Interaction and Multiscale Mechanics, Vol. 3, No. 4 (2010) 373-387

DOI: http://dx.doi.org/10.12989/imm.2010.3.4.373

Assessment of traffic-induced low frequency sound radiated from a viaduct by field experiment

M. Kawatani[1], C.W. Kim[2]* and K. Nishitani[1]

[1]*Department of Civil Engineering, Kobe University, Kobe 657-8501, Japan*
[2]*Department of Civil and Earth Resources Engineering, Kyoto University, Kyoto 615-8540, Japan*

(Received August 20, 2010, Accepted October 28, 2010)

Abstract. This study is intended to assess low frequency sound radiated from a viaduct under normal traffic. The bridge comprises steel box girders and wide cantilever decks on which vehicles pass. The low frequency sound and the acceleration response of the bridge under normal traffic are measured to investigate how bridge vibrations affect the low frequency sound observed near the bridge. Observations demonstrate that strong relationships exist between frequency characteristic of bridge's acceleration response and the sound pressure level of low frequency sound. A noteworthy point is that the dynamic feature of the sound pressure level is mostly affected by dynamic feature of the span locating near the observation point.

Keywords: field experiment; low frequency sound; sound pressure level; steel box girder bridge; traffic-induced vibration.

1. Introduction

Low frequency sound (LFS) causes extreme distress to a number of people who are sensitive to its effects. Such sensitivity may be a result of heightened sensory response within the whole or part of the auditory range or may be acquired. Historically, early work on low frequency sound and its subjective effects was stimulated by the American space program, a source of very high level of LFS (Mohr *et al*. 1965). Recently media on the LFS radiated from wind turbine generators (Pedersen and Persson 2004).

The LFS radiated from bridges under traffic, however, has been one of the environmental problems relating to bridge vibrations, especially in land scarce major cities of Japan, even before occurring LFS associated problems due to the wind turbine generator. In urban areas, viaducts have been constructed even near to the residential zone, and as a result a number of complaints against noise and vibration radiated from those viaducts have been reported.

The LFS is the sound with frequencies below 100 Hz (ISO 1995), which vibrates houses near the sound source and even causes psychological and physiological influences to residents. Usually psychological factors affect the physiological impact of noise (Hatfield *et al*. 2001). Rattling sound of doors or windows is the typical influence to houses due to the sound pressure (Leventhall 2003). As

* Corresponding author, Professor, E-mail: kim.chulwoo.5u@kyoto-u.ac.jp

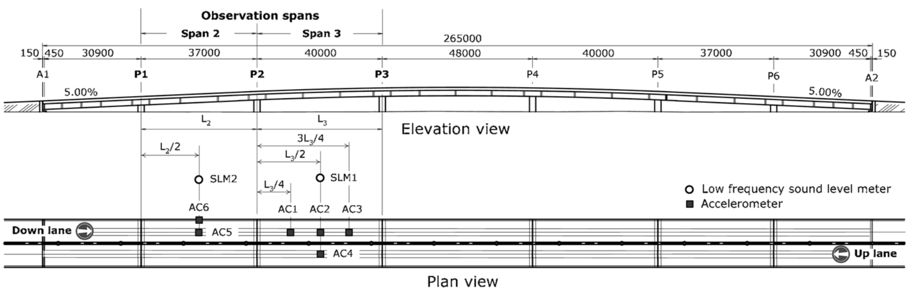
physiological influences to residents, there are nausea, headache, etc. It is also reported that feelings of pressure and vibration are typical reactions of residents for LFS (Johnson 1975, Tokita 1985, Kalveram 2000). Moreover the sound near 40 Hz gives keen sense of such pressure and vibration (Inukai *et al.* 2000). Constant low frequency noise has been classified as background stresses, which are persistent events and may become routine elements of people's life (Benton and Leventhall 1994, Benton 1997).

Among environmental vibrations caused by traffic, the sound radiated from engines and tires of heavy vehicles are regarded as sources of the noise (Eberhardt 1998). The ground vibration due to traffic is another major source for complaints of human reception for vibration (Sheng *et al.* 2006). Comparing with those two problems, the LFS due to the traffic-induced vibration of bridges has been a minor problem, and how to control the LFS has not been fully examined. However the current trend of the bridge design adopting simplified structural details and lighter structures accompanying increase of truck weight and heavy traffic volume exposes the low frequency vibration problems (Kim and Kawatani 2003, Kim *et al.* 2004). Restricted numbers of researches have been focusing on the LFS radiated from highway bridges (e.g. Goromaru *et al.* 1987). It means that effective countermeasure as well as systematic approaches to reduce the LFS radiated from bridges has not been established yet.

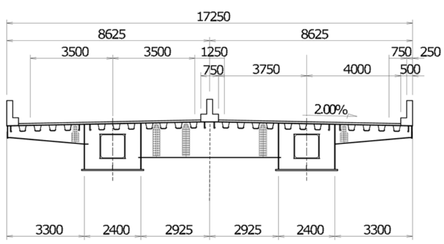
This study is intended to assess traffic-induced LFS radiated from a bridge through a field experiment. Especially how the traffic-induced vibrations affect the LFS observing near bridges is examined using the measured acceleration response of the bridge and SPL of LFS.

2. Observation bridge

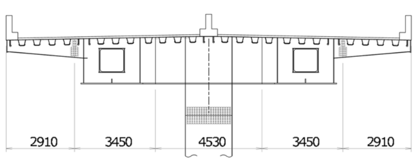
The observation bridge is a seven span continuous steel box girder bridge, as shown in Fig. 1. The total length and width of the bridge are 265.0 m (31.5 + 37.0 + 40.0 + 48.0 + 40.0 + 37.5 + 31.5)



(a) General layout of bridge and observation points



(b) Cross section of bridge between piers



(c) Cross section of bridge on the pier

Fig. 1 General view of bridge

and 17.25 m respectively. The bridge has steel decks and rigid frame piers which are rigidly connected with box girders. The bridge comprises wide decks on which a traffic lane is placed. Actually the bridge is the grade-separation overhead bridge by means of the “Sui-sui module on pier method (MOP)” (JSSC 2010), which is composed of the bridge section consisting of steel bridge girders and piers and the approach section consisting of banking.

