Construction of a Vibration Analysis Model for Railway Vehicles Used for Examination in the Design Phase to Improve Ride Comfort

In this study, we aim at allowing vehicle vibration to reproduce to high frequency in simulation to enable ride comfort improvement to be examined at the design stage. For the model that could reproduce vehicle vibration including high-frequency vibration, we chose the FEM model and built a vehicle vibration model in combination with bogie models. As a result of having carried out simulation to around 300 Hz by the vehicle vibration model that we built, the calculation results almost corresponded with the actual values in vertical vibration acceleration PSD of the vehicle.

**Keywords:** Ride comfort, FEM, Vehicle vibration model, Vibration analysis, Simulation

### 1 Introduction

With high-speed railway rolling stock in recent years, vertical primary bending vibration where a peak in the vicinity of 10 Hz occurs stands out due to factors such as rigidity of lighter rolling stock bodies being lower and rigid body vibration in the vicinity of 1 to 2 Hz being minimized by means such as application of vibration control. In light of this, a variety of simulation analyses have been conducted for this frequency range in order to lead to improved ride comfort. 1) - 4).

Meanwhile, with increases in speeds on high-speed railways, higher 10 to 40 Hz vibrational components (hereinafter, "high-frequency vibration") are tending to increase. The impact of those components cannot be appropriately expressed when assessing by ride comfort levels used since the Japanese National Railways era, and we found that weighting for ride comfort level is too low 5). Therefore, it is necessary to reduce vibration in this frequency range in order to improve ride comfort of high-speed railways.

In this study, we aim to construct a vibration analysis model of running vehicles in order to be able to reproduce in simulations vibration including high-frequency vibration. With that, we hope to be able to examine improvements to ride comfort of rolling stock at the design stage.

For the vehicle vibration model, we selected a high-frequency vibration analysis model for up to 40 Hz, and we compared results from that with measured data to verify accuracy.

### 2 Construction of Vehicle Vibration Model

#### 2.1 Method of Constructing Vehicle Vibration Model

In reproducing vibration of running vehicles, we had analyzed vertical vibration of vehicle bodies including their bending vibration from the past, and the methods as shown in Table 1 have been proposed for constructing a vehicle body model.

In this study, it is important to examine ride comfort in the design stage before the body is actually completed, so a model where calibration with actual data is unnecessary as much as possible is preferable 6). And as we are aiming to recreate vehicle vibration including high-frequency vibration, we decided to apply the FEM model, which can reproduce even complex vibration modes that occur at the high-frequency range. With the FEM model constructed up to now, reproducibility has been achieved up to about 20 Hz 7); however, by more detailed modeling and improvement in computer’s abilities, we believe that we will be able to reproduce vibration greater than 20 Hz.

Middle cars of Series E5 Shinkansen rolling stock are to be modeled, and models are built in 3D according to design drawings and design specifications.

<table>
<thead>
<tr>
<th>Modeling method</th>
<th>Beam</th>
<th>FEM</th>
<th>Shell</th>
<th>Box</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of modeling</td>
<td>○</td>
<td>△</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>3D vibration form</td>
<td>×</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Degree of freedom</td>
<td>Up to a few tens</td>
<td>From tens of thousands</td>
<td>Tens</td>
<td>Hundreds</td>
</tr>
<tr>
<td>Calibration with measurements</td>
<td>Required</td>
<td>Not required</td>
<td>Required</td>
<td>Required</td>
</tr>
</tbody>
</table>

#### 2.2 Construction of Vehicle Body Model

First we modeled the body structure, faithfully reproducing planar shell elements according to design drawings for roof, side, floor, and end components. Shell elements were placed at the center of plate thickness of members. Complex shaped items were reproduced in solid elements. Individual material property values and the like were input for properties of individual elements.

Moreover, a vehicle body model was created by adding interior and under-floor equipment to a body structure model. Fig. 1 shows part of an interior model. In the interior model, locations thought to affect body rigidity (floor plates, etc.) were faithfully reproduced with planar shell elements according to design drawings, and individual material property values and the like were input for properties of individual elements, as was done with the body structure model. Locations that would not affect rigidity were simplified as much as possible (luggage racks, etc.). And locations thought to not affect body rigidity
Next, we will cover creation of track data. Track data for reproducing bogie vibration while running was created from measurements by a track inspection car. The section reproduced was the 375 to 378 km section of the inbound Tohoku Shinkansen track, and data is extracted from results of measurements by a track inspection car. However, extracted results of measurements by a track inspection car can only be reconstructed in wavelengths of 6 to 100 m. For that reason, the scope reconstructed when running at 320 km/h is limited to 0.89 to 14.8 Hz with high-frequency vibration of 15 Hz or higher not included. So, in order to improve reproducibility of bogie vibration, high-frequency components (15 Hz or higher) were reproduced with mass elements, and loads were placed on connection locations through attachment parts.

Locations difficult to reproduce (conduits, etc.) and detailed parts (attachment bolts, etc.) were reproduced by simplifying where possible based on planar shell elements.

In order to raise model accuracy, it is important to match mass with the actual situation.6)

2.3 Constructing Bogie Model Incorporating Track Data

We modeled bogies based on specification data and input track data to reproduce bogie vibration when running. We compared the reproduced bogie vibration with measured data, verified and corrected accuracy, combined the obtained bogie model with the body model built in 2.2 for a full-vehicle model, and input track data and running conditions to make a running model (Fig. 2). In this study, taking into consideration vehicle vibration reproduction results by existing simulations, we made vibration in the vertical direction to be that for which reproduction accuracy is principally improved.

