Traffic-induced vibration analysis of continuous girder highway bridges

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ABSTRACT

At the stage of preliminary design of a highway bridge with length of 93 meters, a continuous girder with three-span is preferable from viewpoint of construction cost. In this case, it is worried about that girder bridges with span length of thirty meters have large traffic-induced vibration because of simultaneous dynamic response with heavy vehicles. Furthermore large traffic-induced vibration of girder bridges causes LFS as one of environmental vibration problems. To avoid the possible occurrence of LFS, another continuous girder with different span length distribution is considered. At the first step, traffic-induced vibrations of the girder bridges are compared each other analyzing coupling dynamic response of bridges due to moving heavy vehicles. And then, LFS radiated from the girder bridges are evaluated and compared.

1. INTRODUCTION

The low frequency sound radiated from bridges under traffic is one of the environmental problems especially in land scarce major cities of Japan, since in urban areas viaducts are constructed even along the residential zone, and noise and vibration complaints arise. The sound radiated from engines and tires of heavy vehicles is usually regarded as one of the most typical environmental vibration problems (Eberhardt 1988). The ground vibration is regarded as another major source for complaints of human reception against vibrations (Sheng et al. 2006). Comparing with those two problems, the low frequency sound due to vibrations of bridges is treated as a minor problem. However, the low frequency sound which is the sound with frequencies below 100Hz (ISO 7196 1995) 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. Historically, early works on the low frequency sound and their subjective effects were stimulated by the American space program (Mohr et al. 1965). Recently media reports on the low frequency sound radiated from wind turbine generators (Pedersen et al. 2004).
The low frequency sound can shake houses near the sound source and also can cause psychological and physiological influences to residents, even though it depends on intensity of the sound pressure level (SPL). Usually psychological factors affect the physiological impact of noise (Hatfield et al. 2001). The rattling noise of doors or windows is a typical influence to houses due to the sound pressure (Leventhall 2003). As 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 the low frequency sound (Johnson 1975). Constant low frequency noises have been classified as background stresses, which are persistent events and may become routine elements of our life (Benton et al. 1994).

Current bridge design adopts simplified bridge systems and light structures despite of increasing truck weight and heavy traffic volume. The current bridge design concept exposes bridges to the environmental vibration problem relating to the low frequency sound (Kim et al. 2004). Very restricted numbers of the research, however, are performed focusing on the low frequency sound radiated from highway bridges, and as a result effective countermeasures as well as systematic approaches to reduce the vibration of bridges have not been established yet. Analytical approaches would be an important breakthrough in the research for the low frequency sound radiated from bridges, if proper numerical and simulation methods to examine the low frequency sound around bridges are available. Recently analytical studies were carried out to estimate the low frequency sound due to traffic-induced vibration of bridges (Kawatani et al. 2011, Wu et al. 2011, Tsubomoto et al. 2014).

This study is intended to assess the low frequency sound radiated from continuous girder viaducts with different span length distribution which have the same bridge length of 93 meters. For the first step assessing the low frequency sound radiated from viaducts, traffic-induced vibrations of girder bridges with span length distribution such as 30m+31m+30m and 28m+35m+28m are compared each other analyzing coupling dynamic response of bridges due to moving heavy vehicles. And then, low frequency sound under girder bridges are evaluated and compared.

2. TRAFFIC-INDUCED VIBRATION ANALYSIS

2.1 Methodology
Dynamic responses of the bridge are taken from a traffic-induced vibration analysis which is based on the finite element method for the modal analysis using three-dimensional models for both vehicle and bridge. The lumped mass and Rayleigh damping are adopted to form mass and damping matrices of the bridge model, respectively. Validity of the analytical method for the traffic-induced vibration of bridges was verified through the comparison to the field-test data (Kim et al. 2005). Details of the traffic-induced vibration analysis can be also referred to the previous study (Kim et al. 2005).

2.2 Analytical Model
2.2.1 Bridge
The girder bridges have 4-steel plate girder. Distance of main girder is 2.8m. The
girder height is 1.7m. The span length distribution is 30m+31m+30m and 28m+35m+28m, respectively. Each bridge is shown in Fig.1. The observation spans of the girder bridges are the second and the third. The FE model with three-span consists of 130 nodes and 203 beam elements. Dumping ratio of the bridge is 0.02.

![Fig. 1 Girder bridges](image_url)
2.2.2 Vehicle

The vehicle is composed of the body, tires and suspension systems. The vehicle is simulated along with the eight degrees of freedom to describe its movement. Properties of the vehicle are summarized in Fig. 2 and Table 1.

