COMPDYN 2013
4th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Kos Island, Greece, 12–14 June 2013

DYNAMIC EFFECT OF RAILWAY VEHICLE ON SEISMIC RESPONSE OF RAILWAY STRUCTURE

M. Tokunaga[1], S. Minoura and M. Sogabe[1]

[1]Railway Technical Research Institute
2-8-38, Hikari-cho, Kokubunji-shi
e-mail: {toku, minoura, sogabe}@rtri.or.jp

Keywords: Railway vehicle, Dynamic interaction, Seismic design, Train load, Earthquake.

Abstract. *The conventional seismic standard of Japan specifies that the seismic inertia force of trains is modeled as a uniformly-distributed load which has upper limit force of 30% of railway vehicle weight assuming that railway vehicles produce damping effects or do not always oscillate in the same phase as structures. However, the damping effect has not been specifically identified and the upper limit is unreliable because actual railway vehicles have a complicated vibration system. The object of this paper is to evaluate the dynamic effect of railway vehicles on seismic response of structures, and to develop a reasonable modeling method of railway vehicles in seismic design. As the result of numerical simulations, following conclusions were obtained: 1) The frequency response function of railway vehicles exceeds 1 without phase lag when the frequency is less than about 1Hz, whereas, that marks below 1 with phase lag when the frequency is more than about 1Hz. 2) The frequency response function of the railway vehicles exceeds 1 without phase lag in the range of less than 1Hz, whereas, that marks below 1 with phase lag in the range of higher than 1Hz. 3) The dynamic effect of vehicles affects the structure response under earthquake motions, and the effect depends on the characteristics of earthquakes, the degree of the plastic behavior of structures and the yield frequency. The structure response varies in the range of -50~20% at its maximum due to the dynamic effect. 4) An estimation method using the equivalent weight rate $\beta_{eq,V}$ was proposed in order to evaluate the dynamic effect of railway vehicles.*

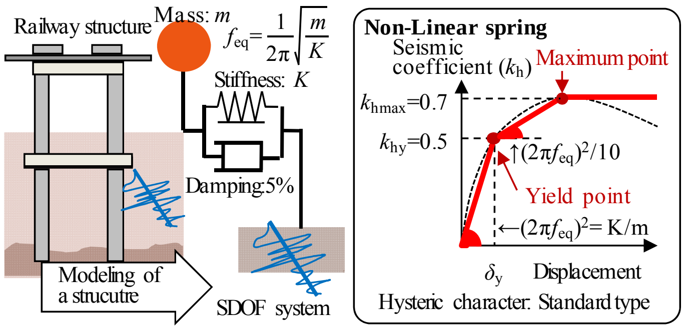


Figure 1: Dynamic model of structure

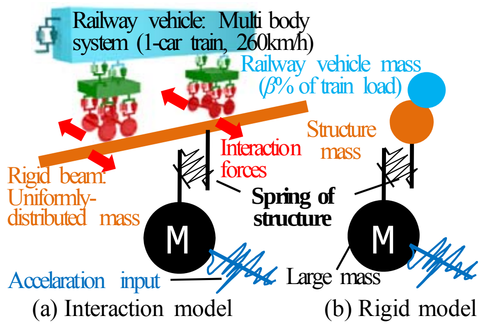


Figure 2: Modeling way of railway vehicles and interaction

1 INTRODUCTION

Lots of old railway steel bridges, which are of open floor type without concrete slabs, are light weight bridges of unit weight/length of 30 kN/m. Therefore, seismic response of these light bridges may be significantly affected by train behavior because the percentage of the train weight, which is assumed to be approximate 35 kN/m, to the entire bridge weight is high.

The Design Standards for Railway Structures and Commentary established by RTRI (Seismic Design)[1] specifies that the seismic inertia force of railway vehicle mas is modeled as a uniformly-distributed fixed load on the condition of riding capacity of 100% (70% for a freight car). The frequencies of trains determine the number of tracks where vehicle weight is loaded. The seismic inertia force has an upper limit value of 30% of the vehicle weight assuming that railway vehicles produce damping effects or do not always oscillate in the same phase as structures.

However, sufficient reasons why the upper limit of the inertia force is 30% of the vehicle weight in these methods have yet to be given, and no action on structures caused by the dynamic effect of vehicles during earthquake motions have been identified. Therefore, it is necessary to investigate more reasonable modeling methods for seismic actions of railway vehicles.

The object of this paper is to evaluate dynamic effects of railway vehicles on seismic response of structures, and to develop a reasonable modeling method of running railway vehicles in seismic design through the following investigations.

(1) To clarify the dynamic characteristics of railway vehicles
(2) To evaluate the dynamic characteristics of structures in consideration of the dynamic effect of railway vehicles
(3) To evaluate the dynamic effect of railway vehicles during earthquake motions
(4) To propose a reasonable railway vehicle modeling method in seismic design

2 ANALYSIS METHOD

A program called DIASTARSIII, which analyses dynamic interaction between vehicles and railway structures, was used in the numerical analysis [2].