First, we will cover constructing a bogie model. Here we used the SIMPACK (Ver. 9.7) multibody dynamics analysis tool to create a bogie model. The exterior and structure of the model are shown in Fig. 3 and 4. The bogie frame was made to be a rigid body, damping coefficient of the dampers was made to be nonlinear characteristics to reproduce an actual car with good accuracy, and cushion rubber too was modeled.
not included in measurement data were added. Specifically, correction is added linearly for power spectrum density (PSD) so bogie vertical acceleration is close to measured values for longitudinal level irregularity and so bogie lateral acceleration is close to measured values for alignment.

2.4 Verification of Bogie Model Accuracy
In order to verify accuracy of the bogie model, we input track data to a full-vehicle model combining models of two bogies and a rigid body model, conducted running simulation, and calculated bogie vibration when running. Track data is for the 375 to 378 km section of the inbound Tohoku Shinkansen track. Wheel profile was set as the Shinkansen arc wheel profile when newly produced, top surface of rail set as that of 60 kg rail when newly produced, and running speed set as 320 km/h. Bogie vibration measurement was done at the locations shown in Fig. 5 with the dampers between cars removed to eliminate the effects of behavior of the adjacent cars.

Fig. 6 shows comparisons of bogie vertical vibration acceleration PSD calculated values and measured values at the No. 1 air spring position with and without track data correction. By correcting track data, results are close to measured values at 15 Hz or higher where there was divergence from the rest. As a result of making the corrections in Fig. 6, there are parts where PSD drops in the vicinity of calculated values for 18 Hz and 53 Hz. The distance between axles used in this study is 2.5 m. At 320 km/h, 1/2 wavelength is equivalent to 17.8 Hz and 3/2 wavelength is equivalent 53.3 Hz. Therefore, the drop in PSD at this part is assumed to be because front and back axles of the bogie were excited at opposite phases. Meanwhile, in the vicinity of measured values for 50 Hz, there is response with high PSD. This is assumed to be due to the vertical bending natural frequency of the bogie frame itself, and it is not present in calculation results. Reproducibility in terms of that will probably improve by creating a bogie FEM model and incorporating that in the full-vehicle model with a framework similar to that of the body model.

The results above show bogie vertical acceleration results are close to those of measured values in the vicinity of 1 to 40 Hz when using the bogie model created and track data after correction. Therefore, we used those in constructing subsequent running models.

2.5 Constructing Full-vehicle Model
A full-vehicle model can be created by combining the body model created in 2.2 and the bogie model created in 2.3. However, when the body model was incorporated in SIMPACK, there are many localized natural modes generated in body and rigging (5,400 at 8 to 20 Hz in this study), so the model was simplified and degenerated (reduced degree of freedom to the extent that structure characteristics are not lost) for simulation in practical calculation time.

As a result, natural frequency modes up to 40 Hz are reduced to 106 and simulation in practical calculation time is possible.

3 Verification of Accuracy of Vehicle Vibration Model

3.1 Measurement of Body Floor Vibration while Running
For measured data used for verification of accuracy of the vehicle vibration model, we measured vertical vibration of the body floor under various running conditions using a Series E5 car. Fig. 7 shows the measurement results. Running conditions were speed of 320 km/h and 375 to 378 km section of the inbound Tohoku Shinkansen track.
3.2 Reproduced Characteristics of Body Floor Vibration

We conducted running simulations with the running conditions shown in 3.1 and reproduced the time series vibration at the body floor vibration measurement positions of Fig. 7. Here we show the body floor vertical vibration acceleration PSD results for b (floor above bogie) and d (center of body) in dotted lines in Fig. 7.

Fig. 8 shows the results when comparing measured and calculated values for vertical vibration acceleration PSD and ride comfort level from improved filter \(f_{\text{LTN}}\). In the range of about 30 Hz, we find that bogie vertical vibration acceleration PSD tendencies correspond for the most part with calculated and measured values. However, at both sides of the floor above the bogie (Fig. 8 (a) and (c)), calculated values tended to be larger in the range 23 Hz or greater. As a result of confirming bogie vertical vibration acceleration PSD with roll components and translational components, calculated values were larger compared with measured values for high-frequency vibration with roll components. With translational components, however, calculated values were smaller, so it is assumed that roll components are emphasized more in calculations and such a phenomenon occurred.

Also, a high peak caused by wheel imbalance can be seen in the vicinity of 33 Hz with measured values. The effects of wheel imbalance are not considered in calculations, so a high peak does not exist there. And with this model, the bogie frame is a solid body and elastic vibration is not considered. Therefore, reproduction accuracy in the high-frequency vibration range is assumed to become higher by considering bogie frame elastic vibration.

4 Conclusion

In order to enable examination of improvements to ride comfort in the design stage of railway rolling stock, we built a vehicle vibration model that is modeled in detail by FEM with an aim of reproducing vibration up to about 40 Hz.

With the vibration model constructed, running simulation results showed that body vertical vibration acceleration PSD trend calculated and measured values correspond for the most part in the frequency range of up to about 30 Hz. In the future, we will examine improving at 30 Hz or higher.

Reference: