Improvement of Running Safety of Railway Vehicles against an Earthquake
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Abstract
In this paper, we developed a lateral damper to improve the running safety of railway vehicles against an earthquake. Although the developed damper has the same damping force characteristics as the conventional lateral damper in the usual piston velocity region, the former has larger damping force characteristics than the latter in unusually high piston velocity region. At first, we experimentally tested the developed damper using a full-scale vehicle model consisting of one bogie and a half carbody on our own large shaking test facility and confirmed that the vehicle equipped with the developed damper was more difficult to be derailed by an earthquake than the vehicle equipped with the conventional damper. Then, we quantitatively estimated the effect of the developed damper on the running safety of Shinkansen trains against an earthquake using numerical simulations. Finally, we carried out on-track running tests and checked that the developed lateral damper behaved like the conventional damper in normal operation.

1. Introduction
After the South Hyogo Prefecture Earthquake in 1995, we started developing a Vehicle Dynamics Simulator (VDS) for seismic vibration\(^1\). We have revealed the dynamic behaviour and the running safety limits of vehicles on a vibrating track using the VDS. The results are applied to the design of railway structures in Japan\(^2\). We have also developed an experimental method to investigate the behaviour of a full-scale vehicle model consisting of a real bogie for Shinkansen and a half carbody in a range of vibrations of large-amplitude\(^3\). The results of numerical simulation are well in agreement with the experimental results. In October 2004, a Shinkansen train was derailed in Japan as a result of the Mid Niigata Prefecture Earthquake. This was the first ever earthquake-related derailment of a Shinkansen train running at high speed. Following the accident, there were calls for safety countermeasures against earthquakes. To respond to this needs, we examined performance improvement for safe running by modifying the parameters of the bogie using the VDS and contrived a concept exchanged the lateral damper between the carbody and bogie for a damper with larger damping force than the conventional damper in high piston speed region\(^4\).

In this paper, we developed the lateral damper to improve the running safety of railway vehicles based on the contrived concept. We experimentally tested the lateral damper using a full-scale vehicle model consisting of one bogie and a half carbody on our own large shaking test facility. In addition, we quantitatively estimated the effect of the lateral damper on the running safety against an earthquake by experiments and numerical simulations. Finally, we carried out on-track running tests and checked that the developed lateral damper behaved like the conventional damper in normal operation.

2. Design concept of the characteristics of the developed lateral damper
Figure 1 shows the external appearance of the developed lateral damper. This damper is designed for a Shinkansen train and can be exchanged for the conventional lateral damper without remodelling bogies. Figure 2 shows the damping force characteristics of the developed damper and the conventional damper. Although the developed lateral damper has the same damping force characteristics as the conventional one in the low piston velocity region, it has a larger damping force than the conventional one in the high piston velocity region. Therefore, the developed lateral damper behaves like the conventional one during the usual running, but shows the effect of large damping force when the train encounters with an earthquake and the relative lateral displacement between a bogie and a carbody becomes extremely large.
3. Experimental Confirmation of the performance of the developed damper

In order to confirm the performance of the developed lateral damper, we put it to a test using a full-scale vehicle model consisting of one bogie and a half carbody on our own large shaking test facility. The schematic drawing of the structure and the main specification of the shaking test facility are shown in Fig. 3 and Table 1, respectively. In the experiments, a 1435mm gauge track is laid in y-direction of the shaking table and the vehicle model is oscillated in x-direction with the maximum acceleration of 9.8m/s² or the maximum amplitude of 1000mm. Figure 4 shows the experimental device on the shaking table. Because of a half carbody model, the carbody is supported by only two secondary suspensions so that the carbody has anti-fall mechanisms to prevent turnover.
3.1 Sinusoidal waveform oscillation test

In order to understand fundamental performance of the developed damper, we firstly tested it by sinusoidal waveform oscillations. In the experiment, we gradually increased the oscillation amplitude at the same frequency and paid attention to the oscillation amplitude when the wheel load became zero. Figure 5 shows the comparison between the developed damper and the conventional damper about the oscillation amplitude when the wheel load becomes zero. As a result, the developed damper improves running safety from conventional damper in the frequency range above 0.7 Hz.
3.2 Real seismic waveform oscillation test
For the evaluation of the running safety against an earthquake, we oscillated the bogie and carbody with a real seismic waveform, changing the amplitude of the seismic waveform. Then we investigated the amplitude of the oscillation when the wheel load becomes zero. Figure 6 shows the comparison between the developed damper and the conventional one with respect to the oscillation amplitude in case that the wheel loads became zero. From Fig. 6, it can be said that the developed damper also improves the running safety more than the conventional damper against real seismic vibration.