2.1 Dynamic model of structure

Fig. 1 shows the dynamic model of structures. The dynamic behavior of railway structures can be often expressed by the single degree of freedom (SDOF). Therefore, structures were modelled as SDOF system with the tri-linear type skeleton curve and the standard type hysteric characters. For the skeleton curve, the yield seismic coefficient k_{hy}, the maximum seismic coefficient k_{hmax}, the yield frequency f_{eq}, and the structure unit weight/length w_s, were set as the parameters. The second gradient was fixed at 1/10 of the first gradient and the third gradi-

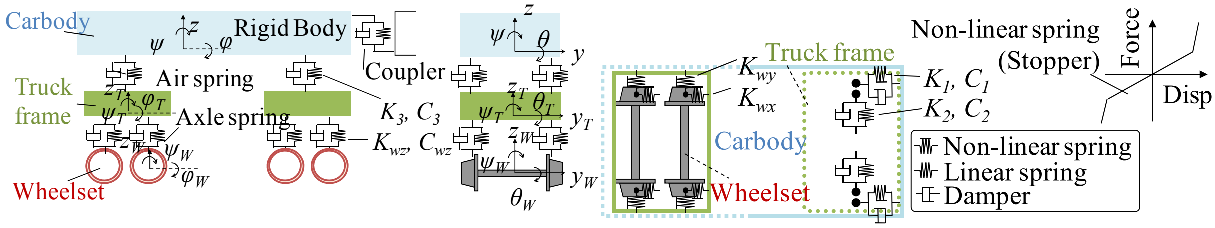
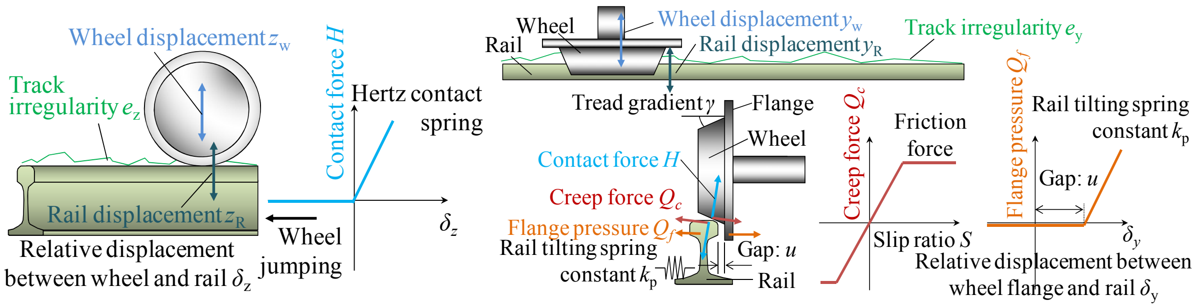


Figure 3: Dynamic model of railway vehicle of interaction



(a) Vertical direction (b) Horizontal direction

Figure 4: Interaction between wheel and rail of interaction model

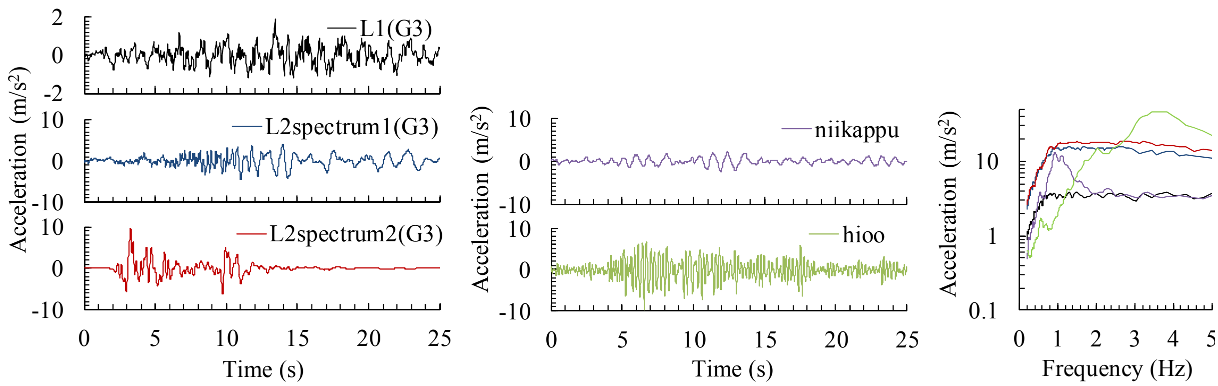
ent was fixed at infinitesimal. The yield frequency of structures f_{eq} was calculated on the basis of structure weight of 100% and train weight of 100%. The structure weight was fixed in consideration of 25m which is the same length as the railway vehicle. The unit weight ratio of structure to train α (= w_s/w_t) was set between 1~20. The unit weight w_t of the vehicle model used in this paper was set to 17kN/m. Old railway steel bridges, which are of open floor type without concrete slabs, are light weight structures of unit weight w_s of more or less 35 kN/m. Concrete RC structures used in Shinkansen lines are usually comparatively heavy weight structures of unit weight w_s of more or less 350kN/m. The value of k_{hmax} was obtained by adding 0.2 to k_{hy}.

2.2 Dynamic model of railway vehicles and interaction model between wheels and rails

Fig. 2 indicates conceptual diagrams of how to model railway vehicles and interaction between wheels and rails. An interaction model and a rigid model were established.

2.2.1 Interaction model

Fig. 3 shows the dynamic model of railway vehicles of the interaction. The railway vehicle model was created in the form of a rigid body, the elements of which was a body, 2 truck frames and 4 wheelsets with springs and dampers. Then, the vehicle has 31degrees of freedom. Actual vehicles have stoppers to control excessive relative displacement at each connection. In order to consider the stoppers, it was assumed that bi-linear springs were used for springs. Adequacy of these dynamic models has already been verified through vibration experiments using a vibration table and a full-scale vehicle model [3]. Tangible vehicle specifications were assumable in reference to a recent high-speed Shinkansen railway vehicle. The main input data of the mass are a vehicle length of 25m, a body mass of 312kN, a truck frame mass of 31kN, and a wheelset mass of 18kN for an empty vehicle. Therefore, the weight of the railway vehicle is 446kN and the unit weight/length of the vehicle is 17.8 kN/m. The main input data of springs and dampers are vertical and horizontal spring constants for the air-spring of 300kN/m and 180kN/m (half side of a truck), a damping constant for the air-spring of 50kN・s/m (half side of a truck), a damping constant for the lateral damper of 40kNs/m (a damper of a truck), 1200kN/m of the spring constant for the axle spring (half side of a wheelset) and the



(a) Design earthquake motions (b) Observed earthquake motions (c) Elastic acceleration response