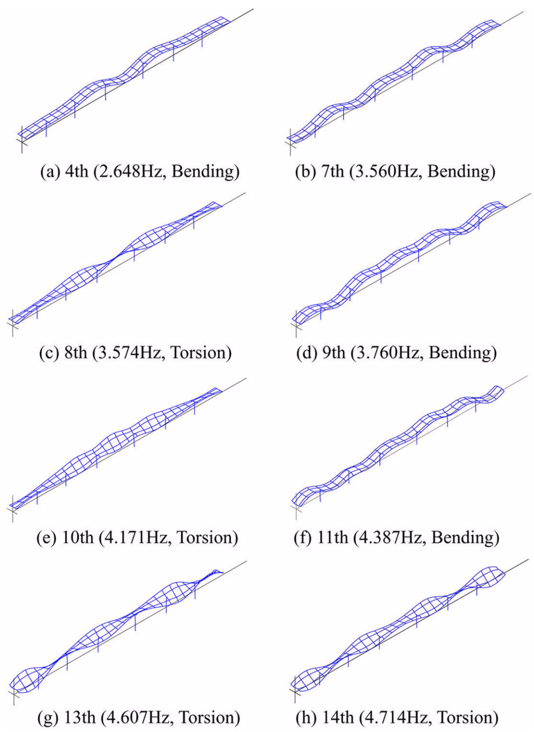


Fig. 2 Analytical natural modes relating to bending and torsional modes of bridge

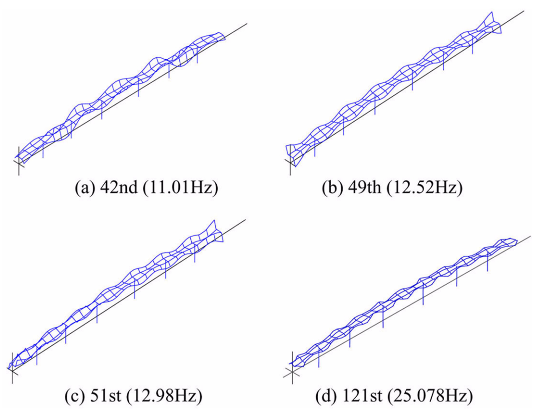


Fig. 3 Analytical natural modes relating to bending of cantilever decks

3. Field experiment

According to the preliminary study by Kawatani *et al*. (2008), the natural frequencies of the bridge for bending and torsional modes are ranging from 3 Hz to 5 Hz, as shown in Fig. 2. Those frequencies for the bending mode of the cantilever deck are from 11 Hz to 25 Hz, as summarized in Fig. 3 with corresponding modes. Moreover the study on a steel box girder bridge by Nagatsu *et al*. (2008) demonstrates that the SPL around 40 Hz strongly links to vibrations of web plates of the steel box girder. Therefore this study focuses SPLs of 3.15 Hz, 4.0 Hz, 5.0 Hz, 25.0 Hz and 40.0 Hz

Table 1 Details of observation points

Observation point of acceleration response	
AC1	$L_3/4$ from P2; Girder of down lane
AC2	Center of Span 3; Girder of down lane
AC3	$3L_3/4$ from P2; Girder of down lane
AC4	Center of Span 3; Girder of up lane
AC5	Center of Span 2; Girder of down lane
AC6	Center of Span 2; Cantilever deck of down lane
Observation point of low frequency sound	
SLM1	Center of Span 3; Border between public and private near down lane
SLM2	Center of Span 2; Border between public and private near down lane

AC: Accelerometer, SLM: Sound Level Meter, L: Span Length

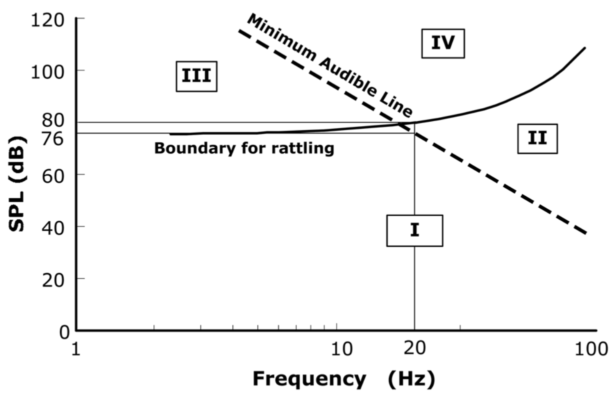


Fig. 4 Classification of low frequency sound

Table 2 Category to assess low frequency sound

Category	Remark
I	No window or door rattling, and no low frequency sound is perceived.
II	Physiological influences may occur despite of no window or door rattling.
III	The low frequency sound is perceived indirectly in forms of door or windows rattling.
IV	Windows or door rattling occurs and low frequency sound is perceived due to high SPL.

