Numerical Simulation of Train-induced Vibration in Consideration of Types of Excitation Forces

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Vibrations caused by running trains sometimes lead to environmental issues. Train-induced vibrations are caused by moving static and dynamic axle loads. In numerical simulations of train-induced vibration, the type of excitation force greatly affects the relevant structure and ground responses. This study evaluated the influence of excitation force types on ground responses. Numerical simulations demonstrated that at frequencies below or equal to 31.5 Hz, a large part of the ground vibration caused by moving excitation forces consists of averaged components such as moving static axle loads. On the other hand, the simulations also showed that at frequencies equal to or over 40 Hz, a large part of the ground vibration due to moving excitation forces consists of varying components such as dynamic axle loads. Furthermore, it was found that there is a frequency at which the moving excitation force acceleration nears the point force excitation acceleration. It was then clarified that the point force excitation acceleration at that frequency can be used as a substitute for moving excitation forces.

Keywords: train-induced vibration, numerical simulation, point excitation force, moving excitation forces, acceleration

1. Introduction

In numerical simulations of train-induced vibration, the type of excitation force greatly affects the relevant structure and ground responses. Kanda et al., [1] gave the definitions of vehicle-synchronized excitation forces and position-synchronized excitation forces, and provided a summary of the response trends obtained under these excitation forces. According to the definitions proposed by Kanda et al., [1], vehicle-synchronized excitation forces are excitation forces, which excite the track synchronously with vehicle arrival. The position-synchronized excitation forces are excitation forces that depending on location on the track. With regards to the real excitation forces of train-induced vibration, it was supposed that the typical position-synchronized excitation forces were moving static axle loads, and the typical vehicle-synchronized excitation forces were moving dynamic axle loads caused by the vehicle shaking due to track irregularities. Kanda et al., [1] showed that attenuation over distance of responses generated by vehicle-synchronized excitation forces are much larger than those generated by position-synchronized excitation forces under continuous excitation on homogeneous ground. Kanda et al., [1] also showed that attenuation over distance of responses generated by vehicle-synchronized excitation forces are not large with discrete excitations on homogeneous ground. These results were obtained homogeneous ground, whereas it is not clear yet what the results would be if there were actual tracks and supporting structures. Clarifying trends in excitation force responses, using numerical simulation in which moving trains, tracks, supporting structures and the ground are factored in, would greatly improve the understanding of train-induced vibration phenomena and help develop countermeasures against ground vibration. This paper evaluated the influence of excitation force types on ground responses using the numerical simulation method proposed by RTRI [2] in which moving trains, tracks, supporting structures and the ground are factored.

2. Numerical simulation of train-induced vibration

The numerical simulation proposed by RTRI [2] was conducted using a combination of a coupled vibration analysis model of running trains, tracks and supporting structures and a three-dimensional vibration analysis model of supporting structures and the ground (Fig.1). The computation was performed in the following sequence:

1) Performance of a coupled vibration analysis of the trains, the tracks and the structures for computing the moving excitation forces generated by the running trains.
2) Input of the moving excitation force computed in (1) into a vibration propagation analysis model of the structure and ground responses. Kanda et al., [1] also showed that attenuation over distance of responses generated by vehicle-synchronized excitation forces are not large with discrete excitations on homogeneous ground. These results were obtained homogeneous ground, whereas it is not clear yet what the results would be if there were actual tracks and supporting structures. Clarifying trends in excitation force responses, using numerical simulation in which moving trains, tracks, supporting structures and the ground are factored in, would greatly improve the understanding of train-induced vibration phenomena and help develop countermeasures against ground vibration. This paper evaluated the influence of excitation force types on ground responses using the numerical simulation method proposed by RTRI [2] in which moving trains, tracks, supporting structures and the ground are factored.