Figure 5: Input earthquake motions

		3.1 Dynamic characteristics of railway vehicle	3.2 Dynamic characteristics of structure	3.3 Dynamic effect of railway vehicle during earthquake motion
Vehicle and interaction model		Interaction model	Interaction model Rigid model	Interaction model Rigid model
Structures	k_{hy}	-	0.3, 0.5, 0.7	0.3, 0.5, 0.7
	f_{eq}(Hz)	-	0.5, 1.0, 1.5, 2.0	0.1, 0.2, …, 3.0
	$\alpha(=w_s/w_t)$	-	1, 5, 10, 20	1
Input wave		Sinusoidal wave (0.01~5.0Hz, 50,200,400gal)	Sinusoidal wave (0.01~5.0Hz, 50,200,400gal)	L1 (G0 ~ 7), L2spectrum I (G0 ~ 7), L2spectrumII(G0 ~ 7) Tokachioki(observed in Niikappu), Tokachioki(observed in Hiroo)

k_{hy} is yield seismic coefficient; f_{eq} is yield frequency; w_s is structure unit weight/length; w_t is train unit weight/length

Table 1: Analysis cases

damping constant for the axle damper of 40 kNs/m (half side of a wheelset). In addition, gaps at each stopper were fixed at 20-30mm. Numerical simulations were conducted under the condition that 1-car train, which keeps running at 260km/h, interacts with structures without derailment and deviation. This condition was supposed to be severest for seismic response of structures.

Fig. 4 shows dynamic interactions between wheels and rails of the interaction model. Dynamic interaction forces between wheels and rails were calculated on the basis of vertical and horizontal relative displacement between them. The dynamic interaction force of vertical direction was modeled as the Hertz contact force and that of horizontal direction was modeled as the creep force and the flange pressure. The Hertz contact force is the vertical force which is a function of the vertical relative displacement δ_z between wheels and trails. The creep force is horizontal force due to the creep of the wheel moving forward by rolling on the rail. This creep force is saturated at the upper limit of friction force when the slipping ratio S of horizontal direction becomes large. The flange pressure is the horizontal force which is caused by the contact between the wheel flange and the rail. It was calculated with the rail tilting spring and the horizontal relative displacement between the wheel flange and the rail δ_y. These contact point and the contact angle were calculated on the basis of contact functions derived from the geometric configuration. Damping by the contact of wheels with rails was not considered.

2.2.2 Rigid model

As shown in Fig. 1**,** in the rigid model, railway vehicles and interactions between wheels and rails were modeled as one degree of freedom under the condition that the train weight of 100% was considered. In this model, the rigidity of the spring connecting a vehicle with a structure was sufficiently increased. This rigid model is a simple model commonly used in practical seismic design.

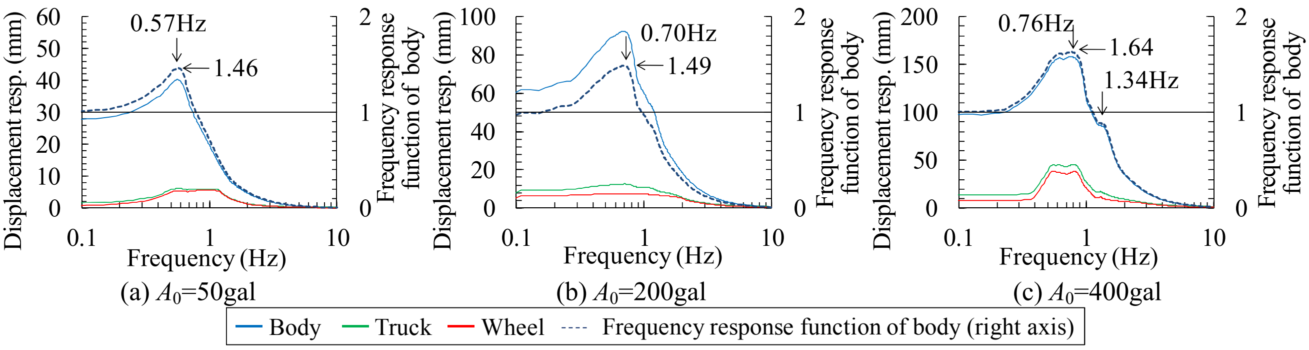


Figure 6: Frequency response function of railway vehicle

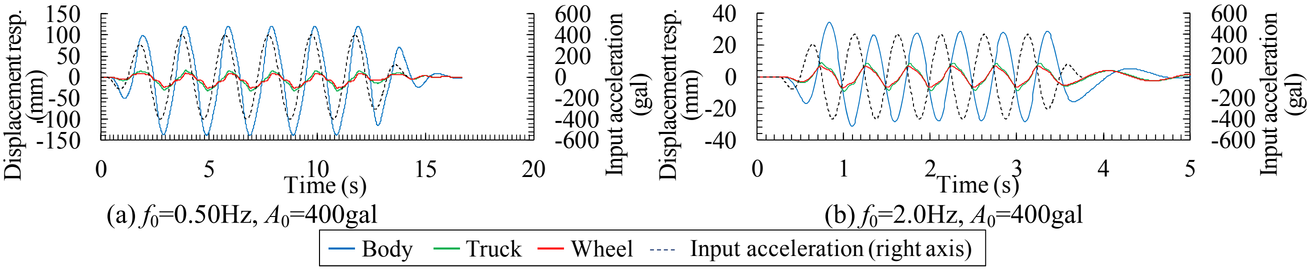


Figure 7: Time history of displacement response of railway vehicle in sinusoidal wave

2.3 Analysis cases

Table 1 indicates parameters and analysis cases in numerical analyses. This paper has 3 phases , to evaluate the dynamic characteristics of railway vehicles in **3.1**, to evaluate the dynamic characteristics of structures in **3.2** and to evaluate the dynamic effect of railway vehicles during earthquakes in **3.2**. Analytical parameter of vehicle and interaction model, structure and input wave was changed depending on each phase as shown in the Table. 24 design earthquake motions of L1, L2 spectrum I and L2 spectrum II for each of 8 ground classifications, G0 to 7 and two observed earthquake motions, at tokachioki(observed in Niikappu town or Hiroo town) , are used as shown in Fig. 5.