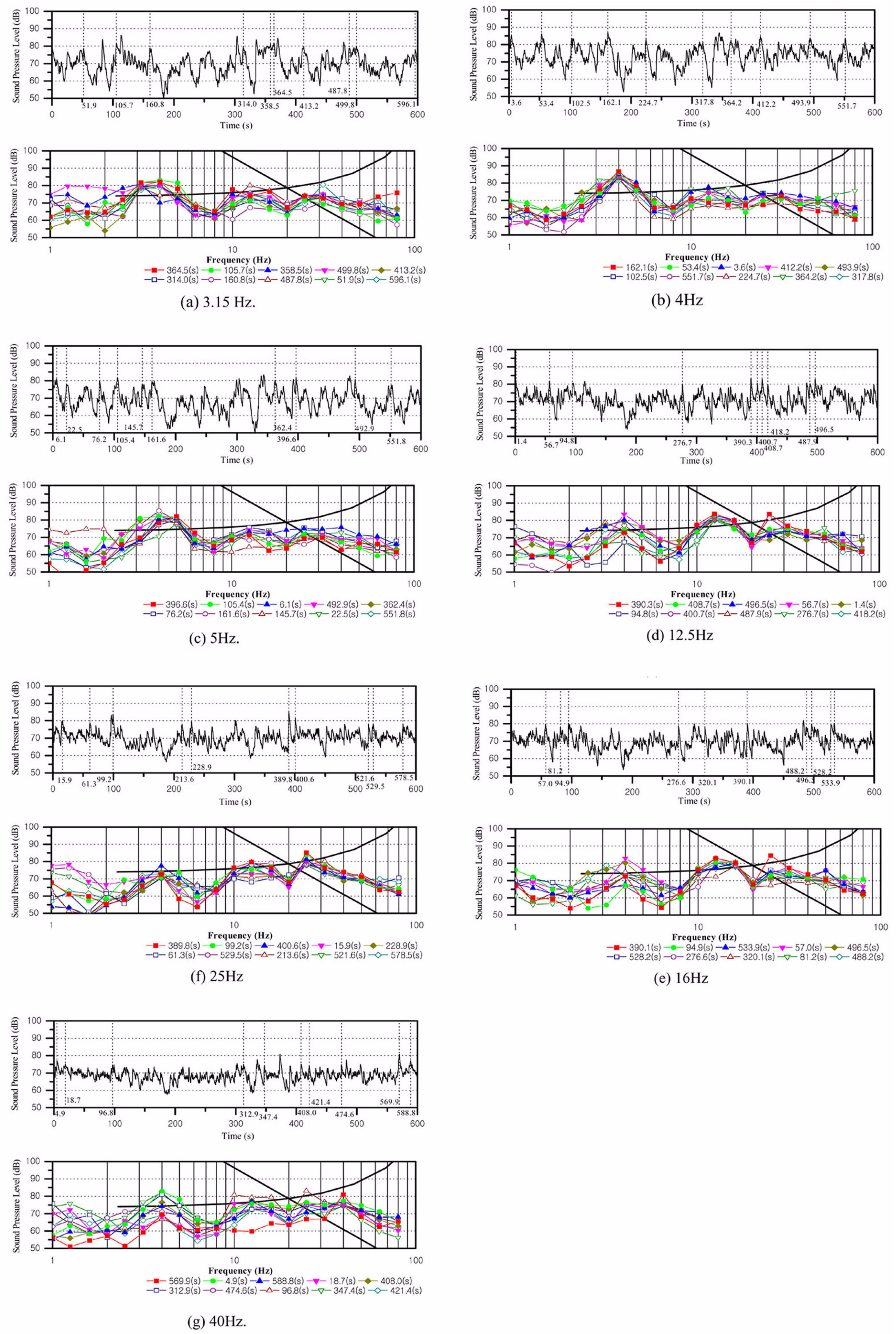


Fig. 5 SPL of target frequencies (SLM1 at Span 3)

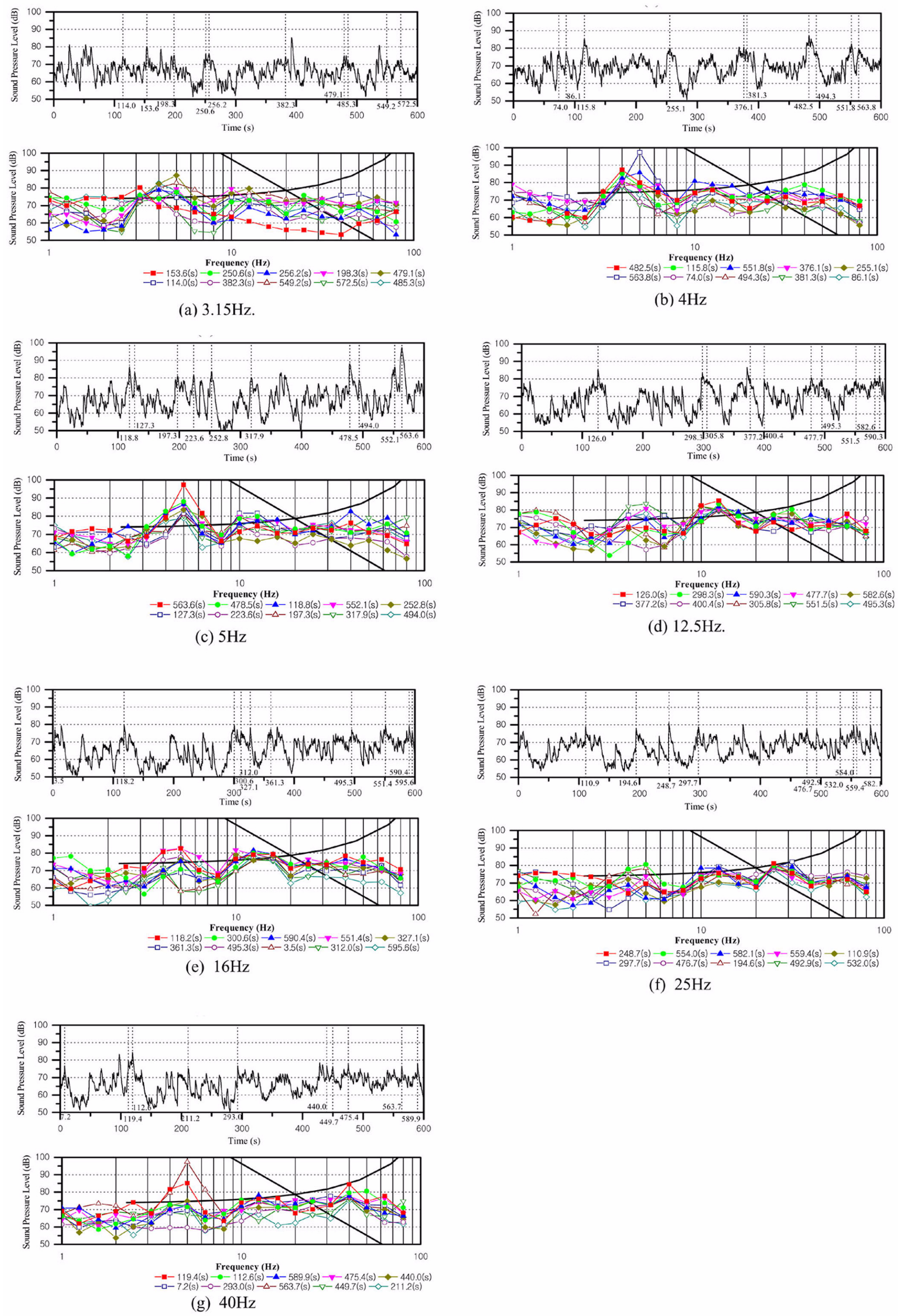
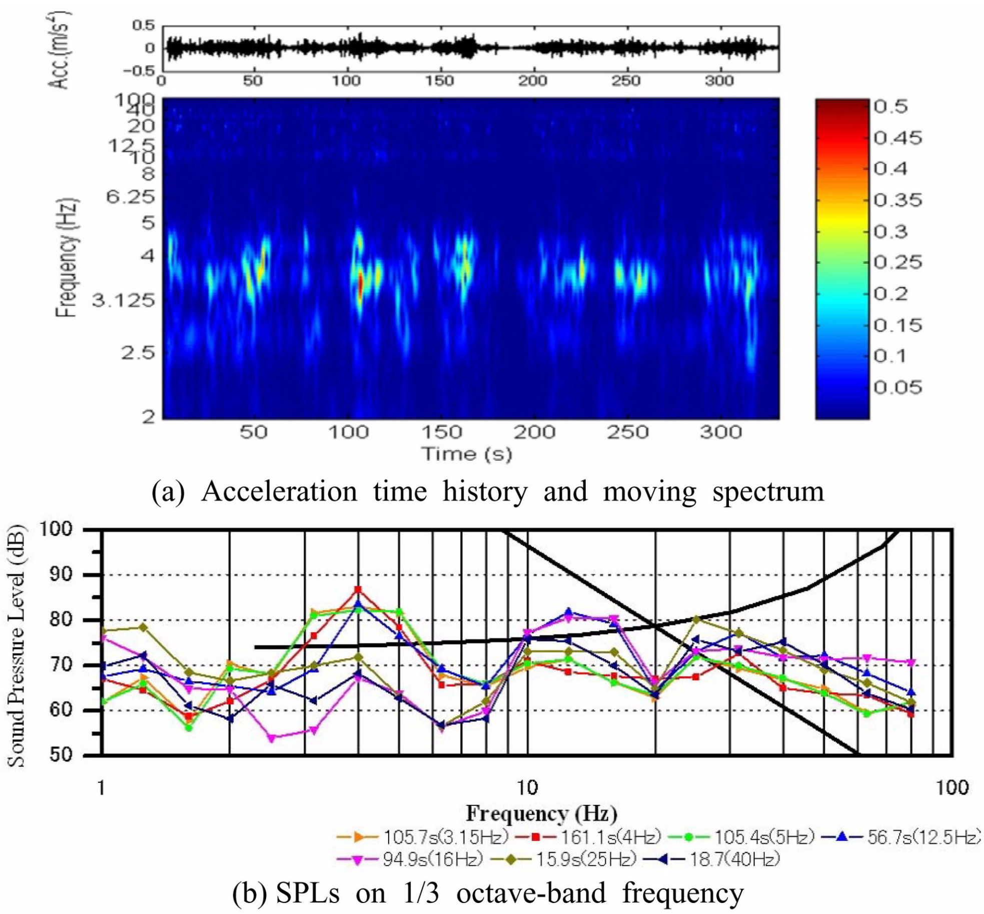