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Fig. 1 Basic design of the simulation [2]
Table 1  Vehicle specifications

| Mass         | ×10$^3$kg | Spring constant (Total of left and right rail) kN/m | Damping coefficient (Total of left and right rail) kN s/m |
|--------------|-----------|---------------------------------------------------|--------------------------------------------------------|
| Car-body mass| 31.83     | Between car-body and truck 400                    | Between car-body and truck 50.60                      |
| Truck mass   | 3.138     | Between truck and wheelset 2366                   | Between truck and wheelset 77.61                      |
| Wheelset mass| 1.950     | Between wheelset and rail 1200000                 |                                                         |

Table 2  Track and Structure specifications (Mass and rigidity)

| Table 2 | Unit length mass (m) | Bending rigidity (MN·m²) | Shaft rigidity (MN) | Note |
|---------|----------------------|--------------------------|---------------------|------|
| Rail    | 0.122                | 13.23                    | 3317                | Total of left and right rail |
| Track slab | 1.067               | 46.80                    | 14040               |      |
| Concrete slab (Viaduct) | 15.03          | 21770                    | 13960               |      |
| Pillar (Viaduct) | 5.808              | 5856                     | 58080               | 2 pillars total          |
| Beam (Simple girder) | 16.07            | 13610                    | 150000              |      |

Table 3  Track and Structure specifications (spring constant and attenuation coefficient)

| Table 3 | Spring constant (kN/m) | Damping coefficient (kN s/m) | Note |
|---------|------------------------|-----------------------------|------|
| Between rail and track slab | 360000 | 98.41                      | Total of left and right rail |
| Between track slab and Concrete slab | 4300000 | 259.2                     |      |

Table 4  Ground specifications

| Table 4 | Layer No. | Layer thickness (m) | Poisson's ratio | Unit mass (10$^3$kg/m) | P-wave velocity (m/s) | S-wave velocity (m/s) | Damping constant (%) |
|---------|-----------|--------------------|-----------------|------------------------|----------------------|----------------------|---------------------|
|         | 1         | 6.0                | 0.497           | 1.70                   | 1500                 | 1.70                 | 1500                | 2.0                 |
|         | 2         | 200.0              | 0.479           | 1.70                   | 1500                 | 1.70                 | 1500                | 2.0                 |

In this paper, the vibration analysis for calculating the moving excitation forces was conducted using DALIA (KOZO KEIKAKU ENGINEERING Inc. (KKE)), and the three-dimensional vibration analysis for calculating the train-induced ground vibrations was conducted using SuperFLUSH/3DS (KKE). The object of the analysis was a rigid frame viaduct with simple girders. Models were made of three viaducts and two simple girders (Fig.2). Maximum frequency of the analysis was 125 Hz. Table.1, Table.2, Table.3 and Table.4 show the specifications of the trains, the tracks, the structures and the ground respectively. The axis positions of the train were the same as those on a typical Shinkansen train. The train had eight cars. The train speed was 260 km/h. The structures were modeled with reference to the design drawing. The track irregularity waveform used for the vibration analysis was set based on observed waveforms on the slab track. The ground was modeled as a two-layer horizontal ground. The moving excitation forces transferred from the vibration analysis to the three-dimensional vibration analysis were assumed to be the forces between track slabs and viaduct slabs.

