

Infrasound and Ground Vibration Transmitted from Highway Bridges Using Moving Trucks

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ABSTRACT

Several complaints arose from houses near the object bridge, with regard to a rattling sound and house vibration caused by infrasound and ground vibration, respectively. General trucks in Japan with rear leaf suspension have vibration frequencies of about 3.0Hz. Also, the frequencies of the tire spring vibration appear at about 10-20Hz. The occurrence of the infrasound and ground vibration radiated from the bridge is related to the trucks' suspension spring vibration and/or the tire spring vibration. In this study, examinations for the bridge vibration were conducted using test trucks and ordinary trucks to investigate the cause of the rattling sound and house vibration. After examination, the trucks' vibration was causing excessive bending vibration in the object bridge, which in turn, was being transmitted to the houses nearby as infrasound and ground vibration.

INTRODUCTION

Ground vibration and infrasound are radiated from the bridge due to running trucks. Complaints about a rattling sound and/or complaints about mental and physical discomfort caused by the infrasound arose from houses near the bridge. Also, complaints about house vibration caused by the ground vibration arose from the bridge. The occurrence of the ground vibration and the infrasound radiated from the bridge is related to the trucks' suspension spring vibration and/or the tire spring vibration. General trucks in Japan with rear leaf suspension [1] have frequencies of about 3.0Hz. Also, the frequencies of the tire spring vibration appear at about 10-20Hz.

In the case of the infrasound, when each truck's vibration (the truck's suspension spring vibration and/or the tire spring vibration) and the bridge vibration are close, complaints about a rattling sound and/or the complaints about mental and physical discomfort occur. The complaints about the rattling sound are related to the trucks' suspension spring vibration, which occurs at about 3.0Hz. Also, it appears the complaints about mental and physical discomfort are much more related to the truck's tire spring vibration at about 10-20Hz.

A human strongly perceives the vertical and horizontal vibration with frequencies of 4-8Hz and 0-2Hz, respectively. In the case of the ground vibration, when each truck's vibration (the truck's suspension spring vibration and/or the tire spring vibration), the house vibration and the bridge vibration are close, complaints about house vibration occur. The complaints about the horizontal house vibration are related to the trucks' suspension spring vibration, which occurs at about 3.0 Hz. Also, it appears the complaints about the vertical house vibration are much more related to the trucks' tire spring vibration at about 10-20Hz.

In past studies [2][3][4], the complaints about house vibration and the complaints about mental and physical discomfort from the infrasound occurred near the bridge. The ground vibration and infrasound was caused by the bridge vibration resonating with the trucks' tire spring vibration at frequency 10Hz.

The complaints about house vibration and also, the complaints about the rattling sound by the infrasound radiated from the bridge occurred in houses near the bridge. In this study, examinations were conducted to investigate the cause using a test truck and ordinary trucks. The results of the examinations showed that the bending vibration of the object bridge generated by the trucks' spring vibration was transmitted to the houses near the bridge by way of the ground vibration and the infrasound.

OBJECT BRIDGES

The object bridges are each comprised of two lanes; one bridge with two eastbound lanes parallel to a bridge with two westbound lanes. The eastbound bridge has a simple steel composite girder bridge with a 25.2m span and three spans of continuous steel composite girder bridges each with a 49.0m span which were constructed in 1967 as shown in Fig. 1(a) and Fig. 1(c).

On the other hand, the westbound bridge has a simple steel composite girder bridge with a 36.47m span and three spans of continuous steel composite girder bridges with 48.59m, 49.09m and 49.09m spans, respectively, which were constructed in 1972 as shown in Fig. 1(b) and Fig. 1(c).

The eastbound and westbound bridges have three girders and four girders, respectively as shown in Fig. 1(d) and Fig. 1(e).

