STUDY ON LOW-FREQUENCY NOISE RADIATED FROM SIMPLY SUPPORTED STEEL BRIDGES

Xu XIE[1], Hengzhi CHEN[2] and Mikio YAMASHITA[3]

ABSTRACT: This paper proposes a numerical method to estimate the sound pressure level of low-frequency noise radiated from steel bridges due to traffic-induced vibration. The applicability of the method is confirmed through the comparison between the analysis results and measured field data. Moreover, the characteristics of sound pressure level caused by moving vehicles are analytically investigated for the simply supported steel bridge with deck plat slab. It is shown that the local vibration mode of deck plate significantly affects the sound pressure level of low-frequency noise.

KEY WORDS: low-frequency noise, traffic-induced vibration, sound pressure level

1. INTRODUCTION

It is well known that people may get headache and feel stuffy because of the low-frequency noise. And many researchers are attracted attention to the propagation and radiation of the low-frequency noise due to the vibration of bridges (MURAI 1999 and SUGIYAMA et al. 1999). However, there are many questions that have yet not been solved completely in this field up to the present. At structural design stage, engineers cannot confirm whether such a public nuisance of low-frequency noise occurs or not near the bridges after their constructions. With the development of traffic load and flexible bridge structures, the public nuisance of traffic-induced vibration is more and more. Consequently, it has been an important assignment how to evaluate and reduce the public nuisance due to traffic-induced vibration of bridges at structural design stage.

This paper trends to present a method to estimate the sound pressure level of low-frequency noise for engineering by the numerical analysis. The sound pressure level of low-frequency noise radiated from vibrating bridges is analyzed based on the coupled vibration of the vehicle and the bridge. The comparison between the analysis results and measured field data demonstrates the applicability of the method. Moreover, the characteristics of sound pressure level caused by the moving vehicles are analytically investigated for the simply supported steel bridge with plat slab deck from the numerical results.

2. METHOD FOR ESTIMATING SOUND PRESSURE LEVEL

Figure 1 illustrates the flow of the method for estimating the sound pressure of low-frequency noise. In the method, the vibration of the bridge due to moving vehicles is taken as the sound source of the low-frequency noise. The influence of boundary reflection is neglected for estimating the sound pressure of low-frequency noise at measurement points radiated from the bridge.

The sound power of the vibration of the bridge can be rendered as (OKAMURA et al. 1999):

$$\begin{cases} W = \rho_a c_a \sum_{i=1}^{n} \overline{u}_i^{\,2} \Delta S_i \\ P_{WL} = 10\log_{10}\left(W/W_0\right) \end{cases} \qquad (1)$$

where, W and P_{WL} are the vibration power of bridge in unit (W) and unit (db), respectively. n denotes the node number of the FEM model of the bridge. ρ_a is the density of atmosphere; c_a is the velocity of sound in the air; $\overline{u}_i$ is the equivalent sound velocity of the node i (m/s); ΔS_i is the equivalent area of the node i (m^2); W_0 is the reference power(10^{-12}W).

The sound pressure at measurement points around the bridge based on the propagation theory of the point sound source can be given by

$$S_{PL} = 20\log_{10}\left(P_{rms}(f,r)/P_0\right) \qquad (2)$$

where r is the distance between the point sound source and measurement point (m), f is the frequency (Hz), P_0 is the minimum pressure of the audible sound (2×10^{-5}N/m^2), P_{rms} is the equivalent value of $P(r,t,f)$ (N/m^2), which denotes the theoretical value of a point sound source with surface area (ΔS) and is given by (MIZUKAMI 1992):

---

[1] Zhejiang University, P. R. China, Ph.D.

[2] Zhejiang University, P. R. China, Ph.D. Student

[3] Kaihatsu Consultant Co. Ltd, Japan

$$P(r,t,f)=\sum_{n=1}^{n}\frac{j\rho_a c_a k}{4\pi r}u_i(f)\Delta S_i e^{j(\omega t-kr)} \qquad (3)$$

where j is the imaginary unit, k is the wave number of the sound.