2.2.3 Roughness

In the traffic-induced vibration analysis of the bridge, the roadway roughness on the bridge surface is simulated based on the PSD curve as shown in Fig. 3, in which the roadway roughness is assumed to be categorized as Class A according to ISO estimate (ISO 8606 1995).

![Fig. 2 Dimension of moving vehicle](image1)

<table>
<thead>
<tr>
<th>Table 1 Dynamic properties of vehicle.</th>
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<tbody>
<tr>
<td>Total Weight</td>
</tr>
<tr>
<td>Axle Weight</td>
</tr>
<tr>
<td>Front</td>
</tr>
<tr>
<td>Rear</td>
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<tr>
<td>Logarithmic Decrement</td>
</tr>
<tr>
<td>Front</td>
</tr>
<tr>
<td>Rear</td>
</tr>
<tr>
<td>Natural Frequency</td>
</tr>
<tr>
<td>Front</td>
</tr>
<tr>
<td>Rear</td>
</tr>
</tbody>
</table>

![Fig. 3 PSD of roadway profile](image2)
2.3 Natural Modes and Frequencies

Frequencies are considered until 100Hz in low frequency sound analysis. So, mode numbers are considered until 139th.

A part of natural modes and frequencies of each bridge estimated from the eigenvalue analysis are summarized in Fig. 4 and Table 2. The first mode (3.09Hz) and the second mode (3.96Hz) correspond to the first bending and torsional modes of the bridge with span length distribution of 30m+31m+30m, respectively. On the one hand, the first mode (2.95Hz) and the second mode (3.97Hz) correspond to the first bending and torsional modes of the bridge with span length distribution of 28m+35m+28m, respectively.

2.4 Dynamic Response of Girder Bridges

In traffic-induced vibration analysis, the observation point is middle of the second span (② in Fig.1) and the third span (③ in Fig.1) of vehicle travel side. Figures 5 and 6 show vertical acceleration responses and their Fourier amplitude spectra under vehicle speeds of 30 km/h, 60 km/h, 80 km/h and 100 km/h, respectively.

As the analytical results at the second span, the RMS values and the maximal values of acceleration response with 30m+31m+30m are larger than those with 28m+35m+28m when vehicle speed is 30km/h and 60km/h. On the other hand, in the cases of vehicle speeds of 80km/h and 100km/h the tendency is contrary.

As the analytical results at the third span, the RMS values of acceleration response with 30m+31m+30m are larger than those with 28m+35m+28m, and the maximal acceleration response has same tendency except the case of vehicle’s speed of 80km/h. Also the bridge with span length of 30m+31m+30m show the frequency dominant at 3Hz.

Table 2 Natural frequencies of the bridges

<table>
<thead>
<tr>
<th></th>
<th>3-span(30m+31m+30m)</th>
<th>3-span(28m+35m+28m)</th>
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<tbody>
<tr>
<td>1st (Bending)</td>
<td>3.09Hz</td>
<td>1st (Bending)</td>
</tr>
<tr>
<td>2nd (Torsion)</td>
<td>3.96Hz</td>
<td>2nd (Torsion)</td>
</tr>
<tr>
<td>3rd</td>
<td>4.03Hz</td>
<td>3rd</td>
</tr>
<tr>
<td>4th</td>
<td>4.68Hz</td>
<td>4th</td>
</tr>
<tr>
<td>5th</td>
<td>5.67Hz</td>
<td>5th</td>
</tr>
</tbody>
</table>
(1) 3-span bridge(30m+31m+30m)

(a) 1st (3.09Hz, Bending)
(b) 2nd (3.96Hz, Torsion)
(c) 11th (12.05Hz, Torsion)
(d) 12th (12.36Hz, Bending)

(2) 3-span bridge(28m+35m+28m)

(a) 1st (2.95Hz, Bending)
(b) 2nd (3.97Hz, Torsion)
(c) 11th (11.02Hz, Bending)
(d) 12th (11.40Hz, Torsion)

Fig. 4 Natural modes of the bridges
(1) 3-span girder bridge (30m + 31m + 30m)

(a) Vehicle speed: 30 km/h

(b) Vehicle speed: 60 km/h

Fig. 5 Acceleration & FFT at the second span
(1) 3-span girder bridge (30m+31m+30m)

(2) 3-span girder bridge (28m+35m+28m)

(c) Vehicle speed: 80km/h

(d) Vehicle speed: 100km/h

Fig. 5 Acceleration & FFT at the second span
(1) 3-span girder bridge (30m + 31m + 30m)

Max = 4.128 x 10^{-1}

(2) 3-span girder bridge (28m + 35m + 28m)