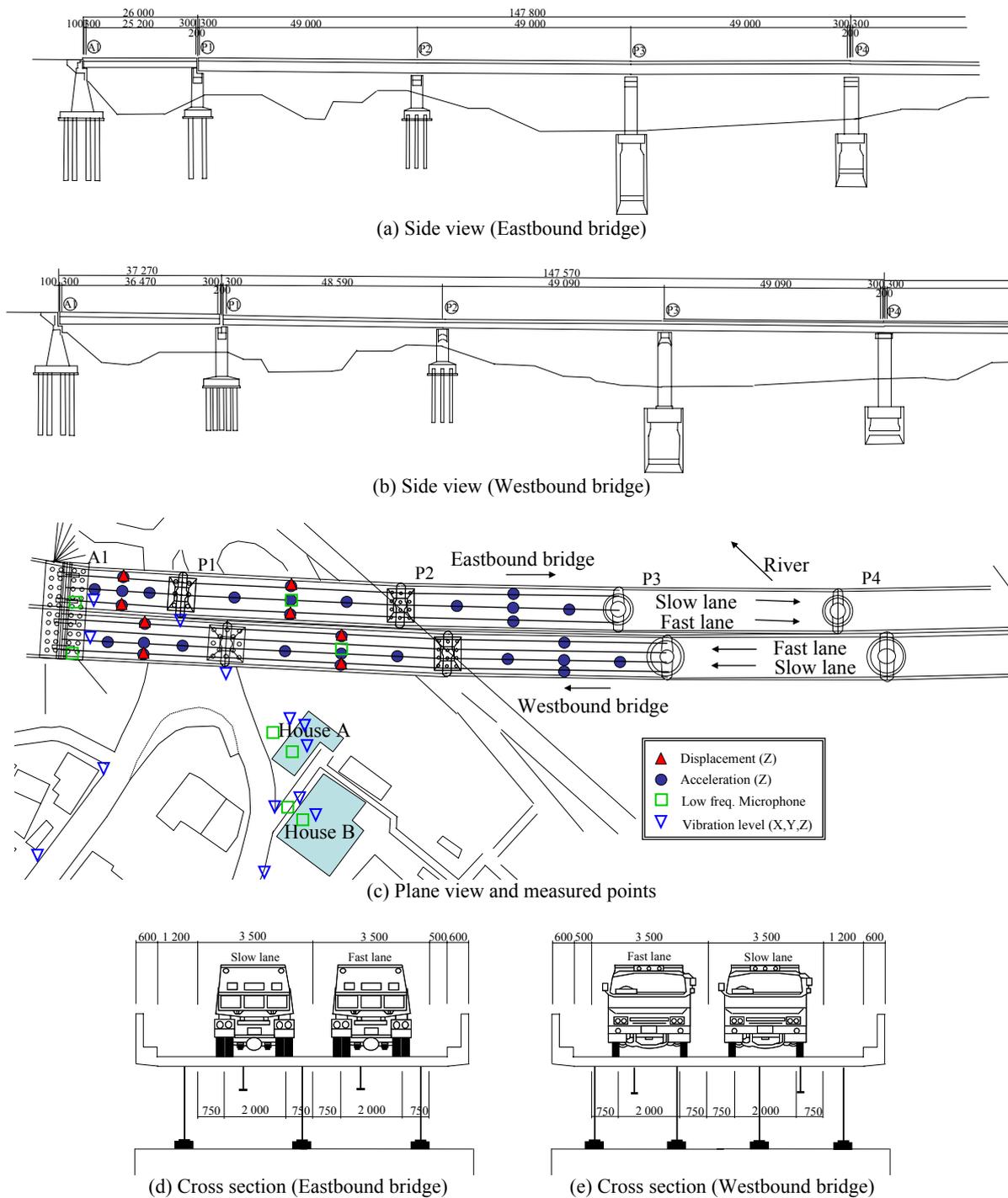


Figure 1. Object highway bridge

The simple composite girder bridges of the westbound and eastbound bridges are jointed with continuous bridges by a joint-less system. The daily traffic is over 30,000-35,000 cars. The traffic flow volume of trucks is about 30%.

