibration for Shinkansen running on an overbridge

3.2 Parametric Study on Track Irregularity Affection

To make an overview image of the affection of track irregularity, we conducted parametric study of Shinkansen line with track irregularity of various wavelength and amplitude (4). To eliminate the effect of track or structural joints, we chose plain ground line model with ballasted track. In this model, sleepers are booted sleepers, and roadbed model is slag roadbed. Figure 9 and Table 3 shows the outline and basic parameters of the analysis model we used. Train model consists of 8 standard Shinkansen cars, and the speed is 270 km/h. We modeled two rails with single beam element with equivalent weight and stiffness; ballast and roadbed were modeled by soft beam elements. Length of track and structure model is 106.25 m. Track irregularity is modeled by a sine wave. The range of track irregularity's wavelength is 1 m to 40 m, and the amplitude is 0.001 mm to 10 mm. In addition, we calculated smooth track (i.e. without track irregularity) model.

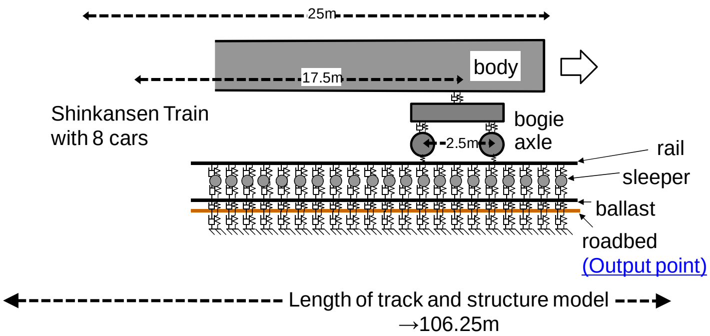


Figure 9 – Analysis model for Shinkansen line

Table 2 – Model parameters

(a) Car

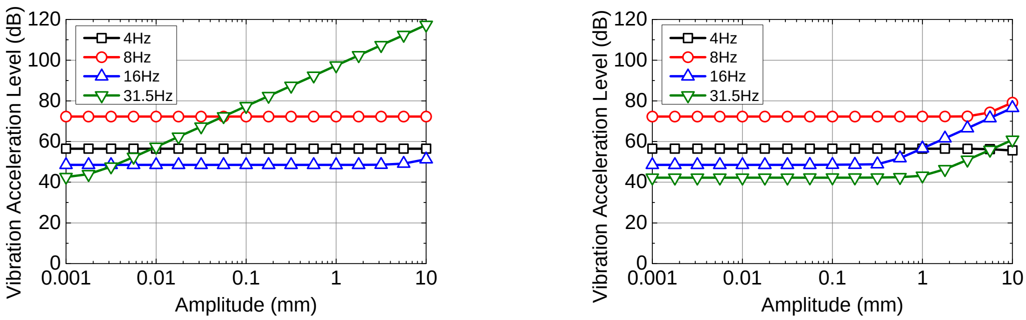
Mass (t)	Body	29.6
	Bogie	3.0
	Axle	1.7
Spring constant (kN / m)	Secondary spring	500
	Axle spring	2400
	Wheel - rail spring	980000
Damping Coefficient (kN s / m)	Air spring damping	93.0
	Axle damper	78.4

(b) Track and structure

	Rail	Ballast	Roadbed
Mass per unit length (t / m)	0.122	1.96	17.0
Bending stiffness *EI* (MN m^2)	13.2	0.958	1070
Axial stiffness *EA* (MN)	3320	94.0	4260
	Rail pad	Sleeper support	Under roadbed
Spring constant (MN / m)	240	13.5	218
Damping coefficient (kN s / m)	339	64	740

Figure 10 shows the relation between the track irregularity amplitude and average vibration level of roadbed. In this chapter, we used power average of the roadbed acceleration for evaluation. Reference acceleration is 10^{-5} m/s^2, and time constant is 0.63 s. Averaging area is the central 65 m of the model.

Through the parametric study, we found that track irregularity amplitude have certain threshold value (4). If track irregularity amplitude is smaller than the threshold, roadbed acceleration is almost independent to the amplitude of track irregularity. However, if track irregularity amplitude is bigger than the threshold, roadbed acceleration increases as the track irregularity amplitude increases. Vibration acceleration level is almost proportional to the common logarithm of track irregularity amplitude for large track irregularity, and the constant of proportion is 19.6.

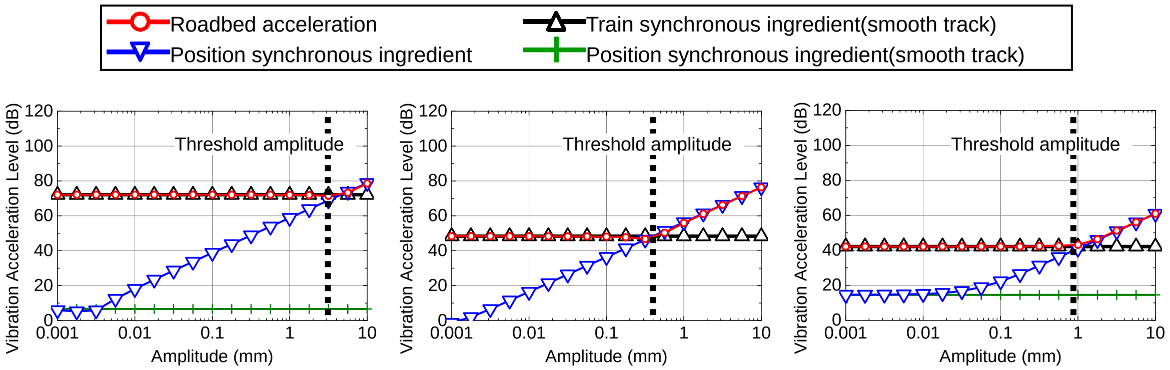


(a) Wavelength of track irregularity = 2 m (b) Wavelength of track irregularity = 10 m

