Characteristics of bridge vibration and infrasound due to different types of trucks

Saiji FUKADA [1]; Hiroshi IWABUKI [2]; Toshikazu OSAFUNE [3];
Yasuyuki SANO [4]; Yasunao MATSUMOTO [5]; Masayuki SHIMURA [6];
Noboru KAMIAKITO [7]; Hirokazu HAMA [8]; Kentaro HAYASHI [9]

[1] Kanazawa University, Japan; [2] Central Nippon Expressway Co., Ltd., Japan
[3] Nippon Expressway Research Institute Co., Ltd., Japan; [4] Aichi Institute of Technology, Japan
[5] Saitama University, Japan; [6,7] Civil Engineering and Eco-Technology Consultants Co., Ltd., Japan
[8] Fuji Engineering Co., Ltd., Japan; [9] Benec Vibration Acoustics Consultants Co., Ltd., Japan

ABSTRACT
The infrasound problem due to moving trucks occurs near highway bridges in Japan. Several prevention measures for solving this problem have been proposed. In order to predict the production of the infrasound, it is necessary to examine the effects of loading properties, which include the type of suspension, running speed, running position, number of axles, and weight.
Therefore, running tests were conducted using three- or four-axle trucks with leaf or air suspension to investigate the characteristics of the bridge vibration and infrasound radiated from the bridge due to moving trucks. As the result of the experiments, it was clarified that the type of suspension did not have a significant influence on the G-weighted infrasound.

Keywords: Infrasound, Bridge, Trucks   I-INCE Classification of Subjects Number(s): 13.2.4

1. INTRODUCTION
Infrasound, which is low-frequency noise in the frequency of 0–20 Hz, is generated from bridges as a result of trucks passing over them. In Japan, this has become a problem around viaducts (1, 2), and prevention measures have been proposed (3, 4).

In general, when the frequencies of the vibrations of the trucks (the suspension spring vibrations and/or tire spring vibrations of the trucks) and those of the bridge closely match each other, the bridge vibrates significantly by resonance. The infrasound produced by the bridge vibrations radiates along the viaduct. From previous studies (1–4), it is clear that the occurrence of the infrasound radiated from the highway bridge is related to the vibrations of the trucks (the suspension spring vibrations and/or tire spring vibrations of the trucks) and the bridge. In addition, the relation of the generation of the secondary bending bridge vibration mode at the frequencies of 10–20 Hz with the occurrence of the infrasound has been clarified (5).

In order to predict the production of the infrasound, it is necessary to examine the effects of loading properties, which include, among other properties, the types of suspension, running speed, running position, number of axles, and weight. In particular, it is well known that bridge vibration is reduced by trucks having air suspension (6). However, the effect of running trucks with this type of suspension on the characteristics of the infrasound is not clear.

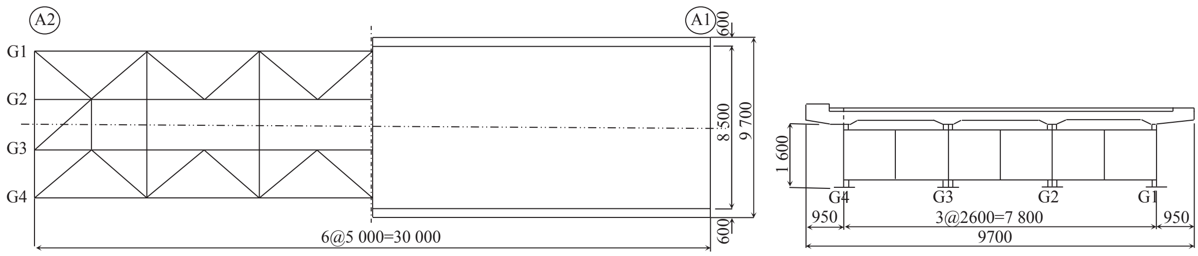
Therefore, running tests using three- and four-axle trucks with leaf and air suspension were conducted to investigate the effects of the moving trucks on the characteristics of the bridge vibration and infrasound radiated from the bridge.