Fig. 6  Experimental results of countermeasure against seismic motion

4. Estimation of the effect of the developed damper on the running safety against an earthquake
4.1 Comparison between experiment and numerical simulation
In the experiment described above, we could test only a vehicle model consisting of one bogie and a half carbody. Therefore, for the estimation of the quantitative effect of the developed damper, it is necessary to simulate the dynamics of a full railway vehicle model consisting of one carbody, two bogies and four wheelsets. At first, we compared the results of the numerical simulation of a half carbody and one bogie model and the experimental results. The simulation program we used was the VDS. Figure 7 shows a simulation model which matches the experimental device consisting of a carbody, a bogie and two wheelsets. Each body has six degrees of freedom, connected with springs and dampers. The anti-fall mechanisms restrict the yawing and pitching motion of the carbody so that those are modelled by stiff rotary springs in both the yawing and the pitching directions.

Fig. 7  Numerical model for the experimental device
Figure 8 shows the typical results of the numerical simulations and the experiments. Although the simulated result does not have very sharp peaks, the other characteristics of the waveform are similar to the experimental result, particularly the time when the wheel load becomes zero is the same. Therefore, it can be said that the results of the numerical simulation are quantitatively in agreement with the results of the experiment.

4.2 Numerical simulation for estimation of the effect of the developed damper

In this section, we numerically simulated the behaviour of Sinkansen train using full vehicle model consisting of one carbody, two bogies and four wheelsets shown in Fig. 9. We compared the running safety limits of the Sinkansen train against sinusoidal vibration, when it is equipped with the developed lateral damper and with the conventional lateral damper. The calculation condition is as follows:

1) The train runs on the straight track with no slope or irregularity at a constant speed of 275 km/h.
2) Four sinusoidal track vibrations are input to the slab under each wheel in the same phase.
3) The amplitude of track vibration is increased every 5 mm with a constant frequency until the vehicle derails.
4) 'Derailment' is judged by a relative lateral displacement of wheel and rail up to 70 mm.
5) If the vehicle derails at a certain amplitude, that amplitude value minus 5 mm is determined as the
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Figure 10 shows the calculated results of the increase ratio of the running safety limit. From Fig. 10, it can be said that the running safety limit with the use of the developed damper is higher than or equal to that with the use of the conventional damper in all frequency region from 0.3 Hz to 3.0 Hz. In particular, the increase ratio in the range from 1.2 Hz to 2.2 Hz is large. Therefore, the developed lateral damper can suppress the upper center rolling vibration of a vehicle efficiently.

5. On-track running test

In order to check that the developed damper does not make the running safety of the usual running worse, we installed the developed damper in an experimental Shinkansen train for the high speed running test and carried out on-track tests. The running speed was from 245 km/h to 315 km/h. The experimental results about the piston speed of the developed damper are shown in Fig. 11. The piston speed is less than 200 mm/s that was the maximum piston speed in design of the conventional damper. The developed damper has been designed to gain the same characteristics as the conventional damper within this piston speed region. Therefore, it is confirmed that the developed damper does not affect the running safety and ride quality under the normal operating condition.

Fig. 10  Increase ratio of running safety limit of Shinkansen train obtained by simulations

Fig. 11  Experimental results of on-track running test
6. Conclusions

In order to improve the running safety of the railway vehicles against an earthquake, we developed a lateral damper. The developed lateral damper behaves like the conventional one during the usual running and shows the effect of the large damping force when the train encounters with an earthquake. We confirmed that the performance of the developed lateral damper by the experiments of full-scale vehicle model consisting of a half carbody and one bogie on our own large shaking test facility. For quantitative estimation of the effect of the developed lateral damper, we firstly showed that the numerical simulation results were quantitatively in agreement with the results of the experiment. Then, by numerical simulations, we showed that the developed lateral damper can increase the running safety limit of Shinkansen train by the maximum value of 17% according to the frequency of seismic vibration than the conventional lateral damper. Finally, we carried out on-track tests of the developed lateral damper and confirmed that the developed damper does not affect the running safety and ride quality under the normal operating condition.

References