EXAMINATION

The complaints about house vibration and the complaints about the rattling sound produced by the infrasound radiated from the bridge occurred in House A and House B near the bridge (P1-P2) of the westbound bridge as shown in Fig. 1(c). In order to investigate the causes of the complaints, running tests using a test truck or ordinary trucks were carried out. The measured points are shown in Fig. 1(c). The measured items were a) the displacement of the superstructure; b) the acceleration of the superstructure's vibration; c) the infra-

sound measured by low frequency microphone, and d) the vibration level.

Fig. 2 shows a) the acceleration at the P1 of the westbound bridge (vertical direction); b) the acceleration at the ground of House A (vertical direction); c) the acceleration at the ground of House B (vertical direction) and d) the sound pressure at the side of House A, when the ordinary trucks pass on the westbound bridges. Also, the spectrums of these waves are shown in Fig.3. The acceleration from the P1 to the houses corresponds to the time of the peak value at the A1. The frequencies of the truck's tire spring vibration (10-20 Hz), the frequencies of the test truck's rear leaf suspension spring vibration (3Hz) and the bending modes (2-4Hz) appear in the spectrums of the acceleration from the P1 to the houses.

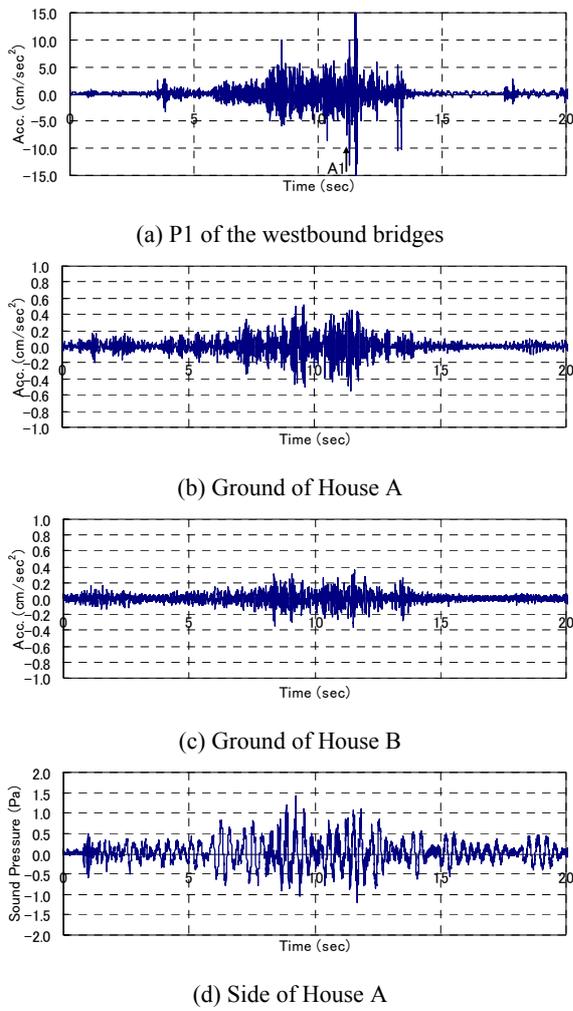


Figure 2. Acceleration and sound pressure

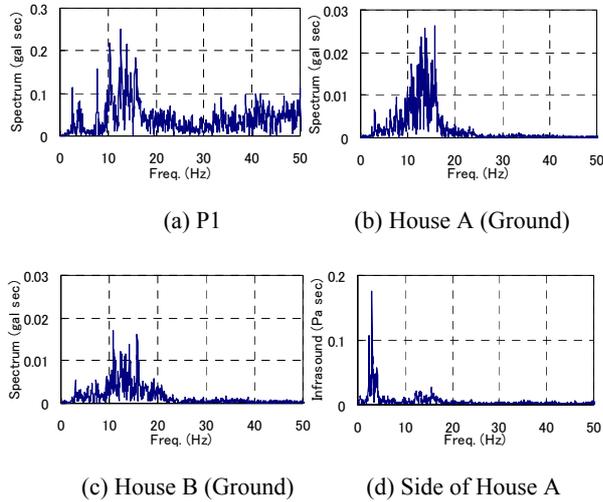


Figure 3. Spectrum of the Acc. and infrasound

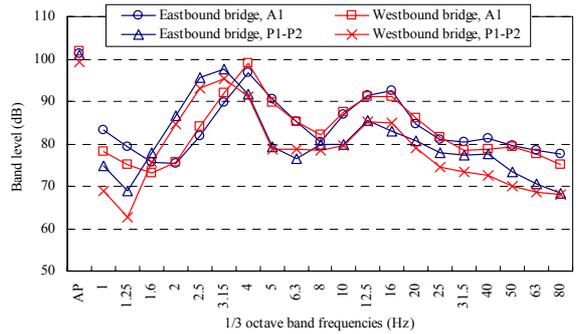
Table 1. Frequencies and damping constant

Vibration mode	Westbound bridge		Eastbound bridge	
	Freq. (Hz)	Damp. (-)	Freq. (Hz)	Damp. (-)
Bending mode 1st	1.93	0.008	1.85	0.019
Bending mode 2nd	2.49	0.013	2.36	0.008
Torsion mode 1st	2.72	0.009	3.40	0.013