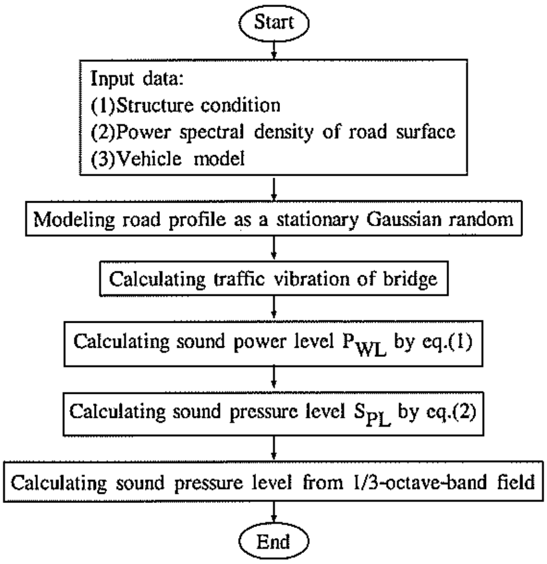
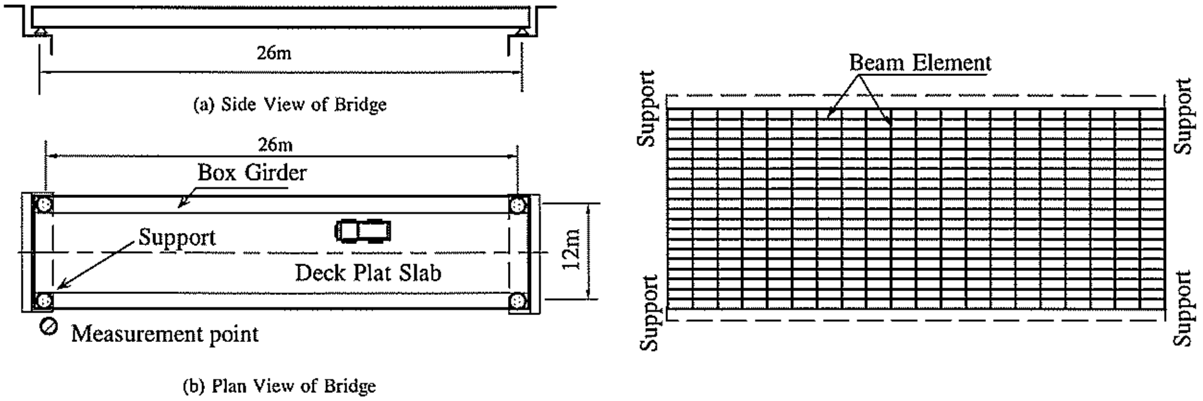


Figure 1. Flow diagram for computing process

Since the low-frequency noise is commonly expressed by the sound pressure corresponding to 1/3 octave of the center frequency (NAKANO 2000), the sound pressure calculated by Eq.2 should be converted to that to 1/3 octave of the center frequency. In addition, the velocity response of bridge vibration u is obtained by the analysis of coupled vibration of the vehicle and the bridge.

3. COMPARISON WITH MEASURED DATA

To illustrate the applicability of the presented method for calculating the sound pressure of low-frequency noise, a simply supported steel bridge shown in Figure 2 is analyzed. The results are compared with the measured data.



(a) Side View of Bridge

(b) Plan View of Bridge

(c) Plan view of modeling

Figure 2. Model of simple supported steel bridge

3.1. BRIDGE MODELING

The analyzed object is the simply supported steel beam bridge with steel deck plat slab. Since the damping and stiffness of steel structure are small, the relatively high sound pressure often occurs, which leads to the public nuisances.

Though the plate element is more available for continuous steel slab, the bridge is modeled by the beam element to avoid complex computation and numerous previous processes. For ensuring the accuracy of calculation, the mesh of the deck is very dense (Fig. 2c).

3.2. COMPARISON OF ANALYSIS RESULTS AND MEASURED DATA

Using the bridge model shown in Figure 2c, the natural characteristic of the free vibration is calculated. Table 1 shows the comparison between the analysis results and the measured field data, which are measured by the accelerometers in the locations shown in Figure 3 . The comparison shows that the analysis results and measured data of the free vibration from 1st to 3rd mode have good agreement.