Fig. 6 SPL of target frequencies (SLM2 at Span 2)

among nominal central frequencies of 1/3 octave-band (hereafter, 1/3 octave-band frequency). In addition, those SPLs of 12.5 Hz and 16.0 Hz of the 1/3 octave-band frequency are also examined because they are frequencies connecting to the motion of vehicle's un-sprung mass. Hereafter this

Table 3 Mean values of SPL at each peak time

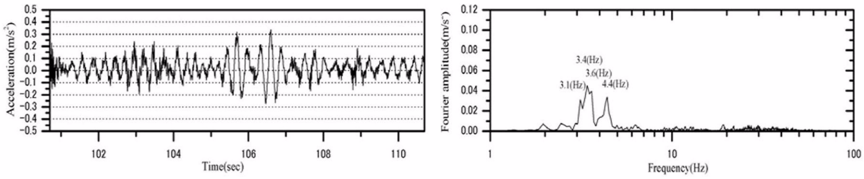
Target frequency	SLM1 (Span 3)	SLM2 (Span 2)
3.15 Hz	80.78 dB	76.61 dB
4.00 Hz	85.40 dB	83.14 dB
5.00 Hz	81.22 dB	86.61 dB
12.5 Hz	82.50 dB	83.68 dB
16.0 Hz	80.22 dB	79.49 dB
25.0 Hz	82.04 dB	80.32 dB
40.0 Hz	77.14 dB	77.64 dB



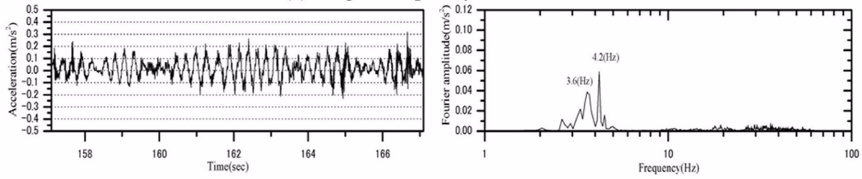
(a) Acceleration time history and moving spectrum

(b) SPLs on 1/3 octave-band frequency

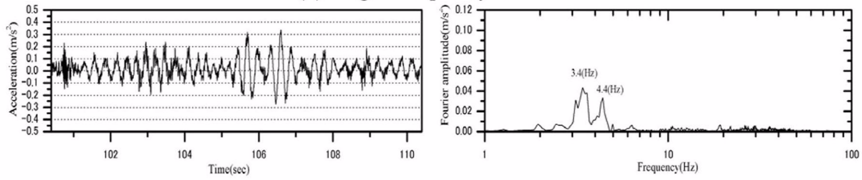
Fig. 7 Acceleration time history observed at AC2 on Span 3 and its moving spectrum, and SPLs of 1/3 octave-band frequency measured at SML1 near Span 3



