A Numerical Simulation Method for Ground and Building Vibration Based on Three Dimensional Dynamic Analysis

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The analysis of the whole model of train-induced vibration, which consists of the moving train, the track, the supporting infrastructure, the ground, and the building, is currently too large to solve. We thus proposed a numerical simulation method by combining two separate dynamic analysis models. One is an analysis model of the dynamic interaction between the moving train and the track-structure system for calculating excitation force. The other is a three-dimensional dynamic analysis model of the supporting structure, the ground, and the building for calculating the propagation of vibration.

Keywords: train induced vibration, dynamic interaction, three dimensional dynamic analysis, three dimensional dynamic combined analyses, ground vibration, building vibration, numerical simulation

1. Introduction

The vibrations of wayside ground and buildings caused by running trains (hereafter referred to as “train-induced vibrations”) can become environmental issues. In clarifying how train-induced vibrations are generated and propagated and studying effective prediction methods and mitigation measures, predictive simulation is an important tool. While train-induced vibrations are generated by running trains just like vibrations caused by road traffic, they have certain properties unique to railway such as high periodicity of exciting force caused by the passing of a series of similarly structured cars, high frequencies caused by the contact between steel wheels and rails, and a coupled vibration system consisting of a track, railway-specific structures, and cars.

In the field of predictive simulation of train-induced vibrations, numerous studies have been conducted from the perspectives stated above on both source and propagation models. Efforts thus far made to develop source models include: those by Furuta et al. [1] who, in an attempt to clarify the vibration properties of tracks with low coefficients of spring, developed a model for analyzing coupled bogie-track vibrations and reviewed the model’s validity; and those by Kawatani et al. [2] who analyzed vibrations of viaducts during the passage of trains using a combination of a three-dimensional car model and a three-dimensional finite element viaduct model and reviewed the validity of the combined method and vibration mitigation measures. Numerous studies have also been conducted on propagation models as well, including a series of studies on high-speed trains by Krylov [3] and a study by Kanda et al. [4] on simulation of wave fields.

RTRI, too, has been active in this area, having developed a vibration analysis method [5] based on a three-dimensional coupled vibration analysis model of cars, a track and supporting infrastructures and utilizing it in studying dynamic interaction between cars and structures. Another example is a ground vibration generation model [6] based on an analysis model of a spring-mass system and double beams on an elastic foundation, which has been used to study the effects of adopting lighter cars and tracks with lower spring coefficients on vibration mitigation.

More recently, efforts have been made to develop and improve the accuracy of a simulation method for predicting ground vibrations in tunnels, embankments and level ground areas that combine a coupled vibration analysis model of a running train, a track and supporting structures and a three-dimensional vibration analysis model of supporting structures and ground [7] [8]. To ensure efficient analysis using this method, in cases of approximate uniformity along the track such as tunnels and level ground, a limited number of excitation points, or less than ten of them, were set up around the center of the model and point excitation solutions were calculated for multiple receiving points arranged along the track and the responses of these points were added up while taking into account the time differences.

In cases of non-uniformity along the track such as rigid-frame viaducts, however, point excitation solutions for excitation points are required for at least, in the case of rigid-frame viaducts, one unit of the viaduct. In cases where the analysis must take into account the receiving buildings or underground vibration isolators, the receiving points cannot be moved.

As computation speeds have improved over recent years it is now possible to complete the analyses, that require different excitation waveforms entered for different excitation points on tracks and structures, within a reasonable time frame. Capitalizing on this facility, a review was made of a predictive simulation method for ground vibrations and vibrations of a building close to a rigid-frame via-
duct route section that takes into account the movement of trains and other factors. The results including actual measurements are discussed below.

2. Composition of proposed model

As trains run, they vibrate together with the track, structures, ground and other wayside elements. This requires any strict analysis to consider all relevant elements including the train and wayside ground and buildings as an integrated model. However, such an extensive analysis is difficult to perform due to limitations including computation range and speed. Thus, predictive simulation of ground vibration was conducted using a combination of a coupled vibration analysis model of a running train, a track and supporting structures and a three-dimensional vibration analysis model of supporting structures and ground.

There are a number of ways to combine two analysis models, such as transferring excitation force, combining structural vibrations and transmitted volumes of vibrations, etc. In the review, the two dynamic analysis models, a coupled vibration analysis model of a running train, a track and supporting structures (excitation force analysis model) and a three-dimensional vibration analysis model of supporting structures and ground for analyzing the propagation of vibrations (vibration propagation analysis model), were interlinked via the transfer of excitation forces from the track bottom floor to the viaduct slabs, etc. (Fig. 1) to compute ground vibrations. Computation was performed in the following sequence.

1. Performance of a coupled vibration analysis of a train, a track and structures to compute the moving excitation forces generated by a running train.
2. Input the moving excitation force computed in (1) into a vibration propagation analysis model of structures, ground and buildings to compute the vibrations of the wayside ground and building.