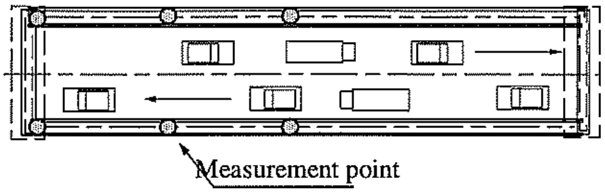


Figure 3. Location of accelerometers

Table 1. Properties of natural vibration of bridge

mode	analysis(Hz)	Measured(Hz)	Mode shape
1	2.76	2.75	First vertical mode
2	4.50	4.65	First torsional mode
3	6.83	6.90	Second vertical mode

3.3. ANALYTIC CONDITIONS OF TRAFFIC VIBRATION

Structural damping is obtained from the measured value of the deflection mode (0.5%). The responses of coupled vibration of the vehicle and the bridge is investigated by the Newmark-β method. For the stability of calculation, β is equal to 0.25. The first 100 modes are then calculated for time interval 0.00025(s). The vehicle modeling and condition of the road surface are stated in detail by followings.

(1) VEHICLE MODELING

Figure 4 shows a 4-DOF (degrees of freedom) vehicle model used in the present work. The vehicle body above the string is treated as rigid body and the axles under the string as particles. They are connected by four spring-dashpot units.

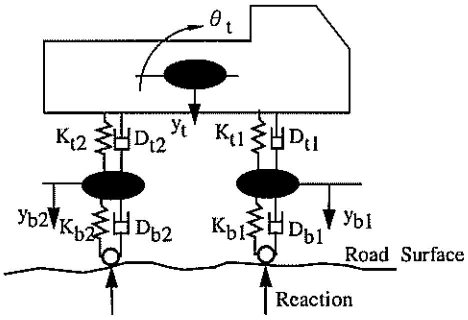


Figure 4. 4 –DOF(degrees of freedom) vehicle model

The parameters involved and the natural frequency of a vehicle with total weight 18T are summarized in Tables 2.

The traffic conditions include the driveway location, vehicle interval space, vehicle speed, roughness of road surface and elevation difference of expansion and shrink joint and so on. According to the condition of the actual locale, one vehicle shown in Figure 4 traveling through the bridge with constant speed (40km/h and 50km/h) is analyzed.

(2) ROUGHNESS OF ROAD SURFACE

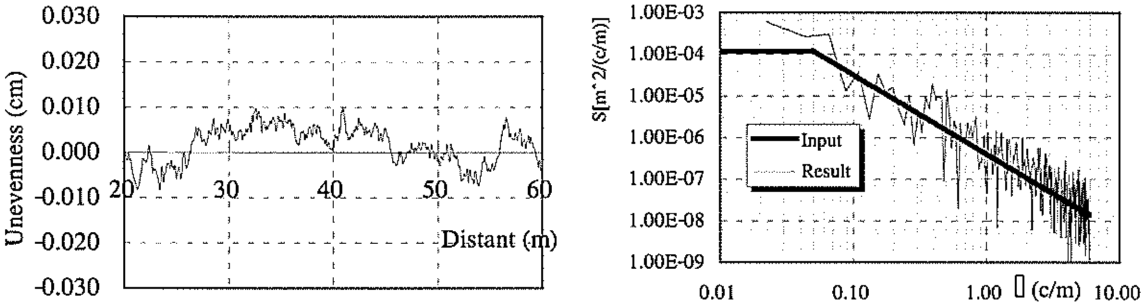
The roughness of the road surface is estimated by the power spectral density function as following (MARUYAMA et al. 1997)

$$S(\Omega)=\begin{cases}0.004\times 0.05^{-1.9} & (0\leq\Omega\leq 0.05)\\ 0.004\times\Omega^{-1.9} & (\Omega\geq 0.05)\end{cases} \tag{4}$$

where Ω is the frequency (c/m), $S(\Omega)$ is the power spectral density of the road surface roughness. It is between common and good conditions of road surface roughness according to ISO. Figure 5(a) shows the sample wave of roughness with zero average obtained by the method of stationary random process. The power spectral density almost coincides with the assumed conditions shown in Figure 5(b). In addiction, the elevation difference of expansion and shrink joints is taken as 5mm.