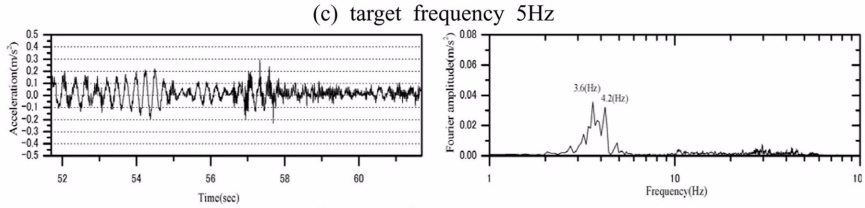
(a) target frequency of 3.15Hz



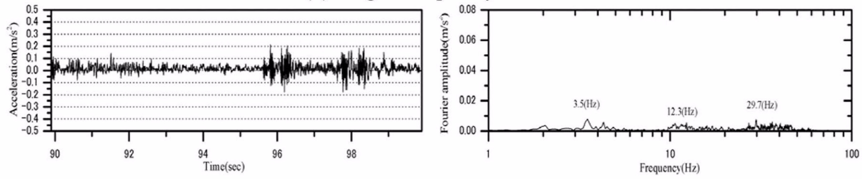
(b) target frequency of 4Hz



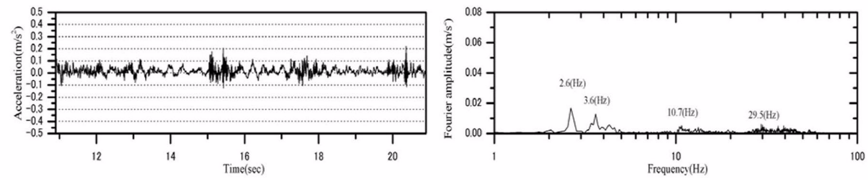
(c) target frequency 5Hz



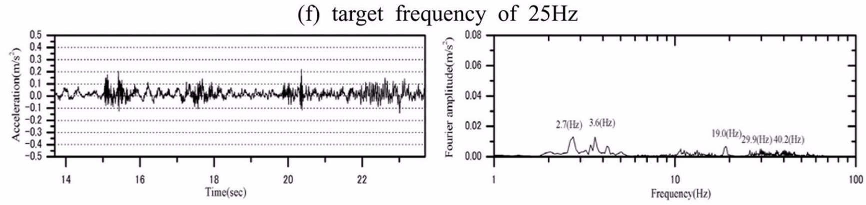
(d) target frequency12.5Hz



(e) target frequency 16Hz



(f) target frequency of 25Hz



(g) target frequency of 40Hz

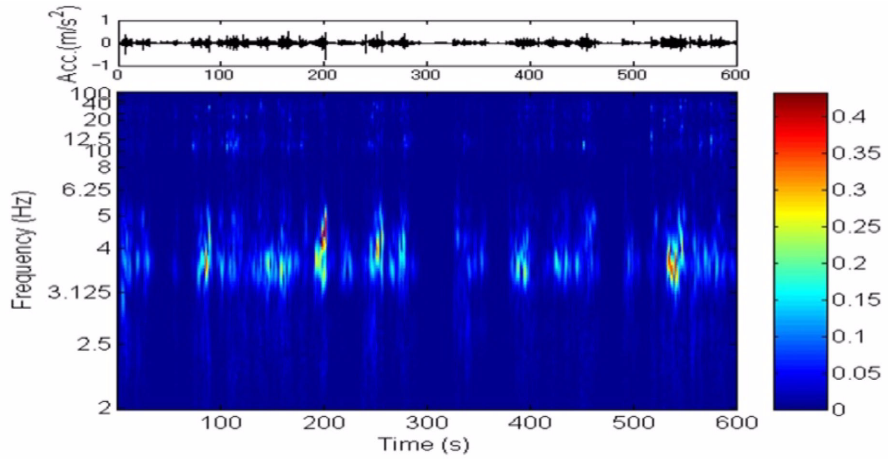
Fig. 8 Acceleration time history taken from five seconds before and after the time of peak SPL of each target frequency and their Fourier spectra observed at AC2 on Span 3

paper designated those seven frequencies as the target frequencies.

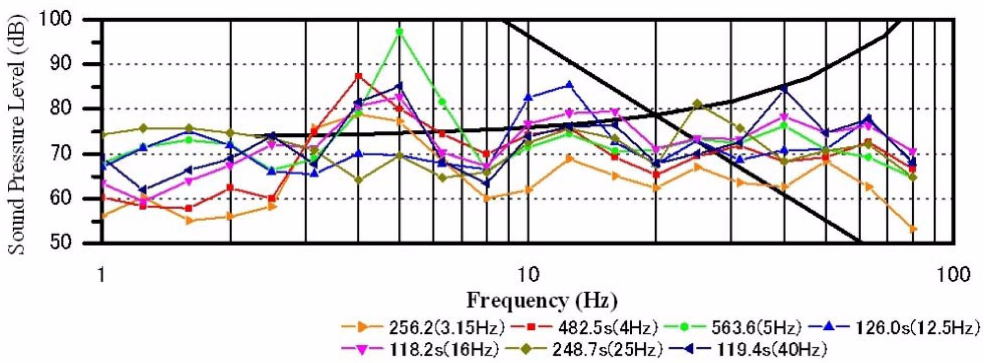
The acceleration responses of the bridge are measured at six observation points. The sound pressure level (SPL) and the acceleration response are acquired during 10 minutes. Table 1 provides details of observation points. Those observation points also appear in Fig. 1 (a).

Ten peaks selected from time series of SPL of each target frequency are plotted on the criterion shown in Fig. 4 to assess the LFS. The criterion is categorized as four regions which are divided by minimum audible line and the boundary for rattling. The meaning of categories I, II, III, and IV in Fig. 4 is described in Table 2 (Ministry of Environment 2004). The 20.0Hz in the figure is the border to classify low frequency sound/noise and infrasound, and the SPLs crossing minimum audible line and rattling at the 20.0 Hz are 76 dB and 80 dB respectively.

In measuring SPL, heavy vehicles passing near the measuring points were observed, and the air pressure generated by passing vehicles affects SPL of 1 Hz to 2 Hz as a result. Therefore among peaks over 80 dB which is the minimum value causing rattling of window or door at 20.0 Hz as previously mentioned, ten peaks except those peaks appearing in 1 Hz to 2 Hz are considered.

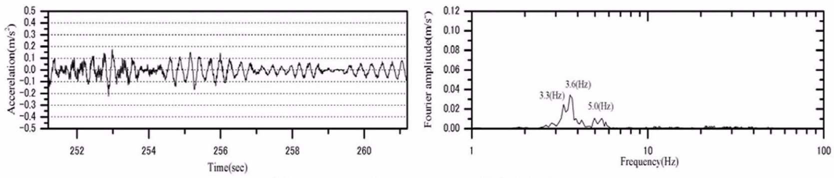


(a) Acceleration time history and moving spectrum

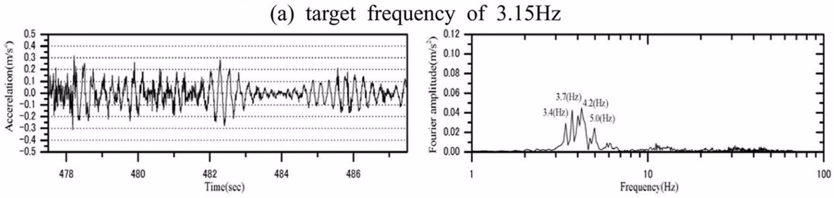


(b) SPLs on 1/3 octave-band frequency

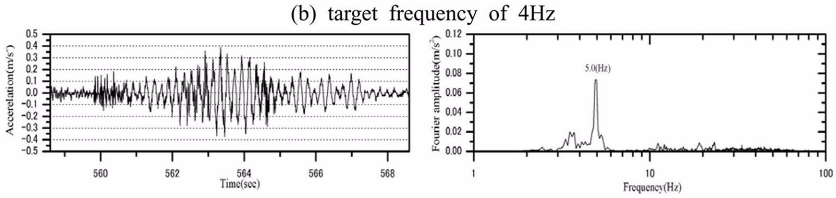
Fig. 9 Acceleration time history observed at AC5 on Span 2 and its moving spectrum, and SPLs of 1/3 octave-band frequency measured at SML2 near Span 2