2.4 Numerical method

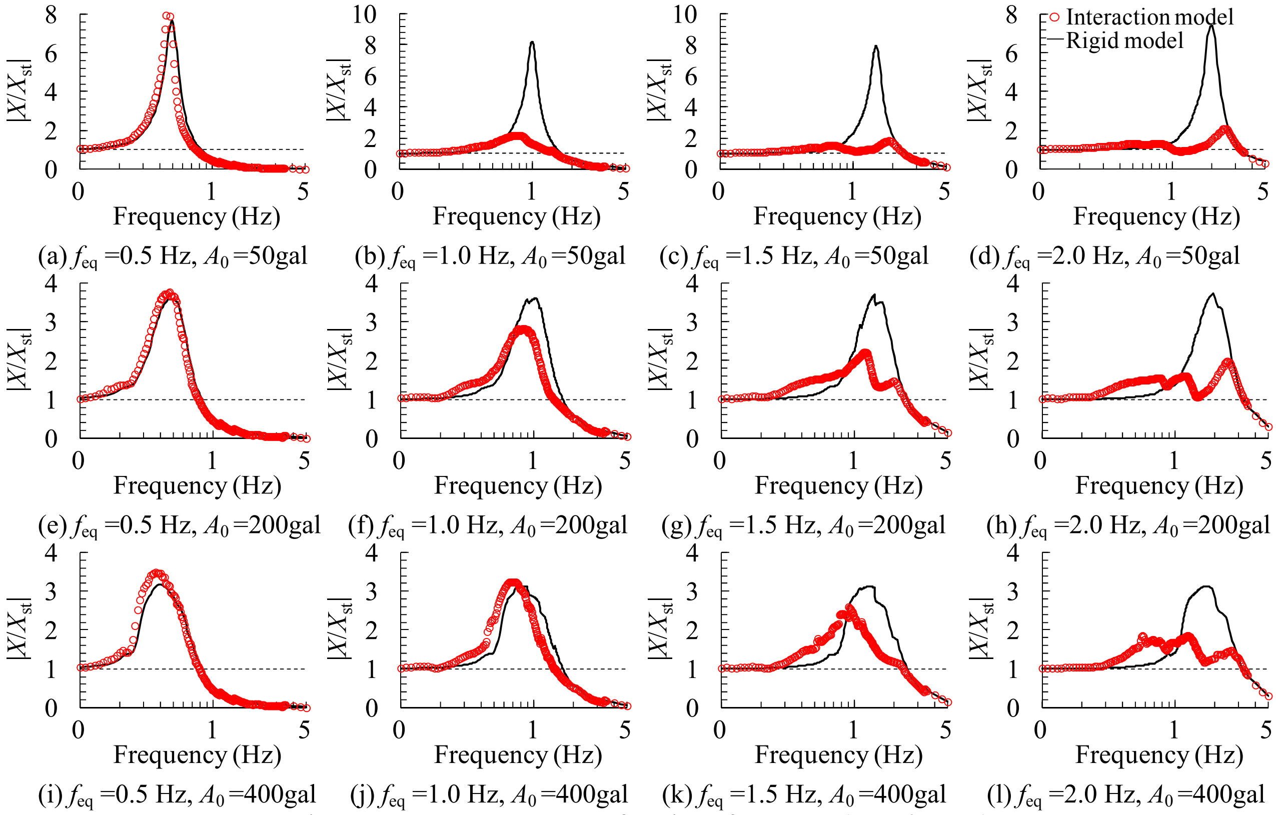
Equations of motion of vehicles and structures were solved in the modal coordinates for each time increment Δt by the *Newmark* time difference scheme. Iterative calculations were needed for each time increment until the unbalanced force becomes sufficiently small because the equations are nonlinear. The modal damping of 5% was considered for each eigenmode.

3 ANALYSIS RESULT

3.1 Dynamic characteristics of railway vehicle

The dynamic interaction analysis using sinusoidal waves was conducted to evaluate the frequency response function of railway vehicles.

The left axis of fig. 6 shows the maximum displacement response of the body, truck and wheelset in the cases where input acceleration is 50, 200 and 400gal, and the right axis of the figure shows the frequency response function of the vehicle body. The frequency response function is a ratio of the maximum displacement response of the body to the static displacement for which the displacement in the case where input acceleration frequency f_0 is 0.1Hz is substituted. The figure indicates that the predominant frequency of the body is 0.57Hz,



(a) f_{eq} =0.5 Hz, A_0=50gal (b) f_{eq} =1.0 Hz, A_0=50gal (c) f_{eq} =1.5 Hz, A_0=50gal (d) f_{eq} =2.0 Hz, A_0=50gal

(e) f_{eq} =0.5 Hz, A_0=200gal (f) f_{eq} =1.0 Hz, A_0=200gal (g) f_{eq} =1.5 Hz, A_0=200gal (h) f_{eq} =2.0 Hz, A_0=200gal

(i) f_{eq} =0.5 Hz, A_0=400gal (j) f_{eq} =1.0 Hz, A_0=400gal (k) f_{eq} =1.5 Hz, A_0=400gal (l) f_{eq} =2.0 Hz, A_0=400gal

Figure 8: Frequency response function of structure (α=1, k_{hy}=0.5)

0.70Hz and 0.76Hz in the cases of 50, 200 and 400gal respectively. It means that the natural frequency of vehicle superficially rises with the increase of input acceleration. In addition, the value of the frequency response function also increases from 1.46 to 1.64 with the increase of input acceleration, which means that railway vehicles can resonate easily when the input acceleration becomes larger. This is because when the input acceleration becomes larger, the wheel flanges are constantly in contact with rails and vehicle stiffness increases due to the contact of the bolster spring to stoppers in horizontal and vertical directions. As shown in the figure, the maximum displacement response of the wheelset exceeds 5mm which is the gap between the wheel flange and the rail in most frequency in the case of 200 or 400gal.