Max = 3.596 x 10^{-1}

(a) Vehicle speed: 30km/h

(b) Vehicle speed: 60km/h

Fig. 6 Acceleration & FFT at the third span
(1) 3-span girder bridge (30m+31m+30m)

(2) 3-span girder bridge (28m+35m+28m)

(c) Vehicle speed: 80km/h

(1) 3-span girder bridge (30m+31m+30m)

(2) 3-span girder bridge (28m+35m+28m)

(d) Vehicle speed: 100km/h

Fig. 6 Acceleration & FFT at the third span
3. LOW FREQUENCY SOUND ANALYSIS

3.1 Methodology
Noise propagation is an ideal application area of the BEM (Wrobel 2002) because of its applicability to infinite domain. Therefore, the sound propagation is estimated by means of the BEM using the analytical velocity responses of the bridge taken from the traffic-induced vibration analysis of the bridge. Details of the method are described in the reference (Kawatani et al. 2008).

3.2 Assess the LFS
The criterion is categorized as four regions which are divided by the minimum audible line and the boundary for rattling. The meaning of categories I, II, III, and IV in Fig. 7 is described in Table 3 (Ministry of Environment of Japan 2004).

SPL at the noted point which is taken from analysis is at the same point as traffic-induced vibration analysis. Analysis time is shown in Figs. 5 and 6.

3.3 Sound Pressure Level
The sound pressure level at the noted point is estimated from the velocity of concrete decks and lower flanges of plate girders taken from the traffic-induced vibration analysis of each bridge. The influence of the sound wave reflected by ground is also considered in the analysis using an image method (Wrobel 2002, Kawatani et al. 2008)

Table 3 Category to assess low frequency sound.

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

Fig. 7 Classification of low frequency sound.
3.4 Analytical Results

The observation point at the second span and the third span of the bridge is 1.2m above the ground.

The SPL at the observation point at the second span with noise criterion is plotted as shown in Fig. 8, where the vertical and horizontal axes denote the SPL in dB and 1/3 octave band frequency, respectively. The SPLs of the bridge with span length of 30m+31m+30m don’t have a large difference with those of the bridge with 28m+35m+28m.

The SPL at the observation point at the third span with noise criterion is plotted as shown in Fig. 9. As expected, the bridge with span length of 30m+31m+30m gives the most severe SPL across the frequency band. The SPLs from the bridge with span length of 30m+31m+30m are larger than those of 28m+35m+28m in Fig. 9(1) ~ (4). Especially, the SPL at 3Hz in the bridge with 30m+31m+30m is highest value. The results show 30m span has the effect about 3Hz. Figure 9 also indicates that the sound radiated from the bridge is categorized as Area III and Area IV. In other words, rattle of doors or windows and low frequency noise may occur due to the sound pressure radiated from the bridge under moving heavy vehicle.

![Fig. 8 Comparison of SPLs at the second span](image-url)
In this study, traffic-induced vibrations of continuous steel girder bridges and sound pressures radiated from the bridges are simulated to assess the low frequency sound in comparison the three-span bridges with span length of 30m+31m+30m and 28m+35m+28m which have the same bridge length of 93 meters. The sound pressure is analyzed by means of BEM using dynamic responses estimated from the traffic-induced vibration analysis of the bridges.

Observations from this study demonstrate that the dynamic response at the third span of the bridge with 30m+31m+30m is larger than that with 28m+35m+28m. The sound pressure level of the low frequency sound taken from the analysis demonstrates that the low frequency sound is greatly affected by the bridge span length. The low frequency sound pressure level with span length of 30m+31m+30m is higher than that with 28m+35m+28m at about 3Hz. The cause is considered that the three-span bridge has span length of thirty meters.

From the above, it encourages use of the analytical approach as a preliminary investigation tool for the low frequency sound radiated from bridges.

**Fig. 9** Comparison of SPLs at the third span

### 4. CONCLUSIONS

In this study, traffic-induced vibrations of continuous steel girder bridges and sound pressures radiated from the bridges are simulated to assess the low frequency sound in comparison the three-span bridges with span length of 30m+31m+30m and 28m+35m+28m which have the same bridge length of 93 meters. The sound pressure is analyzed by means of BEM using dynamic responses estimated from the traffic-induced vibration analysis of the bridges.

Observations from this study demonstrate that the dynamic response at the third span of the bridge with 30m+31m+30m is larger than that with 28m+35m+28m. The sound pressure level of the low frequency sound taken from the analysis demonstrates that the low frequency sound is greatly affected by the bridge span length. The low frequency sound pressure level with span length of 30m+31m+30m is higher than that with 28m+35m+28m at about 3Hz. The cause is considered that the three-span bridge has span length of thirty meters.

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REFERENCES