3. Separation based on the types of excitation forces

In this paper, the excitation forces calculated by vibration analysis of the trains, the tracks and the structures were separated into averaged components and varying components. Here, the averaged excitation force components were the excitation forces which did not differ according to the location on the track. The varying excitation force components were the excitation forces which differed according to the location on the track. The averaged excitation force components were calculated using a method of averaging the excitation forces after removing the time lag factor depending on the location on the track. The varying excitation force components were the excitation forces which differed according to the location on the track. The averaged excitation force components were calculated using a method for subtracting the averaged excitation force components from each excitation force. The varying excitation force components were calculated using a method for subtracting the averaged excitation force components after removing the time lag factor. The averaged excitation force components were the same regardless of location. It was posited that the averaged excitation force components would have the same characteristics as the vehicle-synchronized excitation force components, and the varying excitation force components would have the same characteristics as the position-synchronized excitation force definition. The ground vibration generated by the excitation forces before separation was calculated, along with the averaged and the varying excitation force components. Figure 3 shows the time history waveforms of the excitation forces before separation, the averaged and the varying excitation force components. The vertical axis shows the excitation force and the negative side shows the downward force. In the excitation forces before separation, the values of the negative excitation forces were larger than those of the positive excitation forces. The averaged excitation force components had approximately the same value as the excitation forces before separation. On the other hand, the varying excitation force components had approximately the same value as the averaged components of those in the positive vertical direction and were 1/6 times smaller than the averaged components of those in the negative vertical direction. Figure 4 shows the vibration acceleration level derived from the time history.
waveforms in the Fig.3 by 1/3 octave band analysis. Here, normalization of the 1/3 octave band spectra was processed with the maximum value of the excitation forces before separation given by excitation at a point. In the Fig.4, the averaged excitation force components had approximately the same value as the excitation forces before separation below or equal to 50 Hz and were smaller than those equal to or over 63 Hz. On the other hand, the varying excitation force components were smaller than the excitation forces before separation and the averaged excitation force components below or equal to 50 Hz. The varying excitation force components were larger than the averaged components and were approximately the same as the excitation forces before separation in the range of 80 Hz.

4. Relationship between type of excitation force and response

4.1 Responses at point excitation

Using the three-dimensional vibration analysis, a calculation was made of the ground vibration generated by inputting the three types of excitation force at the center of the excitation position. Figure 5 shows the vertical response waveforms of acceleration at a point 3.65 m away from the center of the viaduct when half the excitation force was input on the left and half on the right rail point in the center excitation section. For comparison, it should be noted that the ratio of the absolute value of the response amplitude generated by the averaged excitation force components to that generated by the excitation forces before separation was 0.59, and the ratio of the absolute value of the response amplitude generated by the varying excitation force components to that generated by the excitation forces before separation was 0.54. Furthermore, the ratio between the response generated by the averaged excitation force components and that generated by the varying components was 1.08. From these results, it was found out that the ratio between the absolute values of the response...
The accelerance in the high frequency range was larger than that in the low frequency range. From Fig. 7, it was posited that the frequency characteristics of the accelerance could be the reason that the ratio between the absolute values of the time history waveforms of the excitation forces was different from the response ratio.

4.2 Responses by moving excitation

To investigate train-induced ground vibration, calculations were made of the ground vibration using the three-dimensional vibration analysis in which three excitation force types were input at points where the rail fastening devices were located. There were 304 excitation points along the track in all (152 excitation points on each rail). The interval between rail fastening devices was 0.625 m. Figure 8 shows the vertical response waveforms of the acceleration at a point 3.65 m away from the center of the viaduct. For comparison, it should be noted that the ratio of the absolute value of the response amplitude generated by the averaged excitation force components to that generated by the excitation forces before separation was 0.66, and the ratio of the absolute value of the response amplitude generated by the varying excitation force components to that generated by the excitation forces before separation was 0.59. Furthermore, the ratio between the response generated by the averaged excitation force components and that generated by the varying components was 1.11. From
4.3 Relationship between range in excitation point position and responses

To examine the effects of averaged and varying excitation force components in more detail, calculations were made of the responses varying the range in which excitation points were positioned (hereinafter referred to as the excitation range). Figure 10 shows the relationship between the excitation range and vibration acceleration levels at 4 Hz, 12.5 Hz and 40 Hz. The horizontal axis shows length of the excitation range. If the excitation range equals zero, it means that excitation forces were only input at the center excitation point. If the excitation range is more than zero, it means that excitation forces input at points positioned in the range of the horizontal axis value.