Table 2. Properties of vehicle model

Gross weight (ton)	18
Mass of vehicle body (KN-sec^2/m)	16
Inertia mass of vehicle body (KN-sec^2-m^2)	54.2
Stiffness of front suspension system (kN/m)	1200
Stiffness of rear suspension system (kN/m)	4800
Damping of front suspension system (kN-sec/m)	5.0
Stiffness of rear suspension system (kN-sec/m)	20
Mass of front wheel (KN-sec^2/m)	0.4
Mass of rear wheel (KN-sec^2/m)	1.6
Stiffness of front wheel (kN/m)	2400
Stiffness of rear wheel (kN/m)	9600
Damping of front wheel (kN-sec/m)	6.0
Damping of rear wheel (kN-sec/m)	24.0
Longitudinal distance between center of gravity and front wheel (m)	2.5
Longitudinal distance between center of gravity and rear wheel (m)	1.5
The first natural frequency (Hz)	1.887
The second natural frequency (Hz)	2.878
The third natural frequency (Hz)	15.159
The fourth natural frequency (Hz)	15.243



(a) Sample wave of road surface roughness (b) Power spectral density of sample wave of roughness

Figure 5. Conditions of road surface roughness

3.4. COMPARISON WITH SOUND PRESSURE FROM MEASURED POINTS

The measurement point is near the expansion-shrink joint (0.5m out of main beam and 1.2m above the ground) shown in Figure 2.

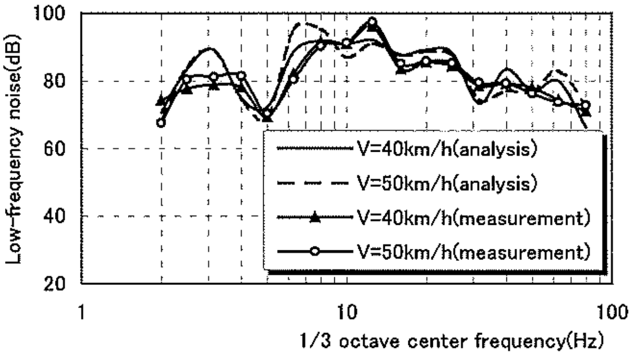


Figure 6. Comparison with measured value and analysis results of sound pressure

Figure 6 shows the measured values and analysis results of sound pressure of low-frequency noise due to the vehicle passing the bridge. The horizontal axis denotes the 1/3 octave of the center frequency and the vertical one denotes the sound pressure in unit dB. Since it is relatively difficult that the analyzed range of the sound pressure is taken the same as that of measured data, the low-frequency noise is calculated during vehicle passing bridge about 2s.

Figure 6 shows the fact that the numerical results and the measured ones have good agreement. The present method is effective to estimate the low-frequency noise radiated from the bridge. On the other hand, the difference between the numerical and measures results is also exist, especially some contrary results is obtained near 11Hz. For this purpose, the present numerical method need improve.

4. REASON OF LOW-FREQUENCY NOISE RADIATED FROM STEEL BRIDGES

Since the aforesaid results indicate that the present method to estimate the sound pressure level of low-frequency noise is feasible, it is used to discover the reason of the low-frequency noise radiated from steel bridges.

4.1. PRINCIPAL MODES OF LOW-FREQUENCY NOISE

Generally, the low-frequency modes are the main components in the vibration induced by the vehicle passing the bridge. In the analysis of structure vibration, the relatively accurate result can be obtained just using some first low frequency modes. However, the response of sound pressure of low-frequency noise is the biggest at the point of 12.5Hz as shown in Figure 6. The effective frequency of sound pressure is higher than that of vibration response and the sound pressure holds about 80dB corresponding to high frequency modes. It reveals that both the low and high frequency modes should be concerned to investigate the characteristics of the low-frequency noise.