![Two analysis models interlinked via the transfer of excitation force](image)

To obtain verification data for numerical analysis, train-induced vibrations were measured on the ground and in a building near a Shinkansen viaduct. Figure 2 shows an aerial view of the site indicating points where the measurements were taken while Fig. 3 shows a sectional view of the site. The viaduct, a rigid-frame, 4-line 5-stud version with middle beams measuring approximately 14 m from the ground surface to the bottom face of the viaduct slab, was located near an end of Station A. The individual blocks of the rigid-frame viaduct were joined via T-beam girders, each supporting a single line, and the tracks were of a ballasted type. The ground was slightly sloped: flat between the viaduct and the area near the building, then rising perpendicularly to the tracks. The ground was also slightly sloped upward in the direction of the tracks from the bottom to the top of Fig. 2. The building stood in a dip in the ground with the floor of the 1st story being lower than the surrounding ground surface.

The building was a 4-story reinforced concrete office building standing about three to eight meters away from the viaduct. Measurements were taken at a total of 25 locations consisting of viaduct pier studs, the ground between the viaduct and building and the pier studs and floor center.
of each of the building’s four stories, along two horizontal planes (X being parallel and Y being perpendicular to the tracks) and one vertical direction (Z), using vibration level meters (for directions X, Y and Z) and universal broadband vibration meters (for vertical direction Z only). In addition, one of the viaduct’s longitudinal beams was measured for vertical vibration using the U-Doppler system [11]. Ground data was obtained through a surface-wave survey conducted in parallel with the vibration measurements.

At the measurement site, a total of 26 inbound and outbound trains were measured for one-third octave-band analysis. A time constant of 630 ms was used while the maximum band values measured during the passage of the trains were used as analytical values. As there were only small variations in measurements between the trains, this report specifically discusses one of the inbound trains (which passed the site at 160 km/h), the measurements of which were determined as relatively less affected by background vibration at all the measurement locations, as the representative of all the other trains. The vertical measurements shown below were taken by universal vibration meters. The results of the analysis shown below are in relative vibration acceleration level based on the maximum vibration-spectrum value at the longitudinal beam (V-1) of the viaduct set as 0 dB.

Figure 4 shows one-third octave band spectra of the vibration acceleration of the viaduct, ground and building. As shown in Fig. 4 (a), a comparison of vertical vibrations of the measurement locations near the viaduct’s pier studs with those from intermediary ground indicates no major difference between the four measurement locations (G1 - G10) near the pier studs in the frequency band of 5 Hz and above. On the other hand, in the frequency band of 4 Hz and below, vibrations were relatively large in two locations (G-3 and G-6) near the non-stop inbound track while they lessened from G-1 (on a pier stud near the non-stop outbound track) to G-10 (at the end of the viaduct) to G-14 (halfway between the viaduct and building). In the 20 to 63 Hz frequency band, vibrations were larger on the ground between the viaduct and building than near the viaduct.

As shown in Fig. 4 (b), a comparison of the three vibration components on the intermediary ground shows that all components peaked in the frequency range of 31.5 to 80 Hz. In the range of 2.5 Hz and below, horizontal vibrations were larger than vertical vibrations. In the range of 63 Hz and above, vertical vibrations were slightly greater than the horizontal vibrations.

Figure 4 (c) shows vibrations measured at the center of the fourth floor of the building. Vibration peaks were observed at 5, 16 to 20, 40 and 80 Hz, with the highest vertical vibration peak occurring at 20 Hz. The frequency range of 8 to 10 Hz transpired to be a transition zone, whereby
horizontal vibrations exceeded vertical vibrations at 6.3 Hz and below, while the opposite was true at 12.5 Hz and above.

In Fig. 4 (d), which shows a comparison between the viaduct, ground and building, the vertical vibration, as it travelled from the viaduct’s longitudinal beam (V-1Z) to the location (G-6Z) on the ground, was attenuated across the entire frequency range measured. Comparison between the ground and the column base (T1-1Z) on the building’s 1st floor shows small differences in vibration acceleration level at around 20 Hz and below but large differences in the range of 25 to 31.5 Hz and above. The difference became more significant at higher frequencies. There were only small differences between the 1st floor and 4th floor (T4-1Z), indicating almost no attenuation of vibrations as they travelled through the building.

4. Three-dimensional vibration analysis of the structures, ground and building [10][12]

4.1 Dynamic analysis of the train-track system

Dynamic analysis was conducted on a train-track system using DIASTARS III (RTRI) [5]. The train-track system analyzed is shown in Fig. 5. The train model consisted of carbodies, bogies and axles, all of which were considered as rigid bodies, and springs and dampers, both of which were used to connect the first three components. The train was based on the current standard Shinkansen cars while the track was of a ballasted type. The track was modeled as three-dimensional finite elements. The rails and ballast were modeled as beam elements. The sleepers were modeled as mass points. The track pads and the ballast mats beneath the ballast were modeled as spring elements. The ballast was modeled as beam elements to ensure load dispersion. The roadbed was modeled as a rigid body.