In the case of the 4 Hz, it was found out that responses generated by the averaged excitation force components were close to those generated by the excitation forces before separation. If the excitation range was less than about 10 m, the responses generated by the averaged excitation force components and those generated by the excitation forces before separation increased monotonically. If the excitation range was more than about 10 m and less than about 30 m, the responses did not vary very much with range. If the excitation range was more than about 30 m and less than about 50 m, responses decreased as range increased. If the excitation range was more than about 50 m, responses became stable. On the other hand, if the excitation range was less than about 40 m, the responses generated by the varying excitation force components fluctuated at short intervals. If the excitation range was more than about 40 m, the size of the fluctuation diminished.

In the case of the 12.5 Hz or the 40 Hz, if the excitation range was less than about 40 m at 12.5 Hz or the excitation range was less than about 30 m at 40 Hz, the responses generated by the averaged excitation force components fluctuated at short intervals. If the excitation range was more than about 40 m at 12.5 Hz or the excitation range was more than about 30 m at 40 Hz, fluctuation diminished. On the other hand, if the excitation range was less than about 40 m at 12.5 Hz or the excitation range was less than about 20 m at 40 Hz, the responses generated by the varying excitation force components increased monotonically. If the excitation range was more than about 40 m at 12.5 Hz or the excitation range was more than about 20 m at 40 Hz, those responses did not vary too much according to the range. As for the relationship between the results of the averaged excitation force components and the varying excitation force components, if the excitation range was more than about 20 m at 40 Hz, the responses generated by the varying excitation force components were greater than those generated by the averaged excitation force components. Furthermore, in the case of 40 Hz, the trend in responses generated by the excitation forces before separation changed at the excitation range of 20 m. From these results, it was found that, the relationship between the excitation range and response showed differences between...
the responses generated by the varying excitation force components and those generated by the averaged excitation force components. In addition, because the responses generated by the excitation forces before separation were the sum of responses generated by the varying excitation force components and those generated by the averaged excitation force components, the responses generated by the excitation forces before separation were close to either the higher responses generated by the varying excitation force components or generated by the averaged excitation force components.

These results suggest that the difference in increment in responses between moving excitation and point excitation was due to the difference in the relationship between excitation range and responses, based on types of excitation force. Yoshioka et al., [3], said that because the phases of the ground vibrations from each vehicle-synchronized excitation force at each point were so overlapped as to cancel the responses, the attenuation of responses over distance, generated by the vehicle-synchronized excitation forces was much larger than that by the position-synchronized excitation forces in the case of continuous excitation on homogeneous ground. Consequently, it is posited that one reason for the difference found with each type of excitation force, in the relationship between excitation range and response, has something to do with the phase of the excitation force.

5. Relationship between type of excitation force and response based on accelerance

In this section, with a focus on the accelerance, a comparison was made of accelerance in the case where half the excitation force was input at points on the left and half at points on the right rail in the center excitation section respectively, and ostensible accelerance in the case where moving excitation forces were input. Here, calculations were made of the ostensible accelerance by dividing the responses by the average of the moving excitation forces.

Figure 11 shows the averaged moving excitation forces of all the excitation points. Calculations were made of the averaged moving excitation forces using a method for averaging the calculated level of the excitation forces at each excitation point in this model. In addition, Fig. 11 shows the standard deviations of the excitation forces before separation and those of the varying components through error bars. On the other hand, because the values of the averaged components became the average of the excitation forces of the averaged components, the average of the averaged components equaled the excitation forces of the averaged components shown in Fig.4.

As shown in the Fig.11, the standard deviations of the excitation forces of the varying components were less than approximately 10 dB. The standard deviations of the excitation forces before separation at more than 40 Hz are larger than those at less than 40 Hz. In addition, the value of the averaged excitation forces of the averaged components at 63 Hz was close to that of the varying components. At 80 Hz, the values of the averaged excitation forces of the varying components were larger than those of the averaged components. These characteristics were the same as the characteristics of excitation forces originating from the center excitation point shown in 4.1. This indicates that these characteristics could be recognized at numerous excitation points in this model.