Bending mode 3rd	3.29	0.011	3.00	0.007
Bending mode 4th	3.94	0.010	5.42	0.017
Torsion mode 2nd	4.52	0.017	6.23	0.020

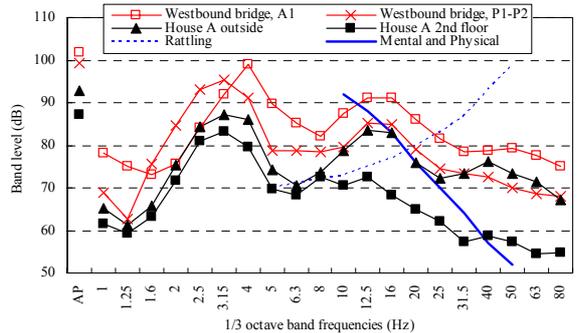
Experimental frequencies and the damping constants were computed by using ERA (Eigensystem Realization Algorithm) [5]. The results obtained by the ERA are shown in Table 1. Experimental damping constants for each mode scatter about 1.0-2.0%.

CHARACTERISTICS OF INFRASOUND

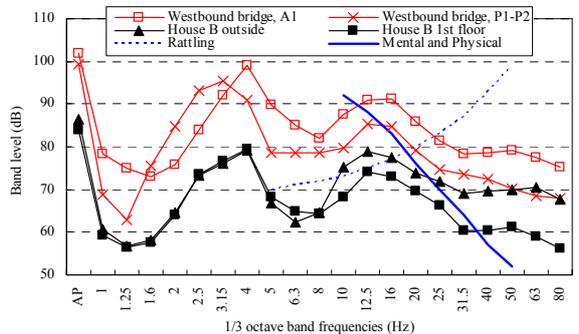
In order to investigate the causes of the complaints about the rattling sound, the infrasound caused by ordinary trucks was measured for 10 minutes per hour from 9:00 PM to 8:00 AM. Low frequency microphones were installed as shown in Fig. 1. Every 1/3 octave band frequency of the infrasound at each measurement point is shown in Fig. 4. Here, these are the averages of the peak levels for each 10 minute per hour period.



(a) Abutment (A1) and mid span (P1-P2) of the westbound and eastbound bridges



(b) Abutment (A1) and mid span (P1-P2) of the westbound bridge and House A



(c) Abutment (A1) and mid span (P1-P2) of the westbound bridge and House B

Figure 4. 1/3 octave band frequencies of the infrasound

Fig. 4 (a) shows the 1/3 octave band frequencies of the infrasound at the abutment (A1) and mid span (P1-P2) of the westbound and eastbound bridges. The westbound and eastbound bridges have almost the same characteristics with regard to their frequencies. The different peak level frequencies

of the abutment (A1) and mid span (P1-P2) appear at frequencies 4.0Hz and 2.5-3.15Hz, respectively. Also, the abutments (A1) of both the eastbound and westbound bridges share the same band level at frequencies 12.5Hz and 16.0Hz. Similarly, the mid spans (P1-P2) of both the eastbound and westbound bridges share the same band level at frequency 12.5Hz.