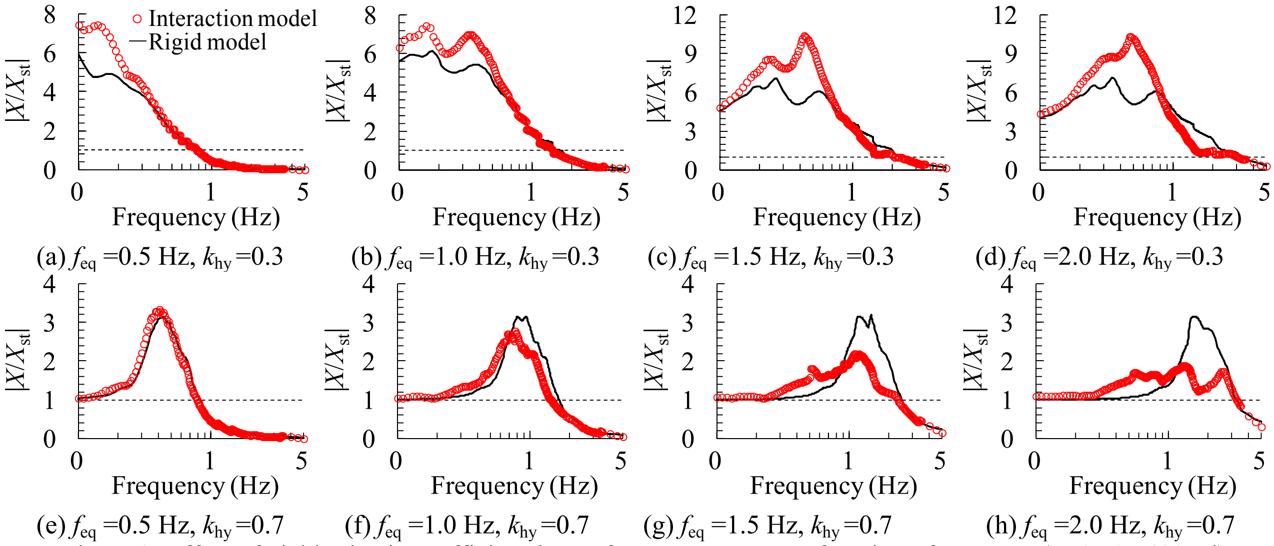
Fig. 7 depicts the representative time history of displacement of the body, truck and wheelset with input sinusoidal waves. The figure implies that each component of the vehicle vibrates in the same phase as the input wave in the case where input wave frequency f_0 is 0.5Hz. On the other hand, the phase lag can be observed in the case where f_0 is 2.0Hz

Therefore, it was found that the frequency response function of the railway vehicles exceeds 1 without phase lag in the range of less than 1Hz, whereas, that marks below 1 with phase lag in the range of higher than 1Hz.

3.2 Dynamic characteristics of structures in consideration of dynamic effect of railway vehicles

The dynamic interaction analysis using sinusoidal waves was conducted to evaluate the frequency response function of the structure.

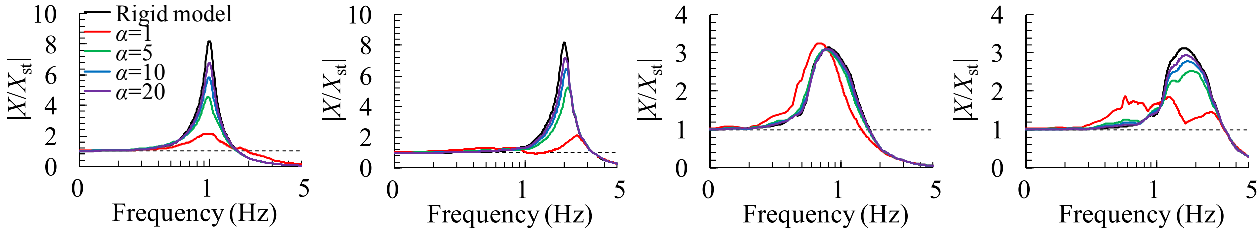
Fig. 8 shows the frequency response function of the structure $|X/X_{st}|$ of the interaction model and the rigid model when the unit weight ratio α is 1 and the yield seismic coefficient k_{hy} is 0.5. The function is a ratio of the maximum displacement response of the structure X to static displacement X_{st} which is gained by Eq. (1)



(a) f_{eq} =0.5 Hz, k_{hy} =0.3 (b) f_{eq} =1.0 Hz, k_{hy} =0.3 (c) f_{eq} =1.5 Hz, k_{hy} =0.3 (d) f_{eq} =2.0 Hz, k_{hy} =0.3

(e) f_{eq} =0.5 Hz, k_{hy} =0.7 (f) f_{eq} =1.0 Hz, k_{hy} =0.7 (g) f_{eq} =1.5 Hz, k_{hy} =0.7 (h) f_{eq} =2.0 Hz, k_{hy} =0.7

Figure 9: Effect of yield seismic coefficient k_{hy} on frequency response function of structure (α=1, A_0=400gal)



(a) f_{eq} =1.0 Hz, A_0 =50gal (b) f_{eq} =2.0 Hz, A_0 =50gal (c) f_{eq} =1.0 Hz, A_0 =400gal (d) f_{eq} =2.0 Hz, A_0 =400gal

Figure 10: Effect of unit weight ratio α on frequency response function of structure

$$X_{st} = \frac{k_h g}{(2\pi f_{eq})^2} \tag{1}$$

These figures indicate that, in the case of f_{eq} =0.5Hz, the frequency response function of the interaction model and that of the rigid model mostly agree with each other and that of the interaction model slightly exceeds that of the rigid model when the frequency is less than 0.5Hz as shown in Fig. 8(i). By contrast, when f_{eq} is more than 1.0Hz, a large difference can be observed between them, which imply dynamic effect of railway vehicles obviously appears. The dynamic effect increases the structure response when the frequency is less than about 1.0Hz, whereas the dynamic effect decreases it when the frequency is more than about 1.0Hz. In addition, the frequency response function of the structure of the interaction model becomes larger with the increase of input acceleration. This is because the amplification ratio of vehicle response becomes large with the increase of input acceleration. Therefore, the frequency response function of structures in consideration of the dynamic effect of railway vehicles varies depending on the degree of the railway vehicle response.