[1] saiji@se.kanazawa-u.ac.jp; [2] h.iwabuki.aa@c-nexco.co.jp; [3] t.osafune.aa@ri-nexco.co.jp
[4] sano-y@aitech.ac.jp; [5] ymatsu@mail.saitama-u.ac.jp; [6] shimura@kensetsukankyo.co.jp
[7] kamiakit@kensetsukankyo.co.jp; [8] hirokazu_hama@fujiengi.co.jp; [9] hayashi-k@benec-vsi.co.jp

2. LOADING TESTS

2.1 Investigated Bridge

Figure 1 shows the bridge investigated in this study, consisting of four girders and with a length of 30 m. The clearance under this bridge is a semi-underground space of about 2 m in height, as shown in Figure 2. The shoes of the A1 approaching side are metal, and those of the A2 side are elastic. The length of this bridge is typical of viaducts in Japan. Generally, bridges of 30 m long have bending vibrations at a frequency of about 3 Hz. Its frequency is close to the body vibration (suspension vibration) of a truck with leaf suspension.



(a) Plan view (b) Cross section
Figure 1 – Investigated bridge (unit: mm)

Figure 2 – Clearance under bridge

2.2 Measurement Sensors

In order to investigate the bridge vibration, displacement, and infrasound due to the moving trucks, measurement sensors were arranged on the bridge as shown in Figure 3. The measured parameters were a) the vibration level on the abutment; b) the acceleration of the girders and slab; c) the infrasound, measured by low frequency microphone; d) the displacement of the girders and shoes; e) the load, measured by load cells installed under the shoes.

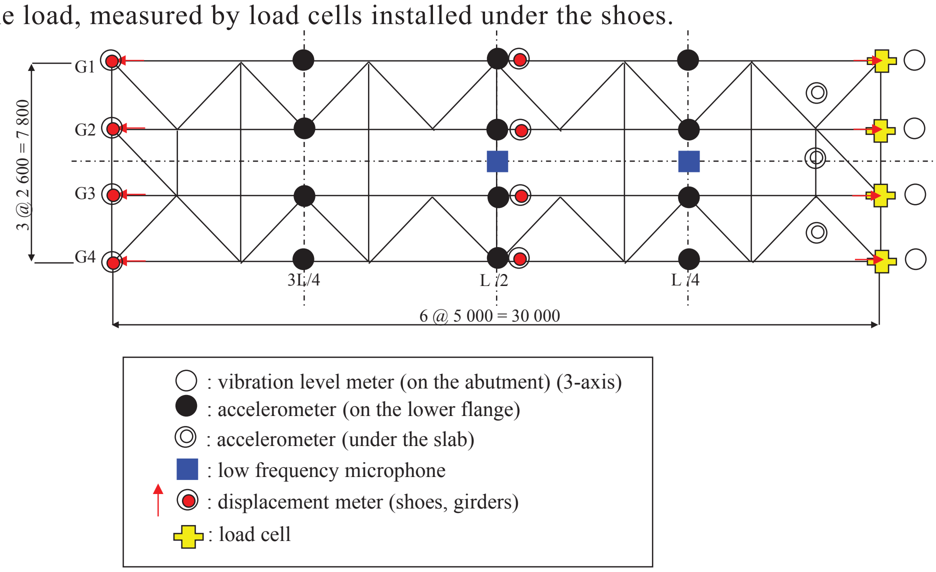
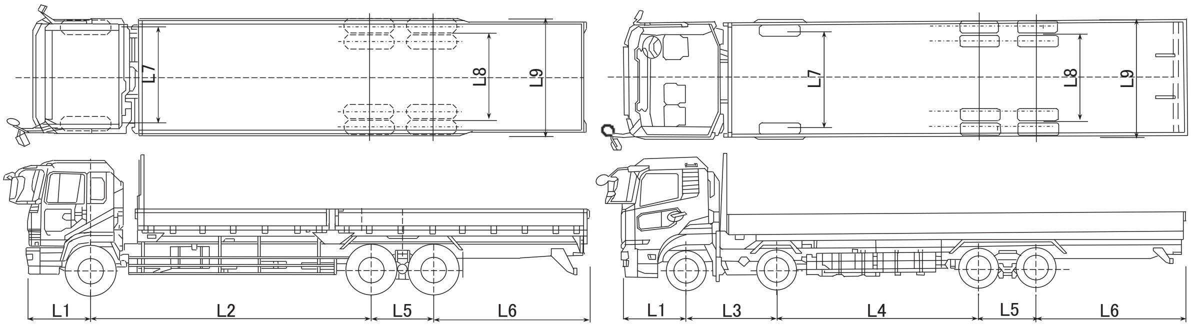


Figure 3 – Measurement points and sensors

2.3 Test Trucks

Four types of trucks that are commonly used for transportation on highways in Japan were selected as the test trucks. The four types consisted of the following axle and suspension arrangements. Type 1: 3-axles with leaf suspension (3-axles leaf, abbreviated 3L); Type 2: 3-axles with leaf (front axle) and air suspension (two rear axles) (3-axles air, 3A); Type 3: 4-axles with leaf suspension (4-axles leaf, 4L); Type 4: 4-axles with leaf (two front axles) and air suspension (two rear axles) (4-axles air, 4A). Diagrams of the 3-axle and 4-axle trucks are shown in Figure 4. The dimensions and weights of each test truck are shown in Tables 1 and 2, respectively.