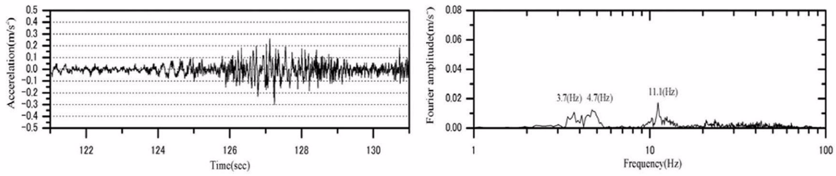
(a) target frequency of 3.15Hz



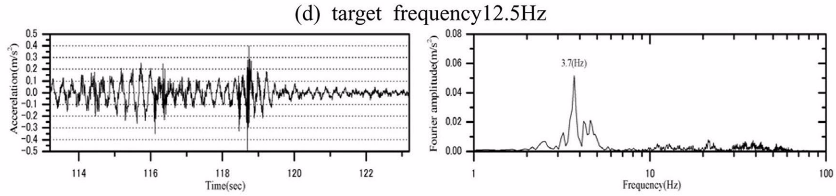
(b) target frequency of 4Hz



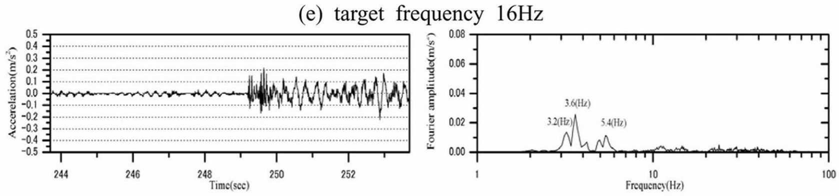
(c) target frequency 5Hz



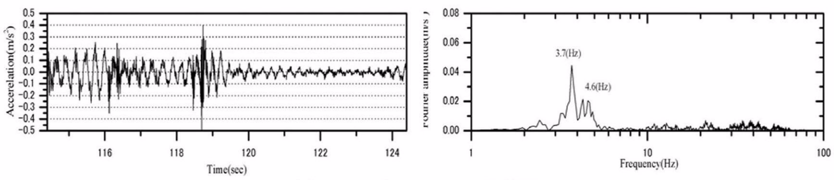
(d) target frequency12.5Hz



(e) target frequency 16Hz



(f) target frequency of 25Hz



(g) target frequency of 40Hz

Fig. 10 Acceleration time history taken from five seconds before and after the time of peak SPL of each target frequency and their Fourier spectra observed at AC5 on Span 2

4. Characteristics of low frequency sound

The time series of SPL of the target frequencies are shown in Fig. 5, which are measured at the observation point SLM1 of Span 3. Therein SLM is abbreviation of Sound Level Meter and the time corresponding to vertical broken lines on the time history of SPL indicate the time of those ten peaks. The SPLs of those ten-peak times with respect to the 1/3 octave-band frequency are also plotted as shown in Fig. 5.

For the time history of SPL of the target frequency 3.15 Hz shown in Fig. 5(a) as an example, 51.9s, 105.7s, 160.8s, 314.0s, 358.5s, 364.5s, 413.2s, 487.8s, 499.8s and 596.1s indicate those times of the ten peaks.

For the frequency characteristics of the SPL of the target frequencies from 3.15 Hz to 5.00 Hz as shown in Figs. 5(a), 5(b) and 5(c) respectively, the peak values of the SPL of each target frequency reach to the category III of the classification of LFS. The SPLs of 25.0 Hz even reach to the category IV as shown from Fig. 5(d) to Fig. 5(g), which can bear complaint due to the LFS. Moreover, the SPLs at 12.5Hz which reach to the category III are also observed as shown in Figs. 5(a), 5(d), 5(e), 5(f) and 5(g). Those frequencies near 12.5 Hz and 25.0 Hz are related to the motion of vehicle's un-sprung mass and the vibration of the cantilever decks. The observations demonstrate that three peaks of the SPL appear near 4 Hz, 12.5 Hz and 25Hz of the 1/3 octave-band frequency. A noteworthy point is that the peaks of SPL near 40 Hz are also observed as shown in Fig. 5(g), even though the effect is not so great since it enters the category II.

Those SPLs measured at the observation point SLM2 of Span 2 are summarized in Fig. 6. The definitions of graphs in Fig. 6 are the same as those depicted to explain Fig. 5. The SPLs on the 1/3 octave-band frequency show similar tendency with that measured at the observation point SLM1. A difference is in the dominant frequency of the SPL below 10 Hz: for the SPL measured near the observation point SLM1 of the Span 3 the SPL is dominant near 4 Hz, on the other hand the SPL measured at SLM2 of Span 2 dominates at 5 Hz as shown in Fig. 6. The dominant frequencies near 4.00 Hz and 5.00 Hz correspond to the torsional modes of Span 2 and Span 3 respectively. It indicates that the SPL of LFS at an observation point is greatly affected by vibrations of the span which is close to the observation point.

In order to clarify the effect of vibrations of the span to the SPL of LFS, the mean value of five peak SPLs is examined and summarized in Table 3. It shows that for target frequencies 3.15 Hz and 4.00 Hz, the SPLs measured at the observation point SLM1 of Span 3 is greater than that measured at the observation point SLM2 of Span 2. For the target frequency of 5.00 Hz, on the other hands, the SPL measured at the observation point SLM2 of Span 2 is greater than that of measured at the observation point SLM1 of Span 3.