Figure 12 shows the ostensible accelerance at a point 3.65 m away from the center of the viaduct. Here, calculations were made of the ostensible accelerance by dividing the vibration acceleration of the responses by the average of the moving excitation forces (Fig.11). In addition, Fig.12 shows the accelerance by point excitation at a point 3.65 m away from the center of the viaduct where the excitation force was input at the center excitation point and the varying ranges of the ostensible accelerance corresponded to the standard deviations.

As shown in the Fig.12, on comparison of the ostensible accelerance with varying components and with averaged components, the ostensible accelerance with averaged components was larger than with varying components between 1 Hz and 4 Hz, and the ostensible accelerance with varying components was larger than with averaged components between 5 Hz and 80 Hz. The ostensible accelerance with varying components was close to the accelerance by point excitation between 1 Hz and 4 Hz. The ostensible accelerance with averaged components was close to the accelerance by point excitation between 8 Hz and 20 Hz. This suggests that the accelerance by point excitation can almost represent the characteristics of ostensible accelerance with varying components between 1 Hz and 4 Hz, and can almost represent the characteristics of ostensible accelerance with averaged components between 8 Hz and 20 Hz. However, the characteristics mentioned here amplitude characteristics and did not include phase characteristics.

Regarding point excitation force (Fig.4) and the moving excitation force average (Fig.11), the excitation forces
before separation had approximately the same value as the excitation forces of the averaged components in the range below 50 Hz. In the averaged components, by definition, the point excitation force equaled the average of the moving excitation forces. Accordingly, regarding the excitation forces before separation, the point excitation force was approximately the same as the average of the moving excitation forces in the range below 50 Hz.

Furthermore, point excitation accelerance and moving excitation ostensible accelerance were calculated by dividing the responses by the average of the excitation forces. Accordingly, regarding the excitation forces before separation in the range below 50 Hz, if point excitation accelerance was close to moving excitation ostensible accelerance, the point excitation response was close to moving excitation response.

Figure 13 shows the response generated by the point excitation force before separation shown in Fig.6 and the response generated by moving excitation forces before separation shown in Fig.9. Between 8 Hz and 20 Hz in which the moving excitation ostensible accelerance before separation was close to point excitation accelerance, the response generated by the moving excitation forces before separation was close to the response generated by the point excitation force before separation. Accordingly, in this model, the response generated by point excitation force before separation can almost represent the response generated by moving excitation forces before separation between 8 Hz and 20 Hz.

According to the above results, in this model, the ostensible accelerance with varying excitation force components was close to point excitation accelerance between 1 Hz and 4 Hz, while the ostensible accelerance of averaged excitation force components and of excitation forces before separation were close to point excitation accelerance between 8 Hz and 20 Hz. In addition, in this model, the response generated by point excitation force before separation can almost represent the response generated by moving excitation forces before separation between 8 Hz and 20 Hz. These results suggest that these phenomena are caused by phase characteristics. However, verifying the mechanisms underlying these phenomena needs to be the subject of future research.

6. Conclusions

In this paper, excitation forces calculated through train, track and structure vibration analyses, were separated into averaged and varying components. The influence on ground response of each type of excitation force was then evaluated. Results showed that in the low frequency range, the averaged excitation force component response contribution to responses generated by excitation forces before separation is large. In the high frequency range, the averaged and varying components can be separated and the response generated by the moving excitation force before separation is close to the response generated by the point excitation force before separation.
range, it is the contribution of varying excitation force components that is large. Results also showed that in terms of the relationship between excitation range and responses, differences existed between the responses generated by varying excitation force components and those generated by averaged excitation force components. In terms of acceleration, it was found that there is a frequency where moving excitation force acceleration comes close to point force excitation acceleration. Confirmation was obtained that at that frequency the point force excitation response can substitute moving excitation force response. It is posited that the phase characteristics are attributable to these characteristics. However, further work must be carried out to investigate the mechanisms underlying these characteristics and to develop countermeasures against train-induced vibration.

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