(a) 3-axles (b) 4-axles

Figure 4 – Top and side views of 3-axle and 4-axle test trucks

Table 1 – Dimensions of each test truck (unit: mm)

	3-axles leaf	3-axles air	4-axles leaf	4-axles air
L1	1400	1400	1400	1400
L2	5825	5885	—	—
L3	—	—	1910	1910
L4	—	—	4290	4230
L5	1320	1350	1200	1320
L6	3390	3305	3130	3070
L7	2040	2040	2085	2090
L8	1840	1840	1860	1860
L9	2490	2490	2490	2490

Table 2 – Weights of each test truck (unit: kN)

		3-axles leaf		3-axles air	
		unloaded	loaded	unloaded	loaded
Front wheel	1st axle	49.8	60.2	51.0	66.7
	—	—	—	—	—
Rear wheel	2nd axle	35.8	93.1	36.8	91.6
	3rd axle	31.6	86.1	31.0	82.7
Total		117.2	239.4	118.8	241.0

		4-axles leaf		4-axles air	
		unloaded	loaded	unloaded	loaded
Front wheel	1st axle	39.0	51.1	34.9	45.6
	2nd axle	43.0	43.7	40.5	41.1
Rear wheel	3rd axle	28.3	85.6	25.7	81.3
	4th axle	28.9	81.2	24.4	79.6
Total		139.3	261.5	125.4	247.6

2.4 Running Tests

Running tests were conducted for the four different types of trucks in order to investigate the response of the bridge vibration and infrasound. The running test cases combined the parameters of the suspension type, running position, running speed, and the weight (shown in Table 3).

Table 3 Running test cases

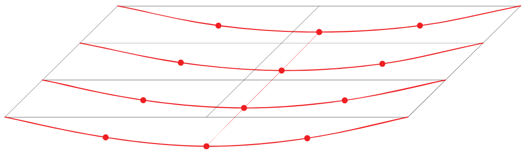
		Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8
Position	Center	○	○	○	○				
	Side					○	○	○	○
Running speed (km/h)	5	○				○			
	80		○				○		
	40			○				○	
	60				○				○

The running positions were the center of the bridge, in which the truck ran down the middle of the bridge, and the side of the bridge, in which the truck ran keeping to a side of the bridge. The running speeds were 5, 40, 60, and 80 km/h. However, owing to safety considerations, case 6 could not be conducted.

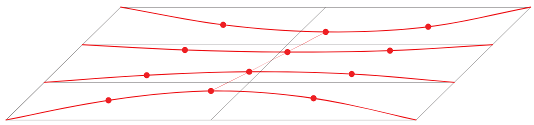
3. Vibration Characteristics of Bridge

The frequencies, damping constants, and vibration modes obtained by the running tests were analyzed using ERA (Eigen-value Realization Algorithm) (7), as shown in Figure 5. The first bending vibration appears at a frequency of 3.3 Hz, and its damping constant (h) is 0.023. The first torsion vibration is at 4.7 Hz, and its damping constant is 0.016. The second bending vibration is at 12.1 Hz.

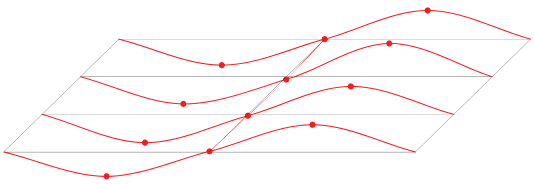
The frequency of the body vibration (suspension vibration) of the truck with leaf suspension is close to that of the first bending vibration (3.3 Hz). Many vibrations (the second bending vibration at 12.1 Hz, torsion at 13.2 Hz, bending at 15.0 Hz, and torsion at 18.6 Hz) are in the range of the tire vibrations of the trucks with both leaf and air suspension (10-20 Hz).