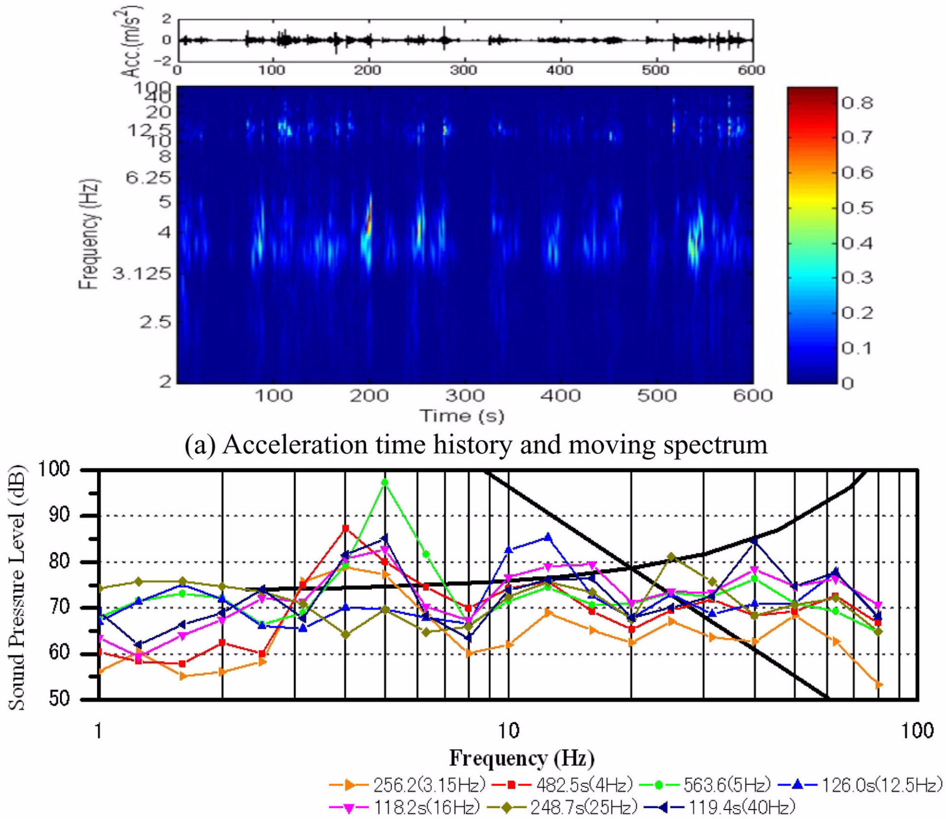
Therefore, it can be concluded again that the vibration characteristic of the span which is close to observation points of LFS greatly influences the SPL of LFS. This result is discussed later again by comparing frequency features of LFS with those of bridge responses.

5. Correlation between bridge acceleration and LFS

To investigate correlation between the acceleration response of the bridge and LFS that is observed near the bridge, the dominant frequencies of the acceleration response measured at observation points AC2, AC5 and AC6 are compared with those of SPLs. In order to see how vehicles affect bridge vibrations as shown in Figs. 7(a), 9(a) and 11(a), the frequency characteristics of bridge's acceleration responses are firstly investigated using the moving spectrum obtained by means of a wavelet transformation. Moreover, the correlation between bridge vibrations and LFS is investigated by comparing the dominant frequency of SPL with Fourier spectra of acceleration responses which are taken from five seconds before and after the peak-time of SPL of each target frequency (totally 10 seconds) as shown in Figs. 8, 10 and 12.

The moving spectrum clearly shows the frequency characteristic of each span: 2.5 Hz to 4.0 Hz are dominant for the observation point AC2 on Span 3, as shown in Fig. 7(a); on the other hand for AC5 on Span 2, frequencies from 4 Hz to 5 Hz are dominant, as shown in Fig. 9(a); for AC6 on the cantilever deck of Span 2, the dominant frequency near 12.5 Hz is observed including dominant frequencies from 4 Hz to 5 Hz under normal traffic, as shown in Fig. 11(a). The trend of dominant frequencies in moving spectra corresponds to the trend of SPL of the 1/3 octave-band frequency shown in Figs. 7(b), 9(b) and 11(b).

Looking into the Fourier spectra of the acceleration responses taken from five seconds before and after the time of the dominant SPL of each frequency, the frequency below 5 Hz dominates as shown in Figs. 8, 10 and 12. A noteworthy point is that the spectrum of the acceleration response of AC6 of Span 2 shows clear peaks near 12.5 Hz which cannot be clearly observed from the

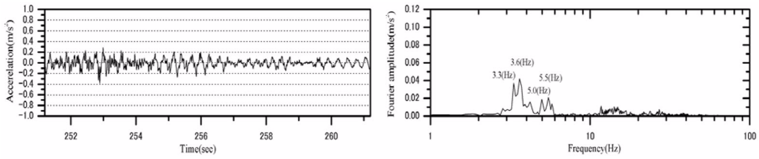


(a) Acceleration time history and moving spectrum

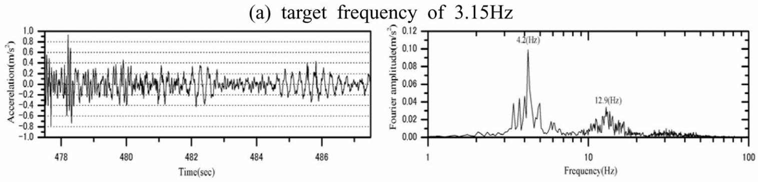
(b) SPLs on 1/3 octave-band frequency

Fig. 11 Acceleration time history observed at AC6 on Span 2 and its moving spectrum, and SPLs of 1/3 octave-band frequency measured at SML2 near Span 2

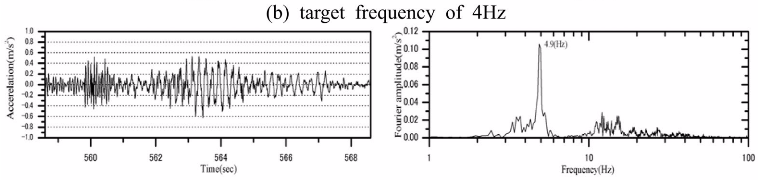
responses of observation points AC2 and AC5 at the mid-span of main girder. It is straightforward having clear peaks near 12.5 Hz because its observation point is on the cantilever deck and is easily affected by vehicles' un-sprung mass movement.