Fig. 4 (b) shows the 1/3 octave band frequencies of a) the infrasound at the abutment (A1) of the westbound bridge; b) the mid span (P1-P2) of the westbound bridge; c) outside House A; and d) the 2nd floor of House A. The 2nd floor of House A has the characteristics of frequencies (2.5-4.0Hz and 12.5Hz) with the same characteristics of frequencies (2.5-4.0Hz and 12.5Hz) at the mid span (P1-P2). House A is affected by the frequencies 2.5-4.0Hz and 12.5Hz.

Fig. 4 (c) shows the 1/3 octave band frequencies of a) the infrasound at the abutment (A1) of the westbound bridge; b) the mid span (P1-P2) of the westbound bridge; c) outside House B; and d) the 1st floor of House B. The 1st floor of House B has the characteristics of frequency (4.0Hz and 12.5Hz) with the same characteristics of frequency (4.0Hz and 12.5Hz) at the abutment (A1). House B, as well as House A, is affected by frequencies 2.5-4.0Hz and 12.5Hz. Therefore, it turned out that the two houses are influenced by the westbound and eastbound bridges' vibration modes at 2.5-4.0Hz and 12.5Hz.

Also, the comparison of 1/3 octave band frequencies with the reference values for the complaints about the rattling sound and for the complaints about mental and physical discomfort by the Japanese Ministry of Environment is shown in Fig. 4 (b) and Fig. 4 (c). Though this rattling sound curve is only defined beginning from 5Hz, it seems that these levels measured in House A and House B are larger than the rattling sound curve as defined by the Japanese Ministry of Environment for the frequencies 2.5-4.0Hz. Therefore, House A and House B are more affected by the infrasound at frequencies 2.5-4.0Hz radiated from the westbound and eastbound bridges.

CHARACTERISTICS OF GROUND VIBRATION

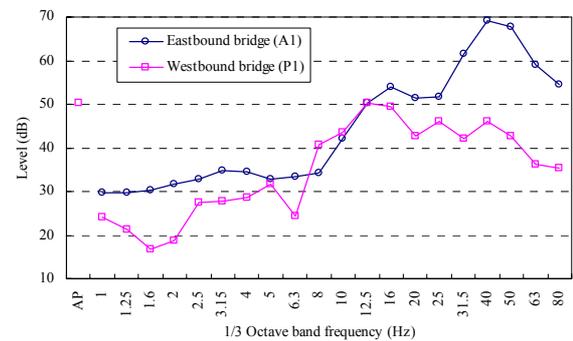
The house vibration caused by ordinary trucks was measured for 10 minutes per hour from 9:00 PM to 8:00 AM to investigate the causes of the complaints about house vibration. Vibration level meters were installed as shown in Fig. 1. Every 1/3 octave band frequency of the vibration level at each measurement point is shown in Fig. 5. Here, these are the averages of the peak levels for each 10 minute per hour period.

Fig.5 (a) shows the 1/3 octave band frequencies of the vibration level at the abutment (A1) of the eastbound bridge and the pier (P1) of the westbound bridge. The westbound and eastbound bridges have the same peak level frequencies at 10-20Hz caused by the trucks' tire spring vibration passed at the A1 joint. Also, the different peak level frequencies of the abutment (A1) appear at 25-80Hz.

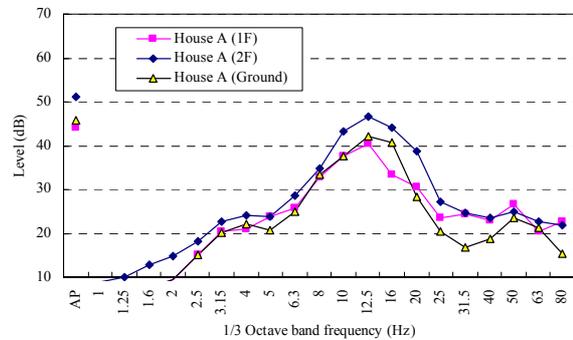
Fig. 5 (b) shows the 1/3 octave band frequencies of the vibration level at the ground, the 1st floor and the 2nd floor of House A. These have the same characteristics of frequencies (3.15-4.0Hz and 10-16Hz) with those frequencies of the westbound and eastbound bridges. Therefore, House A is affected by the frequencies 3.15-4.0Hz and 10-20Hz of the westbound and eastbound bridges.