To determine the main reason of bridge radiating low-frequency noise, the paper investigates the response power of sound source corresponding to all the modes of bridge vibration whose frequencies are below 30Hz. It is noticeable that non-linear relationship of the response power and response velocity leads to the sum of response power of each mode is not equal to that of the bridge structure.

Figure 7 shows the modes with relatively high response power. The orders of some modes with high power are mentioned in the figure and the powers of the first 100 modes are also drawn as references.

It is obvious that the modes of low order play main role in the response power of the sound caused by the bridges. However, the power of the noise of 10~ 30Hz are significantly affected by the modes of high order. Especially higher than 10Hz, the modes of 7th and 8th order, which is vibration of the deck and shown in Fig. 8, lead to noise with big power since the deck have a much bigger area than the beams. The frequencies of these two modes are 12.8Hz and 13.7 Hz, respectively, and are both within the range of 1/3 octave of the centre frequency (12.5Hz) with (11.2-14Hz).

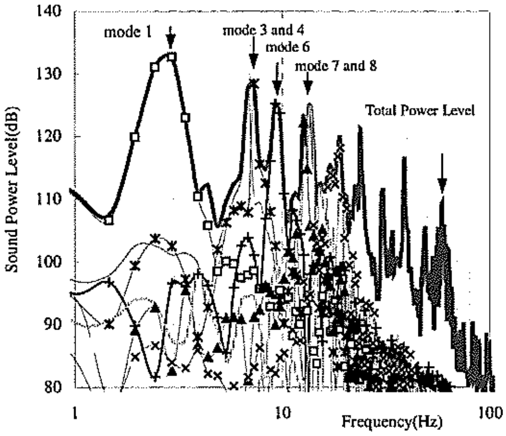
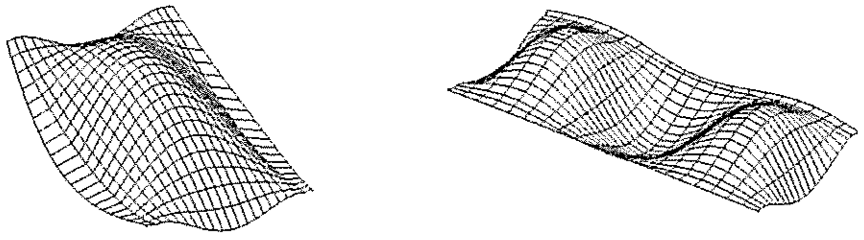


Figure 7. Response power of apiece mode



(a) Mode 7

(b) Mode 8

Figure 8. Modes of high response power

As a result, the sound pressure of low-frequency noise is relatively high around 12.5Hz caused by the vibration of the deck. Consequently, it is very important to accurately simulate the vibration of the deck for an accurate sound pressure of low-frequency noise by the numerical method.

4.2. TREATMENT TO REDUCE LOW-FREQUENCY NOISE

To reduce the low-frequency noise, the mode shown in Figure 8 should be controlled according to the above-mentioned results. Therefore, the main treatment is reinforcement of the stiffness of cross beams at the bridge ends to reduce the vibration of the deck.

To check the applicability of the treatment, the temporary supports shown in Figure 9 are installed at the bridge ends and the sound pressure is measured and compared to that without the temporary supports. The sound pressure of low-frequency noise due to a vehicle traveling through the bridge is shown in Figure 10 and indicates that the treatment is available to reduce the low-frequency noise.

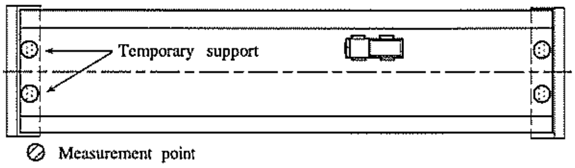


Figure 9. Temporary support

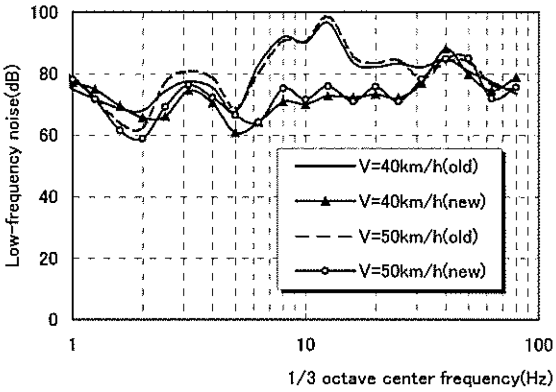


Figure 10. Measured data before and after treatment

The comparison between the analytical results shown in Figure 11 indicates that the increased supports can reduce the response of the low-frequency noise in the range of 5.0Hz-20Hz.