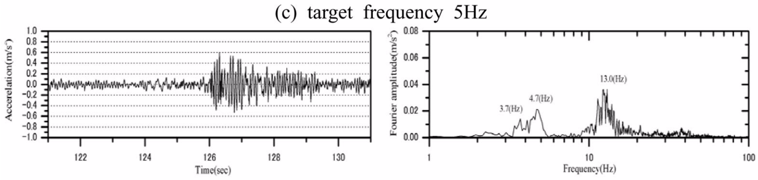
(a) target frequency of 3.15Hz



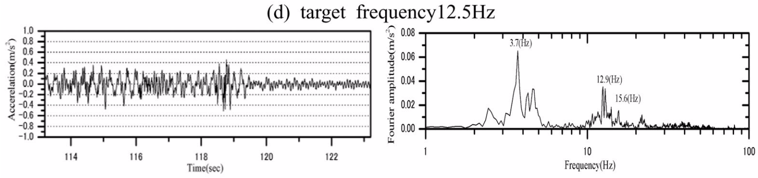
(b) target frequency of 4Hz



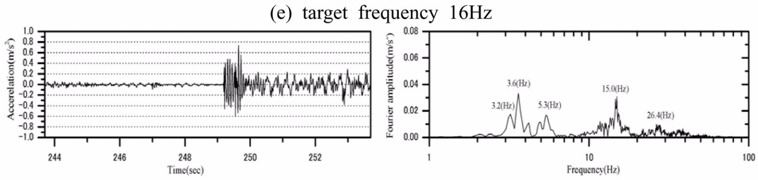
(c) target frequency 5Hz



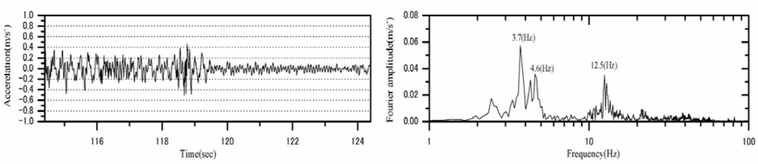
(d) target frequency12.5Hz



(e) target frequency 16Hz



(f) target frequency of 25Hz



(g) target frequency of 40Hz.

Fig. 12 Acceleration time history taken from five seconds before and after the time of peak SPL of each target frequency and their Fourier spectra observed at AC6 on Span 2

6. Conclusions

In this study traffic-induced LFS radiated from a steel box girder bridge is investigated through a field experiment. In order to examine the major sources of the LFS near the bridge, the relationships between bridge vibrations and LFS are investigated: the dominant frequency of SPL is compared with Fourier spectra of acceleration responses taken from five seconds before and after the time of the peak SPL.

From the experiment, it demonstrates that the SPLs near 4.0Hz and 5.0Hz which is similar with bridge's fundamental frequencies become dominant. Therefore, it can be concluded that the vibration characteristic of the span near measuring points influences the SPL of low frequency sound. Especially, the vibration of cantilever decks which are easily induced by vehicles' un-sprung mass motion also affects LFS near the bridge.

The study also demonstrates that reducing or controlling bridge vibrations can decrease LFS near the bridge. In the next step for this study, therefore, the effectiveness of countermeasures against the LFS will be examined with an analytical method.

References

Benton, S. and Leventhall, H.G. (1994), "The role of "background stressors" in the formation of annoyance and stress responses", *J. Low Freq. Noise Vib*., **13**, 95-102.

Benton, S. (1997), "Low frequency noise and the impact upon an individual quality of life: case study reports", *J. Low Freq. Noise Vib*., **16**, 203-208.

Eberhardt, J.L. (1998), "The influence of road traffic noise on sleep", *J. Sound Vib*., **27**(3), 449-455.

Goromaru, H., Shiraishi, K., Hara, H. and Komori, T. (1987), "Prediction of low frequency noise radiated from vibrating highway bridges", *J. Low Freq. Noise Vib.*, **6**(4), 155-166.

Hatfield, J., Job, R., Carter, N., Peploe, P., Taylor, R. and Morrell, S. (2001), "The influence of psychological factors on self-reported physiological effects of noise", *Noise Health*, **3**, 1-13.

Inukai, Y., Nakamura, N. and Taya, H. (2000), "Unpleasantness and acceptable limits of low frequency sound", *J. Low Freq. Noise Vib.*, **19**, 135-140.

ISO7196 (1995), *Frequency weighting characteristics for infrasound measurements*.

Johnson, D.L. (1975), "Auditory and physiological effect of infrasound", *Inter-noise 75; Proc. of Int. Conf. on Noise Control Eng.,* Sendai, Japan, 475-482, August.

JSSC (2010), "Sui-sui MOP method-rapid construction technology for grade separation", *Steel Constr. Today Tomorrow*, **29**, 3-4, March.

Kalveram, K.T. (2000), "How acoustical noise can cause physiological and psychological reactions", *5th Int Symp Transport Noise and Vibration*, St. Petersburg, Russia, June.

Kawatani, M., Kim, C.W., Kawada, N. and Koga, S. (2008), "Assessment of traffic induced low frequency noise radiated from steel girder bridge", *Steel Struct.,* **8**(4), 305-314.

Kim, C.W. and Kawatani, M. (2003), "End-cross beam reinforcement against traffic-induced high-frequency vibration of steel twin-girder bridge", *Steel Struct.,* **3**(4), 261-270.

Kim, C.W., Kawatani, M. and Hwang, W.S. (2004), "Reduction of traffic induced vibration of two girder steel bridges seated on elastomeric bearings", *Eng. Struct.,* **26**(14), 2185-2195.

Leventhall, G. (2003), *A review of published research on low frequency noise and its effects*, Department for Environment, Food and Rural Affairs, UK.

Ministry of Environment of Japan (2004), *Manual for countermeasures of low frequency sound*. (in Japanese)

Mohr, G.C., Cole, J.N., Guild, E. and von Gierke, H.E. (1965), "Effects of low frequency and infrasonic noise on man", *Aerospace Medicine*, **36**, 817-824.

Nagatsu, S., Satou, S. and Hirano, H. (2008), "Study about reduction measurement for the relatively low frequency sounds radiated from Steel Bridge", *Proc. of the 63rd JSCE annual conference,* I-578. (in Japanese).

Pedersen, E. and Persson Waye, K. (2004), "Perception and annoyance due to wind turbine noise-a dose-response relationship", *J. Acoust. Soc. Am.*, **116**(6), 3460-3470.

Sheng, X., Jones, C.J.C. and Thompson, D.J. (2006), "Prediction of ground vibration from trains using the wave number finite and boundary element methods", *J. Sound Vib.,* **293**, 575-586.

Tokita, Y. (1985), "About assessment of low frequency sound", *J. Acoust. Soc. Jap.*, **41**(11), 806-812. (in Japanese)