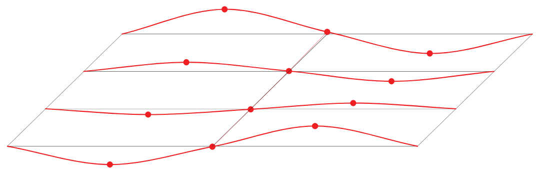
(a) Bending 3.3 Hz, h = 0.023



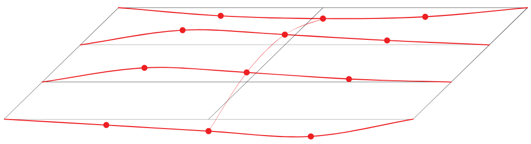
(b) Torsion 4.7 Hz, h = 0.016



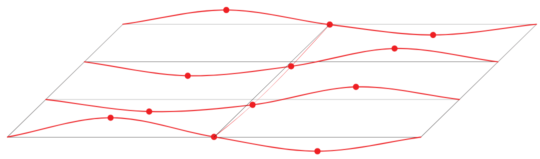
(c) Bending 12.1 Hz, h = 0.022



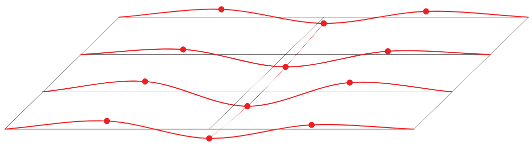
(d) Torsion 13.2 Hz, h = 0.022



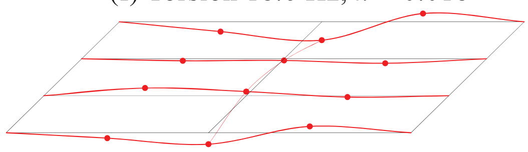
(e) Bending 15.0 Hz, h = 0.018



(f) Torsion 18.6 Hz, h = 0.018



(g) Bending 23.0 Hz, h = 0.017



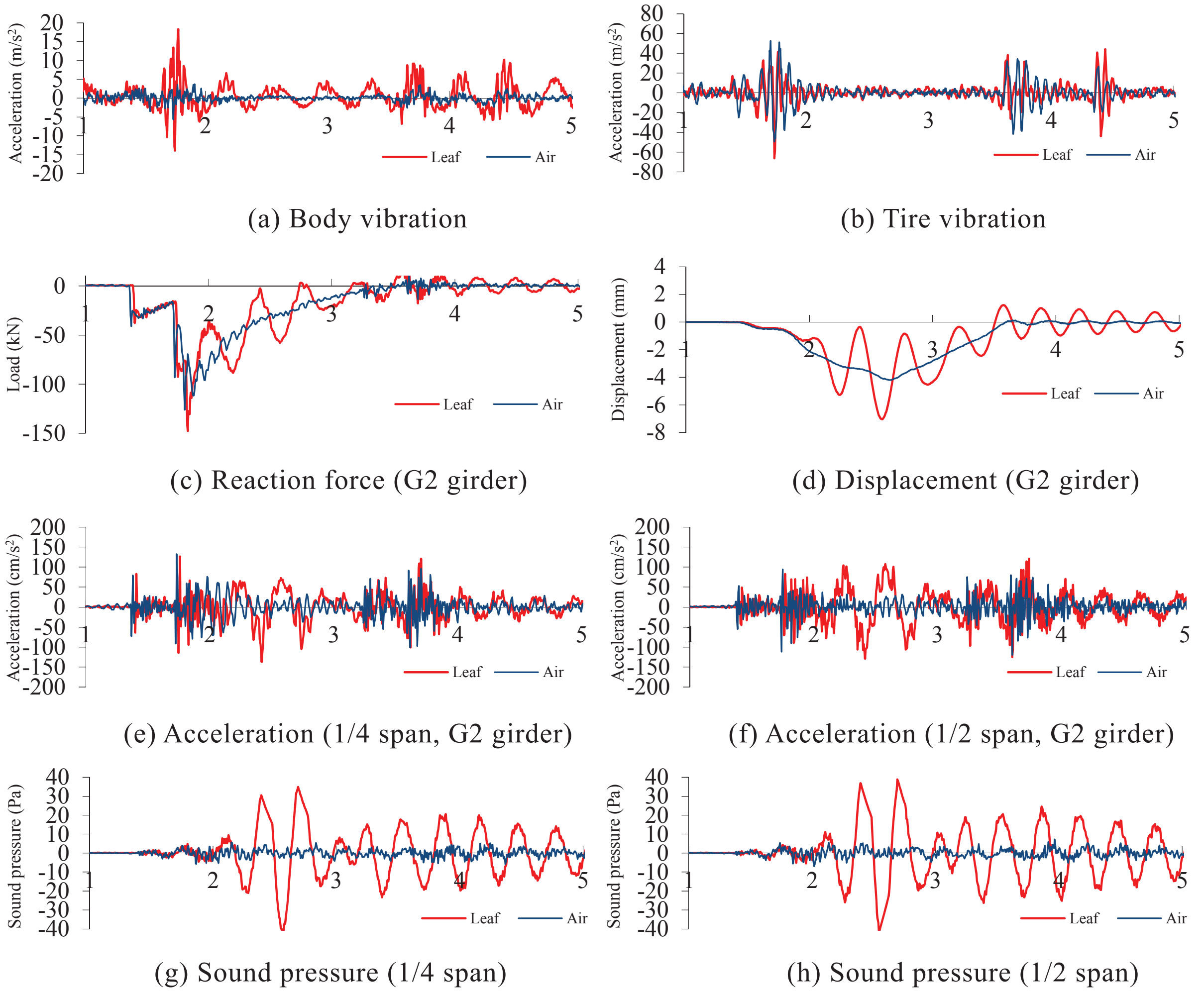
(h) Bending 26.0 Hz, h = 0.003

Figure 5 – Vibration characteristics obtained by the running tests

4. Infrasound

4.1 Relation between Bridge Vibration and Infrasound

For a loaded test truck with leaf suspension or air suspension running on the test bridge at 60 km/h (center case), the body and tire vibrations of the truck, reaction force at the A1 shoe (G2 girder), displacement at 1/2 span (G2 girder), and acceleration and sound pressure of the infrasound at 1/4 and 1/2 span are shown in Figure 6. Excluding the vibrations of the tire (Fig. 6 (b)), the difference between leaf and air suspension