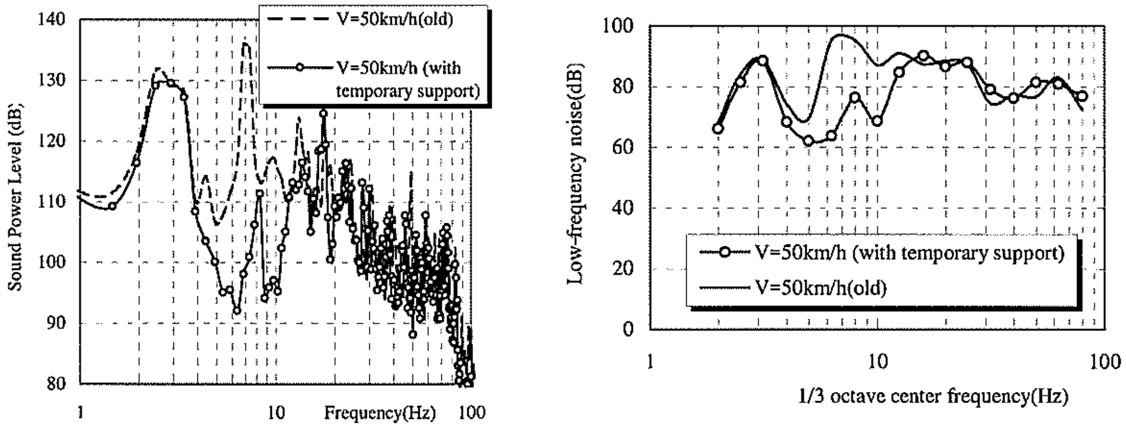


Figure 11. Analytical results before and after treatment

5. CONCLUSION

In this paper, taking the vibrating structure as sound source, the low-frequency noise is investigated based on the propagation theory of the point sound source. The results are compared with that of measurement to illustrate the availability of the present method through some departure exists. It is possible to analyze the low-frequency noise radiated from steel bridges using numerical method with the theory of point sound source.

The comparison among the powers of the sound pressure of all the modes shows that the vibration of steel deck plays main role in the radiation of low-frequency noise. Thus, the accurate analysis of deck vibration is very important to improve the accuracy of the total calculation.

In addiction, the treatment to reduce low-frequency noise is given according to the results of the present method. Its availability is demonstrated by the actually measured results.

REFERENCES

[1] Itsuru MURAI, The Low Frequency Noise Problem about the Road Project, Journal of Ince/J, Vol.23, No.5, pp.319-323, 1999.

[2] Toshiyuki SUGIYAMA et al., Characteristics of Low Frequency Sound Radiated from Both Steel and Concrete Girder Highway Bridges and Reduction Measure Against Low Frequency Sound Radiated from Steel Ones, Journal of Structural Engineering, JSCE, Vol.45A, pp.671-682, 1999.3.

[3] Koyichi MIZUKAMI, Study on Low Frequency Noise Characteristics Radiated from Highway Bridges under Moving Vehicles, Master's Thesis, Yamanashi University, 1992.3.

[4] Miyashi OKAMURA and Yasuharu FUKASAWA, Reduction Characteristics of Vibration and Radiated Sound of Composite Plates Consisting of Steel and Rigid Urethane, Journal of Structural Engineering, JSCE, Vol.45A, pp.683-691, 1999.3.

[5] Aritomo NAKANO, Noise Countermeasure, THE NIKKAN KOGYO SHIMBUN, LTD., 2000.2.29.

[6] Osamu MARUYAMA and Karsura HIDESHIMA, Vibration Control of a Simple Beam under Running Loads, Journal of Structural Engineering, JSCE, Vol.43A, pp.703-712, 1997.3.