The vertical spring reaction force of the spring elements representing the ballast mats was computed. The computed reaction force was then entered as excitation force into the analysis model of the structures, ground and building. A train speed of 160 km/h was used. Figure 6 shows an example of the excitation force waveforms.

4.2 Analysis of the structures, ground and building

The vibration of the ground near the viaduct and that of the office building were computed by entering the excitation force waveforms computed in the previous paragraph into the analysis model shown in Fig. 7. SuperFLUSH/3D (Kozo Keikaku Engineering Inc.) was used for the analysis. The viaduct and building were modeled as beam and shell elements. The ground was modeled as a horizontally layered ground using the thin layer method. Using the surface wave survey results and other data as references, the ground’s P-wave speed ($V_p$) was set at around 1500 m/s, S-wave speed ($V_s$) at around 300 m/s and damping constant (h) at 5%. The building’s damping constant was also set at 5%.

Figure 8 shows the results of the analysis and actual measurements of the viaduct’s longitudinal beam (V-1Z). The analyzed results are a good match with the actual measurements, proving the validity of the excitation force setup.

Figure 9 shows the results of the analysis and actual measurements of the ground (G-14Z) between the viaduct and building. In the frequency range of 80 Hz and below, the analyzed and measured values roughly follow the same trend, although difference of around 10 dB in relative vibration acceleration level was observed in many ranges. There are a number of possible reasons for the gap, including errors in the ground’s physical properties, errors attributable to the modeling of the ground as a horizontally layered structure and local variations of the ground around the foundation of the structures. Further study will be needed to eliminate the gap.

Figure 10 shows the results of the analysis and measurement of the building’s 4th floor (T4-2). The analyzed and measured values follow a roughly the same trend be-
low 80 Hz in all directions, and the gap in the acceleration level between them was around 5 to 10 dB or less in most frequency ranges.

To identify possible reasons for the gap between the analytical and measured values, alternative excitation methods and ground properties were used for further experiment. Figure 11 shows the results of analysis in which moving and linear excitation forces were applied to the ground (G-14). In the linear excitation, the same excitation force waveform was applied in the same phase to all the excitation points, not considering the movement of trains. Regarding the spike occurring frequencies and relative sizes of the peaks, differences of the results of analysis under the moving conditions and those under the linear conditions were relatively small. On the other hand, the acceleration levels under the linear conditions are much higher, by around 30 to 40 dB, than those under the moving conditions below 20 Hz. Overall, the results under the moving conditions match the actual measurements better than the results under the linear conditions.

Figure 12 shows the results of analysis on the ground (G-14) using alternative properties for the surface layer up to 3.4 m deep, i.e. $V_s = 170$ m/s and $h = 2\%$. The surface layer depth and $V_s$ were chosen based on data from the borehole log that relates to the locations nearest to the measurement made. As shown in the figure, change to the properties of ground can have significant impact on the results of analysis. In analyses, properties of the ground...
are selected based on the relevant borehole log, geophysical survey results and other data, and it is difficult to clarify properties down deep into the ground. Selecting appropriate ground property values for higher analytical accuracy is a challenge for the future.

5. Impact of excitation force analysis modeling on analytical results

As described previously, vibrations of the structures, ground and building were computed using an excitation force analysis model featuring a rigid roadbed with fixed bottom of track supporting spring system, succeeding in roughly reproducing the actual measurements of the structural vibrations (Fig. 8). The viaduct analyzed this time was a 5-stud, rigid-frame viaduct at a station, which was more rigid than the 2-stud viaduct in the ordinary section. Therefore, as a basic study of the impact of coupled car-structure vibration on the excitation force analysis of ground vibration, a trial analysis on the response of rigid-frame viaduct slabs of the 2-stud viaduct in the ordinary section was performed using two excitation force analysis models (Fig. 13), a rigid roadbed model and a beam model representing slabs and longitudinal beams of viaduct (Fig. 14). The track used was of a slab track type.

These figures show that the results of the two models are relatively close to each other. In certain conditions, however, the difference between the two models can have significant impact on analytical results. Around 4 to 5 dB of gaps were observed at certain frequency ranges on both the center and cantilever slabs. Further studies on appropriate modeling methods for structures in excitation analysis are required.

6. Conclusion

With the train-induced excitation forces obtained through train-track modeling, to which the moving excitation source taken into account, used as inputs, a Shinkansen-induced vibration simulation was conducted using three-dimensional analysis model of structure, ground and building. Overall, the analysis models used for the simulation showed a good match with actual measurements. In further improving the accuracy of simulation, a series of challenges lie ahead including the modeling of vibration propagation specific to railway structures, building and other structures and the ground, selection of appropriate ground property values and the impact that the modeling of structures can have on excitation force analyses. We will tackle these challenges to improved simulation accuracy, while investigating the measures to mitigate the train-induced vibrations using the method described in this report.
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