is clear. Comparing trucks with leaf and air suspensions, the behavior of the tire vibrations were almost identical. The behavior of the infrasound (shown by the red line in Fig. 6 (g), (h)) is synchronized with the bridge vibrations (Fig. 6 (c)-(f)), and the body vibration of the truck with the leaf suspension (Fig. 6 (a)).The spectra of truck vibration, acceleration, and infrasound at 1/4 span are shown in Figure 7. The frequency of the body vibration can be seen at 2.6-2.7 Hz (Fig. 7 (a)), and this vibration approximates the frequency of the first bending vibration (3.3 Hz) (Fig. 7 (c)). Moreover, the frequency of the tire vibration for both the leaf and air suspension types in the range 10-15 Hz (Fig. 7 (b)) was close to the frequencies of the bending and torsion modes (12.1, 13.2, 15.0 Hz) (Fig. 7 (c)). The frequencies of the infrasound (Fig. 7 (d)) were consistent with those of the bridge vibration (Fig. 7 (c)).



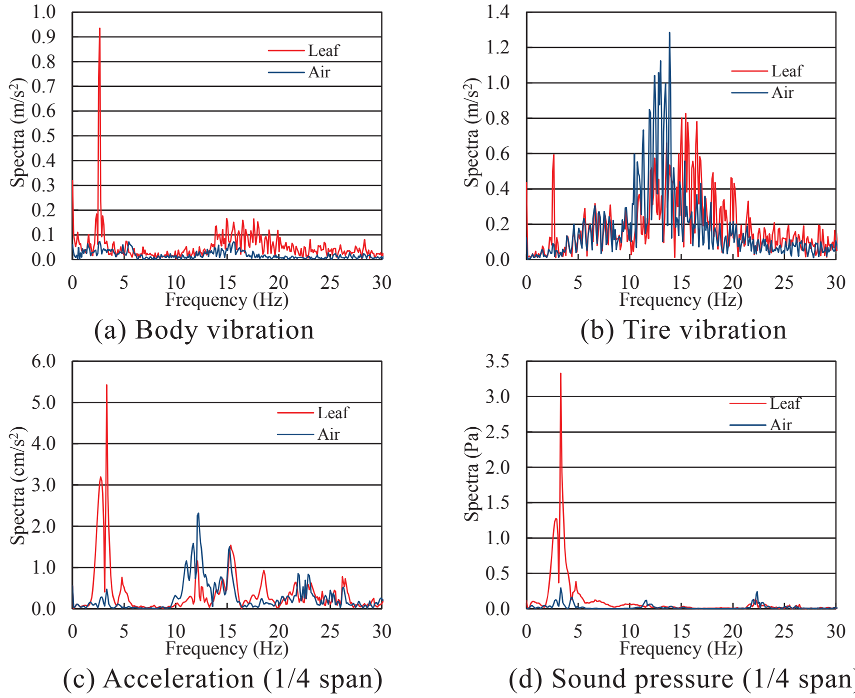
(a) Body vibration (b) Tire vibration

(c) Reaction force (G2 girder) (d) Displacement (G2 girder)