Fig. 5 (c) shows the 1/3 octave band frequencies of the vibration level at the ground and the 1st floor of House B. These have the same characteristics of frequencies (3.15-4.0Hz and

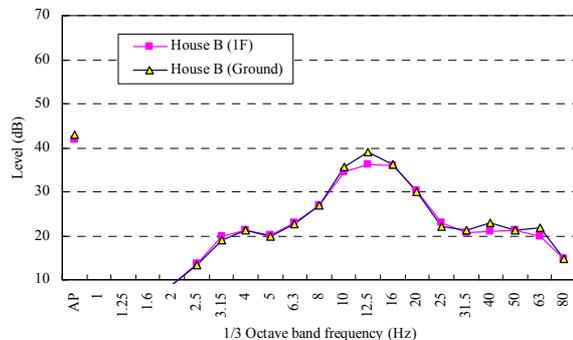
10-16Hz) with those frequencies of the westbound and eastbound bridges, as well as House A. House B, as well as House A, is affected by frequencies 3.15-4.0Hz and 10-20Hz of the westbound and eastbound bridges. Therefore, it turned out that the two houses are influenced by the westbound and eastbound bridges' vibration at 3.15-4.0Hz and 10-20Hz.



(a) Abutment (A1) of the eastbound bridge and pier (P1) of the westbound bridge



(b) House A



(c) House B

Figure 5. 1/3 octave frequencies of the vibration level

ANALYTICAL BRIDGE MODELS

Analytical bridge models of the westbound and eastbound bridges were made in order to grasp the vibration mode at frequency 2.5-4Hz, which predominately affected House A and House B. Analytical bridge models [6][7] of each bridge are shown in Fig. 6. The decks and webs of the steel girders and the central crossbeams were modeled using shell elements. The other components, the upper and lower flanges, lateral bracings and sway bracings, were modeled using beam elements. The steel girders were jointed with the decks using rigid elements. The stiffness and mass of copings were considered in the analysis. The pavement was considered only as mass without stiffness. The bearings were modeled as spring elements.

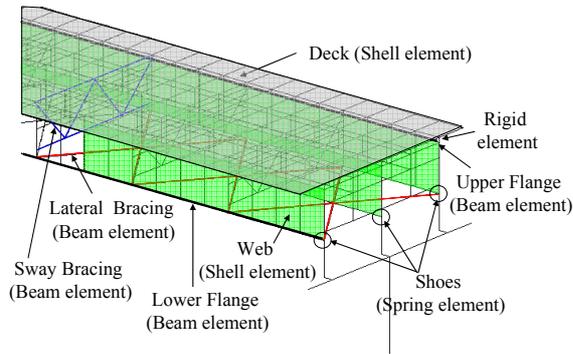


Figure 6. Detail of analytical bridge models

VIBRATION CHARACTERISTICS

Fig. 7 and Fig. 8 show the vibration modes obtained by the Eigen value analysis of the westbound and eastbound bridges, respectively. The validities of these vibration modes were confirmed by comparing with the measured frequencies and mode shapes. These bridges have many similar vibration modes at frequencies 2-5Hz. It is clear that the bending vibration modes with the same phase at each span in the westbound bridge at the frequency of about 2.5-4.0Hz (anal.: 2.43Hz, 3.24Hz, 3.90Hz, exp.: 2.49Hz, 3.29Hz, 3.94Hz) affect House A and House B. Since each span vibrates with the same phase, it seems that the most powerful sound pressure is caused by the infrasound transmitted to House A and House B. The bending vibration modes with the same phase in the eastbound bridge appear at about 2.5-3.0Hz (anal.: 2.35Hz, 3.11Hz, exp.: 2.36Hz, 3.00Hz). It seems that these vibration modes affect House A and House B by comparing with the measured 1/3 octave band frequencies of the infrasound.