Fig. 9 shows the effect of the yield seismic coefficient k_{hy} on the frequency response function of structures in the case where the unit weight ratio α is 1 and input acceleration is 400gal. The figure, in the case of k_{hy}=0.3, shows that the frequency response function of the interaction model significantly exceeds that of the rigid model especially in a low-frequency, compared to the case of k_{hy}=0.5 as shown in Fig. 8(i)~(l). In addition, the reduction degree due to the dynamic effect which is found in the frequency from 1 to 2 Hz becomes lower. On the other hand, in the case where k_{hy} is 0.7 shown in Fig. 9(e)~(h), the plastic structure response becomes small and the frequency response function of the interaction model shows smaller value, which is the opposite trend to the case of k_{hy}=0.3. This is because structures of small k_{hy}

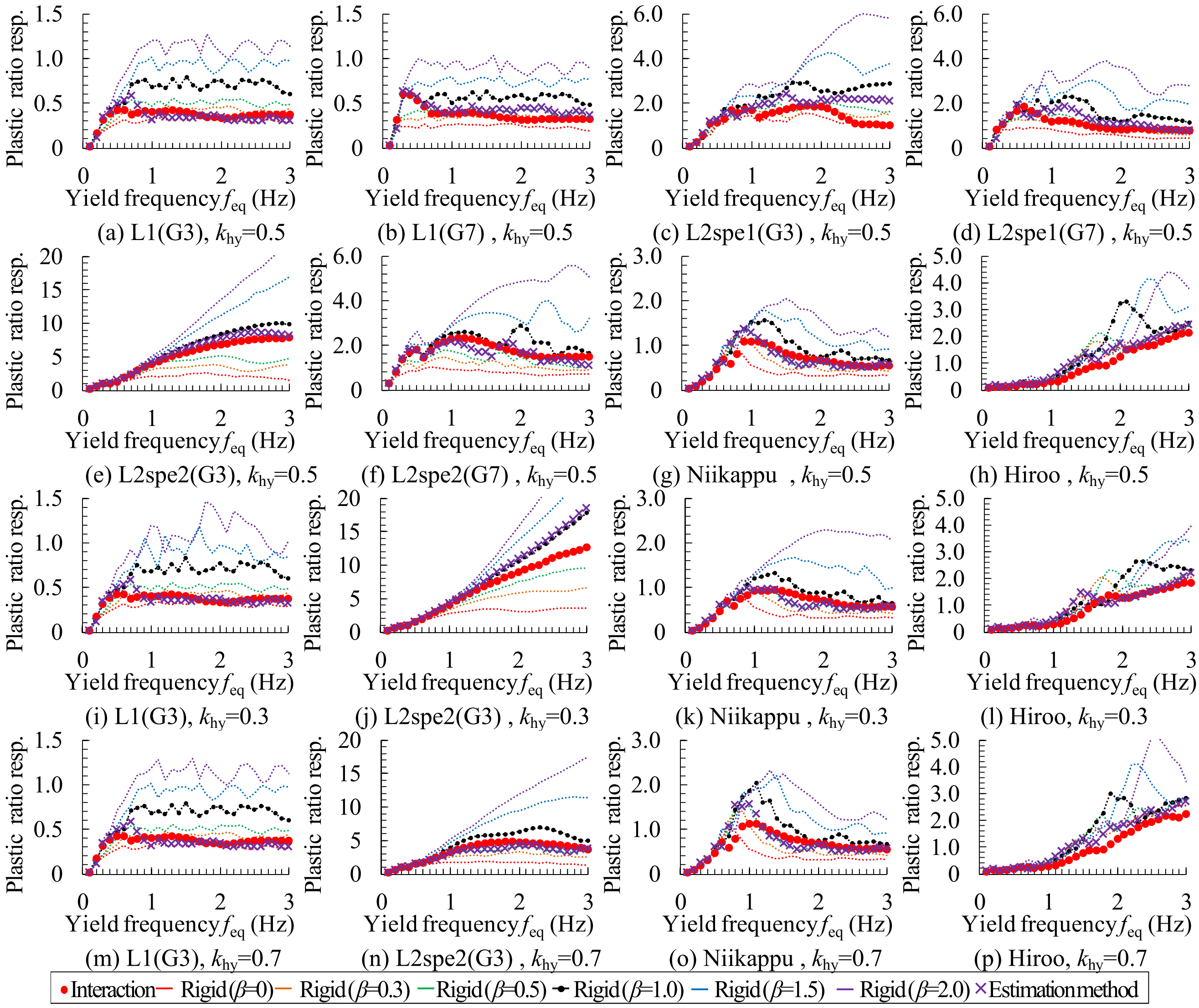


Figure 11: Dynamic effect of vehicle on structure under earthquake motion (α=1)