(e) Acceleration (1/4 span, G2 girder) (f) Acceleration (1/2 span, G2 girder)

(g) Sound pressure (1/4 span) (h) Sound pressure (1/2 span)

Figure 6 – Vibration response of the bridge and truck for a loaded truck running at the center position



(a) Body vibration (b) Tire vibration

(c) Acceleration (1/4 span) (d) Sound pressure (1/4 span)

Figure 7 – Spectra of the bridge and truck for a loaded truck running at the center position at 60 km/h

4.2 Infrasound due to Different Types of Moving Trucks

The sound pressure levels (flat-weighted) of the infrasound were obtained by running tests for each truck at speeds of 40, 60 and 80 km/h, and are shown in Figure 8. The figure has different parts so that the weight (unloaded and loaded) and running position (center and side of the bridge) can be compared.

The sound pressure level of the infrasound increases with an increase in the running speed. However, it is not a proportional relation, because the generation of the first bending vibration is different in relation to the matching of the frequency of the trucks' body vibration, first bending vibration, and the wavelength road roughness (8).

By comparing leaf and air suspension, the difference of the sound pressure levels caused by reduction of the first bending vibration at 3.3 Hz, as shown in Figure 6, is 10-15 dB. In addition, the level caused by a 3-axles truck running is slightly larger than that caused by a 4-axle truck. For air suspension, when comparing the sound pressure levels from unloaded trucks with those from loaded trucks, there was little difference except for the unloaded condition at 40 km/h. Under certain conditions, the responses for the unloaded trucks were larger than those for the loaded trucks. The influence of weight was therefore less important than that of the running speed.