Figure 10 – The relation between track irregularity amplitude and vibration acceleration level

To explain the cause of this threshold, we assumed that the roadbed acceleration could be expressed as the summation of two ingredients. One is called train synchronous ingredient, which is caused by the loads moving with the train and their waveforms are independent to the train position only except for the time delay. The other one is called position synchronous ingredient, which is caused by location dependent factor like track irregularity, structure joint, etc. Theoretically, train synchronous ingredient is independent to track irregularity for a longitudinally homogeneous model, so we at first applied delay-and-sum method for roadbed acceleration wave of smooth track model to calculate train synchronous ingredient wave. Then, by subtracting train synchronous ingredient wave from roadbed acceleration waves of certain track irregularity, we can get the position synchronous ingredient wave at each position.

Figure 11 shows the result of decomposition for the track irregularity wavelength of 10 m. As seen in this figure, rising points seen in Figure 10 (a) correspond to the cross points of train synchronous ingredient and position synchronous ingredient in Figure 11.

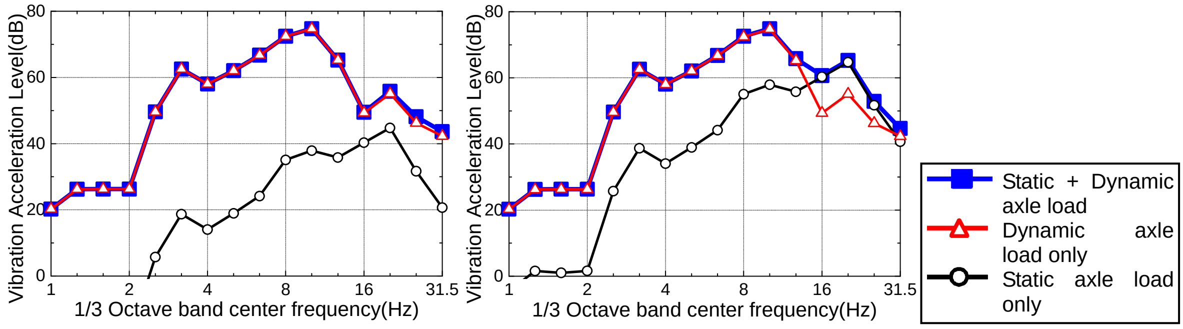


(a) 8 Hz (b) 16 Hz (c) 31.5 Hz

Figure 11 – Result of decomposition (wavelength of track irregularity = 10 m)

We surmised from the definitions of two ingredients that the source of train synchronous ingredient is mainly static axle load, while the source of position synchronous ingredient is mainly dynamic axle load excited by track irregularity.

Figure 12 shows the one third octave band spectra of two running condition with the ordinary case (case (1)). In this figure, case (2) shows the average vibration acceleration level without static axle load (i.e. no gravitation condition), and case (3) shows the average vibration level of smooth track model (i.e. no track irregularity). We can see that the effect of static axle load is dominant for small track irregularity (Figure 12 (a)). On the other hand, for larger track irregularity case (Figure 12 (b)), vibration caused by dynamic load is dominant in higher frequency range (16 Hz ≤). Hence, the threshold amplitude found in Figure 10 corresponds to the balance point of static axle load and inertial force excited by the track irregularity.



(a) Amplitude = 0.2 mm (b) Amplitude = 2 mm

Figure 12 – Effect of static and dynamic axle load (wavelength of track irregularity = 10 m)

4. CONCLUSIONS

To estimate the influence of track irregularity upon train induced ground vibration, we performed a parametric study using a program for solving coupled vibration of moving-vehicle and structure. We at first confirmed the accuracy of the program by comparing measured and calculated vibration of an in-situ measurement site. In the parametric study, we calculated the acceleration of roadbed caused by sine wave form track irregularity with various wavelength and amplitude.

The results of this study are as follows:

(1) Calculated vibrations are in good agreement with measured vibration in both Freight Line and Shinkansen model. Thus, we could confirm that the simulation model we used is adequate for the evaluation of track irregularity affection.

(2) Track irregularity amplitude was found to have certain threshold value. If track irregularity amplitude is bigger than the threshold, roadbed acceleration increases as the track irregularity amplitude increases. However, if track irregularity amplitude is smaller than the threshold, roadbed acceleration is almost independent to the amplitude of track irregularity.

(3) Vibration acceleration level is almost proportional to the common logarithm of track irregularity amplitude for large track irregularity, and the constant of proportion is 19.6.

(4) The threshold amplitude corresponds to the balance point of static axle load and inertial force excited by the track irregularity.

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