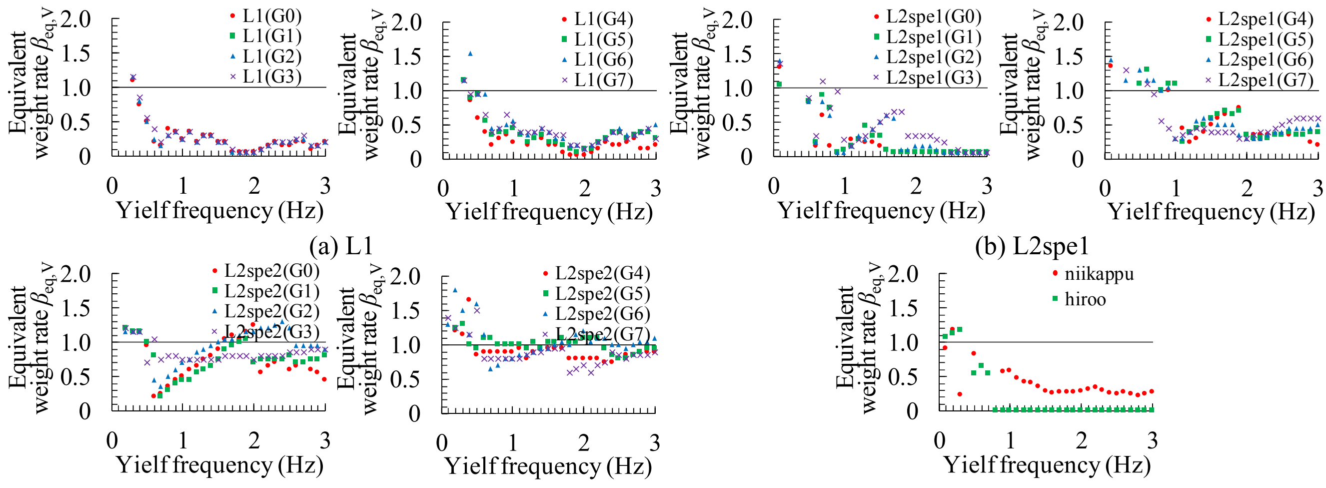
tend to respond plastically and the natural frequency of structures superficially decreases when the structure response is amplified.

Fig. 10 shows the effect of the unit weight ratio α on the frequency response function of structures in the case where f_{eq} is 1.0 or 2.0Hz and input acceleration is 50 or 400gal. The figure explains that the difference of functions between the interaction model and the rigid model becomes larger with the decrease of α, whereas the functions mostly matches and the dynamic effect of railway vehicles becomes small when α is larger than 10.

3.3 Dynamic effect of railway vehicles during earthquake motions

The dynamic interaction analysis using earthquake motions was carried out to evaluate the dynamic effect of vehicles on structures under earthquake motions.

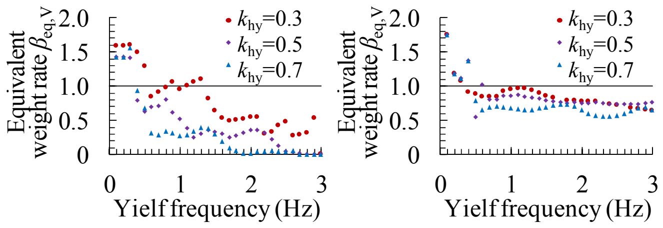
Fig. 11 shows the dynamic effect of vehicles on structures under earthquake motion by means of a comparison of plastic ratio response between the interaction model and the rigid model in the case where the unit weight ratio α is 1. The plastic ratio is a ratio of the maximum displacement to the yield displacement. Horizontal axis is the yield frequency f_{eq} calculated in consideration of 100% of vehicle weight. The f_{eq} of actual railway structures ranges approximately within 0.5~2.0Hz. As shown in these figures, in the cases where f_{eq} is less than 0.5Hz, the plastic ratio response of the interaction model mostly becomes equivalent to or ex-



(a) L1 (b) L2spe1

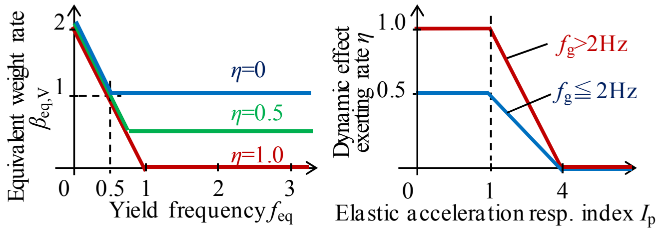
(c) L2spe2 (d) Observed earthquake

Figure 12: Equivalent weight rate to dynamic effect of railway vehicle $\beta_{eq,V}$ (α=1, k_{hy}=0.5)



(a) L2spe1(G3) (b) L2spe2(G3)

Figure 13: Effect of k_{hy} on $\beta_{eq,V}$



(a) Proposed method $\beta_{eq,V}$ (b) Proposed method η

Figure 14: Proposed method for estimating $\beta_{eq,V}$

ceeds that of the rigid model. On the other hand, in the cases where f_{eq} is more than 0.5Hz, that of the interaction model becomes smaller than that of the rigid model. The dynamic effect significantly appears especially in the case of small α. Furthermore, the dynamic effect is dependent on the earthquake, that is, it can be obviously seen when structures respond elastically due to small motions such as L1 earthquake, but it diminishes when structures respond plastically due to large motions such as L2 earthquake. In addition, there are characteristic cases in which the dynamic effect can be seen clearly even when the plastic ratio is comparatively large such as Niikappu earthquake or it becomes small even when the plastic ratio is comparatively small such as Hiroo earthquake. From these tendencies, the degree of the dynamic effect under earthquake motions depend on the difference of the frequency response function of the interaction model shown in Fig. 8 and the characteristics of input earthquake motions. For example, in the case of f_{eq}=0.5Hz shown in Fig. 8, there is little difference between the interaction model and the rigid model regardless of earthquake motions, because the frequency response function of both models matches. In the cases where f_{eq} is more than 0.5Hz, the response reduction effects exceed the enhancing effect because the frequency response function of the interaction model falls below that of the rigid model in a high frequency.