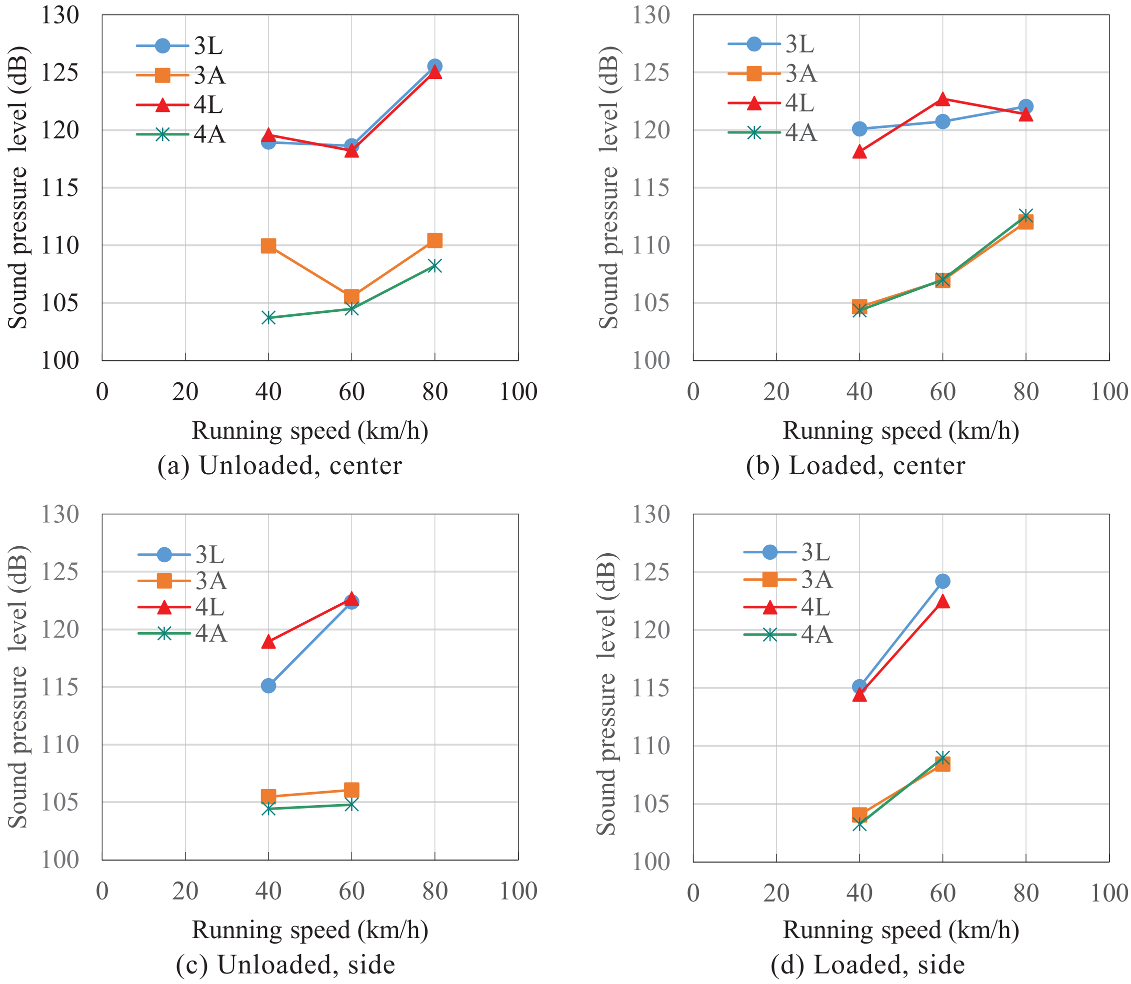
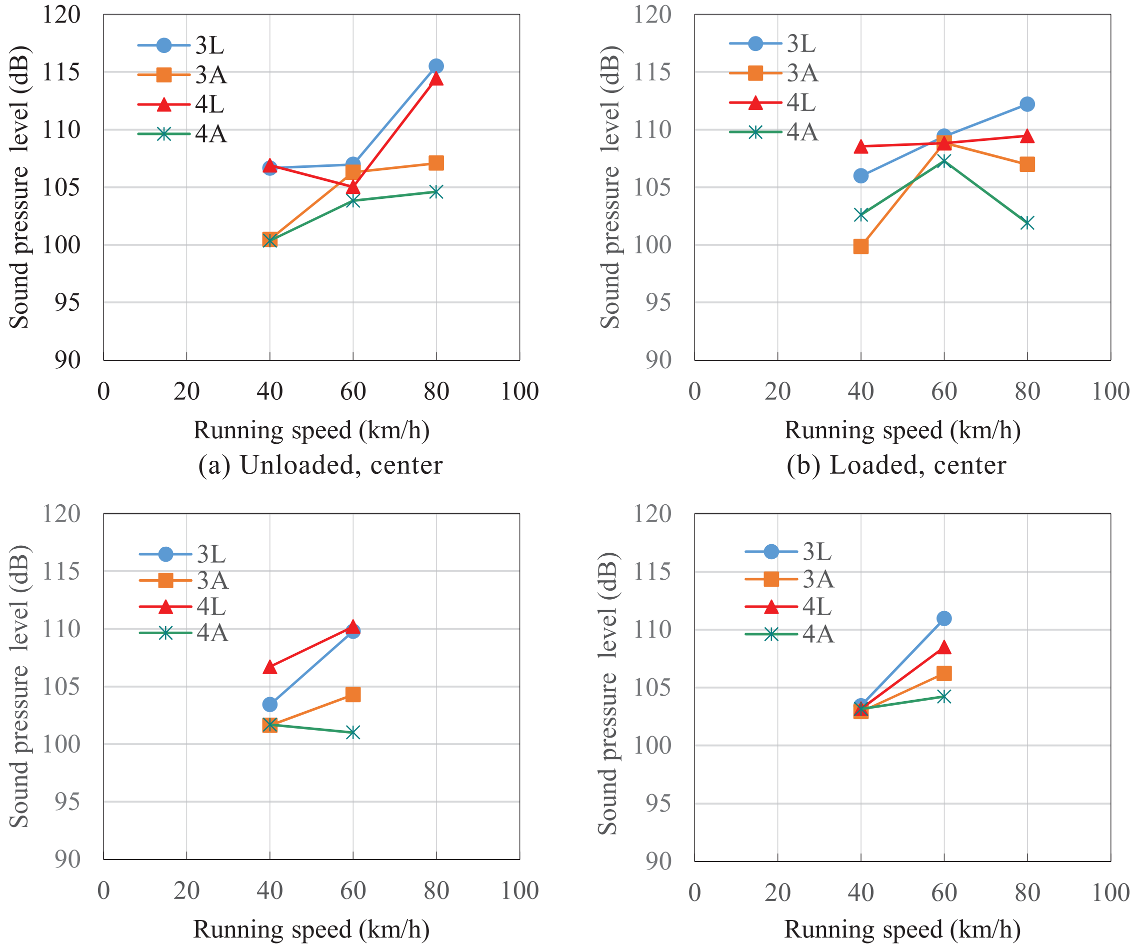