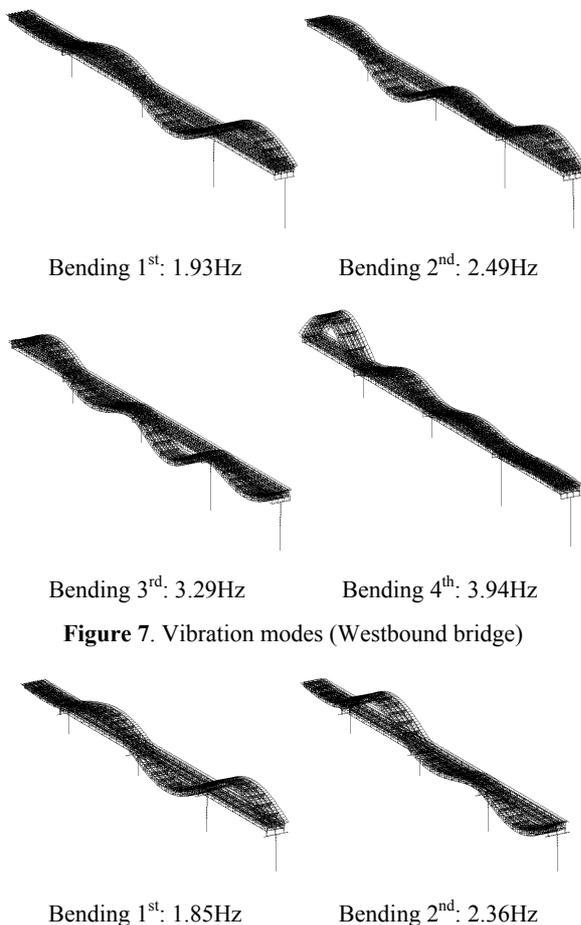


Figure 7. Vibration modes (Westbound bridge)

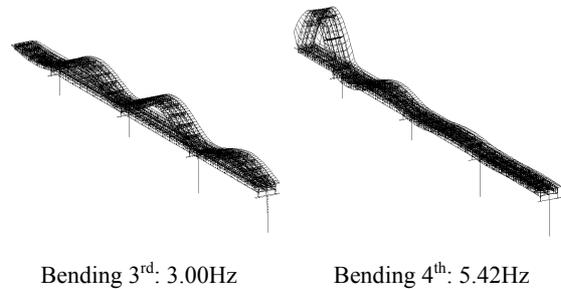


Figure 8. Vibration modes (Eastbound bridge)

CONCLUSIONS

In this study, examinations for the bridge vibration were conducted using test trucks and ordinary trucks to investigate the cause of the rattling sound and house vibration. After examination, the trucks' vibration was causing excessive bending vibration in the object bridge, which in turn, was being transmitted to the houses nearby as infrasound and ground vibration.

The knowledge acquired by this study is as follows:

- (1) Comparing with the 1/3 octave band frequencies of the infrasound for the westbound and eastbound bridges and object houses, House A and House B are affected by frequencies 2.5-4.0Hz and 12.5Hz. Especially, House A and House B are more affected by the infrasound at frequencies 2.5-4.0Hz radiated from the westbound and eastbound bridges.
- (2) Comparing with the 1/3 octave band frequencies of the vibration level for the bridge and object houses, House A and House B are influenced by the westbound and eastbound bridges' vibration at 3.15-4.0 Hz and 10-20Hz.
- (3) The westbound and eastbound bridges have many similar vibration modes at frequencies 2-5Hz.
- (4) The frequencies of 10-20Hz appearing at the object houses, the westbound and the eastbound bridges are caused by the trucks' tire spring vibration, when the trucks pass at the A1 joint of each bridge.
- (5) The bending vibration modes with the same phase at each span in the westbound bridge at the frequency of about 2.5-4.0 Hz affect House A and House B. Since each span vibrates with the same phase, it seems that the most powerful sound pressure is caused by the infrasound transmitted to House A and House B.

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