Therefore, the dynamic effect of vehicles affects the structure response under earthquake motions, and the effect depends on the characteristics of the earthquake, the degree of the plastic behavior of the structure and the yield frequency. The structure response varies in the range of -50~20% due to the dynamic effect of railway vehicles in the case of α=1.

3.4 Modeling of dynamic effect with equivalent vehicle weight rate $\beta_{eq,V}$

Fig. 12 shows the equivalent weight rate to dynamic effect of railway vehicles $\beta_{eq,V}$ in the cases where α=1 and k_{hy}=0.5. $\beta_{eq,V}$ is the value of β at which the plastic ratio response of the rigid model and that of the interaction model agree each other. It was calculated as a function of the characteristics of earthquake motions, f_{eq} and k_{hy}. As shown in Fig. 12(a)~(b), $\beta_{eq,V}$ marks less than 0.3 in the cases where f_{eq} is more than 1Hz under L1(G0~3) or L2spectrum2(G0~3) earthquakes and it marks more than 0.5, which is comparatively large value, in the cases where f_{eq} is more than 1Hz under L2spectrum2(G0~3) earthquakes. In the cases of earthquakes of G4~7 ground, $\beta_{eq,V}$ rises by 0.1~0.5 in comparison to the results of earthquakes of G0~3 ground because these earthquakes contain lots of low-frequency components which do not contribute to the response reduction effect. In most cases where f_{eq} is less than 0.5Hz, $\beta_{eq,V}$ exceeds 1 and the enhancing effect appears remarkably.

As shown in Fig. 12(c), $\beta_{eq,V}$ marks around 0 which is a small value under Hiroo earthquake because the earthquake contains lots of high-frequency components although the plastic ratio response of structures excessively exceed 1. On the contrary, $\beta_{eq,V}$ marks about 0.5 under Niikappu earthquake because the earthquake contains lots of low-frequency components although the plastic ratio response of structures is below 1.

Fig. 13 shows the effect of the yield seismic coefficient k_{hy} on the equivalent weight rate $\beta_{eq,V}$. As shown in the figure, $\beta_{eq,V}$ increases with decrease of k_{hy}, which explains that the dynamic effect doesn't tend to appear when k_{hy} is small.

Fig. 14 is the proposed method of estimating the equivalent weight rate $\beta_{eq,V}$. $\beta_{eq,V}$ was modeled on the basis of the result of Fig. 12~13; $\beta_{eq,V}$ varies from 0 to 2 depending on the characteristics of earthquake motions, f_{eq} and k_{hy}. It was calculated by Eq. (2) the function of which is f_{eq} and dynamic effect exerting rate η.

$$\beta_{eq,V} = \begin{cases} -2f_{eq} + 2 & (0.1 \le f_{eq} \le 0.5\eta + 0.5) \\ 1 - \eta & (0.5\eta + 0.5 \le f_{eq} \le 3) \end{cases} \tag{2}$$

The dynamic effect exerting rate η is defined as Eq. (3) which varies from 0 to 1 as a function of I_g depending on the ground natural frequency f_g and the elastic acceleration response index I_p.

$$\eta = \begin{cases} I_g & (0 \le I_p \le 1) \\ I_g(1.5 - 0.5I_p) & (1 \le I_p \le 4) \\ 0 & (4 \le I_p) \end{cases} \tag{3}$$

I_g is fixed at 1 when f_g is more than 2Hz and at 0.5 when f_g is less than 2Hz in order to express the frequency characteristics of earthquake motions containing lots of low-frequency components. I_g which expresses the degree of the plasticity of structures is calculated by a ratio of $A_r/k_{hy}g$. A_r is the elastic acceleration response in the case of f_{eq}.

Fig. 11 shows a comparison of plastic ratio response between the interaction model and the rigid model applying the proposed estimation method based on the equivalent weight rate $\beta_{eq,V}$. The figure shows that the estimation method is generally able to reproduce the response of the interaction model regardless of earthquake, including observed earthquake, motions, f_{eq} and k_{hy}. Thus, the validity of the proposed method is confirmed.

4 CONCLUSION

This paper aims to evaluate dynamic effects of railway vehicle on seismic response of structures, and to develop a reasonable modeling method of running railway vehicles in seismic design. As the result of numerical simulations, this paper concludes as follows.

- The frequency response function of the railway vehicles exceeds 1 without phase lag in the range of less than 1Hz, whereas, that marks below 1 with phase lag in the range of higher than 1Hz.
- The frequency response function of structures in consideration of the dynamic effect of railway vehicles varies depending on the degree of the railway vehicle response. The dynamic effect increases the structure response when the frequency is less than about 1Hz, whereas it decreases that when the frequency is more than about 1Hz.
- The dynamic effect of vehicles affect the structure response under earthquake motions, and the effect depends on the characteristics of the earthquake, the degree of the plastic behavior of structures and the yield frequency. The structure response varies in the range of -50~20% at its maximum due to the dynamic effect at a maximum.
- An estimation method using the equivalent weight rate $\beta_{eq,V}$ is proposed in order to evaluate the dynamic effect of railway vehicles.

REFERENCES

[1] Railway Technical Research Institute, *Design Standards for Railway Structures and Commentary (Seismic Design)*, Maruzen Co., Ltd, Tokyo, 2012 (in Japanese).

[2] Wakui, H., Matsumoto, N., and Tanabe, M., *A Study on Dynamic Interaction Analysis for Railway Vehicles and Structures - Mechanical model and practical analysis method -*, *Quarterly Report of RTRI*, *Vol.35*, *No.2*, 96-104, 1994.

[3] Miyamoto, T., Matsumoto, N., Sogabe, M., Shimomura, T., Nishiyama, Y. and Matsuo, M., *Full-scale Experiment on Dynamic Behavior of Railway Vehicle against Heavy Track Vibration*, *Journal of Environment and Engineering*, *Vol.2*, *No.2*, 419-428, 2007.