Figure 8 – Sound pressure level vs. running speed

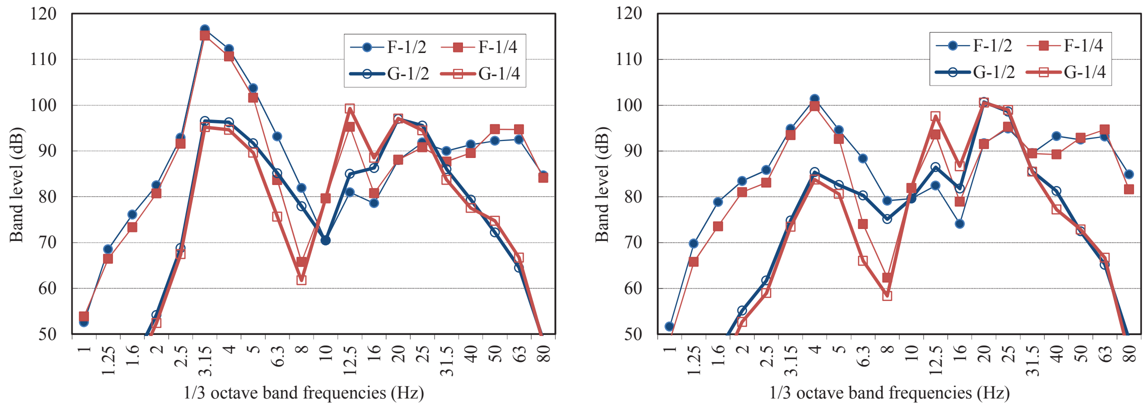
G-weighted sound pressure levels were calculated using G-frequency weighting according to ISO 7196 (9), and are shown in Figure 9. In addition, flat and G-weighted 1/3 octave band levels for leaf and air suspensions were compared for an unloaded 3-axle truck running at the center position at a speed of 60 km/h, as shown in Figure 10. In the case of an unloaded 3-axle truck running at center position at a speed of 60 km/h, because the generation of the first bending vibration (3.3 Hz) decreased according to G-frequency weighting and the band levels at frequencies of 12.5, 20, and 25 Hz were almost identical for leaf and air suspensions, the differences in level between leaf and air suspensions was small. Therefore, the differences between leaf and air suspension of G-weighted sound pressure levels were smaller than those for the flat-weighted level.



(a) Unloaded, center (b) Loaded, center

(c) Unloaded, side (d) Loaded, side

Figure 9 – G-weighted sound pressure level vs. running speed



(a) 3-axles with leaf suspension (b) 3-axles with air suspension

Figure 10 –Flat and G-weighted band level for unloaded truck running at center position (60 km/h)

5. CONCLUSIONS

Running tests using trucks with three- and four-axles and with leaf and air suspension were conducted to investigate the characteristics of the bridge vibration and infrasound radiated from the bridge due to moving trucks.

As a result of this study, the following conclusions were made.

(1) The frequency of the body vibration of the truck with leaf suspension is close to that of the first

bending vibration (3.3 Hz). Many vibrations (second bending vibration 12.1 Hz, torsion 13.2 Hz, bending 15.0 Hz, torsion 18.6 Hz) are within the range of the tire vibrations of the trucks with both leaf and air suspension (10–20 Hz).

(2) The behavior of the infrasound is synchronized with the bridge vibrations and the body vibration of the truck with leaf suspension. The frequencies of the infrasound are consistent with those of the bridge vibration.

(3) The sound pressure level of the infrasound increases with an increase in the running speed. However, it is not a proportional relation, because the generation of the first bending vibration is different in relation to the matching of the frequency of the trucks' body vibration, first bending vibration, and the wavelength road roughness.

(4) In the case of air suspension, when comparing the sound pressure levels from unloaded trucks with those from loaded trucks, there was little difference except for the unloaded condition at 40 km/h. Under certain conditions, the responses for the unloaded trucks were larger than those for the loading trucks. The influence of weight is therefore less important than that of the running speed.

(5) In the case of an unloaded 3-axle truck running at center position at a speed of 60 km/h, because the generation of the bending vibration (3.3 Hz) decreased by G-frequency weighting, and the band levels at frequencies of 12.5, 20, and 25 Hz were almost identical for leaf and air suspensions, the differences in level between leaf and air suspensions was small. Therefore, the differences between leaf and air suspensions of G-weighted sound pressure levels are smaller than those of flat-weighted level.

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