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Noise-radiation Analysis of Box-shaped Rail Bridges Considering Multi-span Effects

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Abstract

Low-frequency structure-borne noise radiation from train-induced vibration of railway bridges is of concern to assess environmental impacts induced by urban metro system. To carry out the bridge-radiated noise analysis in assessing environmental impacts, the bridge vibration is regarded as an acoustic source of noise radiation so that the finite element (FE) bridge model combined with the acoustic boundary element (BE) method of spatial noise radiation is adopted in performing acoustical computations. For verification, an in-situ experimental noise measurement of rail box-shaped bridge on the selected metro line of Nanchang Metro is used to evaluate the feasibility of the present hybrid FE-BE approach. In addition, the method of panel acoustic contribution analysis is proposed to assess the noise levels radiated from a single/multi-span box-shaped bridges, respectively. With the present investigations, the multi-span bridges may result in larger structure-borne radiated sound pressure levels at far-fields than a single-span. Such a multi-span effect on bridge-radiated noise should be accounted for environmental noise evaluation along urban metro lines.

Key Words: Acoustical Boundary Element Method, Box Girder, Finite Element Modeling, Panel Acoustic Contribution Analysis, Structure-borne Noise

1. Introduction

Structure-radiated noise generated by concrete bridge vibrations in urban rail transit system is of concern in environmental evaluation since its sound pressure levels are usually within the special low-frequency range (10–200 Hz) of environmental noise radiation [1,2]. The key factors to affect the structure-borne noise radiated from the train-induced vibrations of railway bridges include moving speed, track structure, structural material and design of bridge systems. These factors may govern the peak amplitudes and dominant frequencies of sound pressure levels in the structure-borne noise analysis [3, 4].

Ngai and Ng [5] conducted vibration and noise tests on concrete box girders of high-speed railway in Hong Kong and concluded that the noise and vibration frequency levels of the elevated bridges are within 20~ 157 Hz, which is within the low-frequency noise. By modeling a train as a series of moving loads and using transient boundary element method (BEM) to simulate the sound propagation in spatial domain, Li et al. [6] performed the vibrational and noise analysis of a 32 m single-span box girder in urban rail transit for parameter studies of bridge-radiated noise analysis, in which the authors adopted their numerical results to provide the noise assessment basis for bridge noise control. Combining the structural analysis of vehicle-track-bridge coupling system in temporal domain with the acoustical boundary element method in frequency-spatial domain, Zhang et al. [7] carried out the structure-borne noise analysis of a 32 m single-span railway box girder under the action of a train

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moving with different speeds and they concluded that the overall sound pressure level of a single-room box girder is larger than that of a two-room one. This point indicated that a stiff box-shaped bridge has a benefit to reduce noise propagation. Li et al. [8] adopted the modal acoustic transfer vector (ATV) method and the train-track-bridge structural model to investigate train-induced structure-borne noise radiation from a single-span railway bridge. Concerning the noise reduction of bridges, Schulte-Werning et al. [9] proposed an integrated project to develop specifications for constructing the generic low-noise bridges based on an effective and cost-efficient combination of experiments and simulations. Zhang et al. [10] investigated the structure-radiated noise and cavity resonance phenomena of a box-shaped bridge and suggested 3 effective noise reduction measures, one of which is to add a horizontal baffle in the interior cavity. Such an approach is feasible and convenient way for practical box-shaped bridges. As previous description, most of existing researches are focused on the structure-borne noise prediction of a single-span bridge but little literatures on multi-span bridges, especially for the sound pressure level at far-fields from the noise source of the railway bridges in vibration.

A 32 m pre-stressed concrete (PC) box girder with simply supported ends is a typical bridge type in current urban metro system of China. Based on conventional theory in structural dynamics and well-developed computational methods in acoustics [7,8], this study adopted the ANSYS software to create a three-dimensional (3D) finite element (FE) bridge model with a single-cell box-girder (see Figure 2) for dynamic response analysis of a bridge subject to moving train loads and then introduced the LMS Virtual Lab software with acoustical boundary element (BE) method to predict the bridge-radiated noise levels in sound field. It is emphasized that the 3D FE bridge modeling is necessary to capture all the local vibration modes of the box-shaped girder model in simulating the multiple vibration sources of noise radiations in assessing environmental sound levels. With the present numerical technique, a comparative analysis including the in-situ experimental measurements and the numerical predictions for noise radiation analysis of multi-span box-shaped bridges is carried out to verify the feasibility of the proposed hybrid FE-BE approach. By using the method of panel acoustical contribution analysis to assess the sound pressure levels from the box-girders in vibration, the present results indicated that the multi-span effect of railway bridges on structure-radiated sound pressure levels should be taken into account in low-frequency noise radiation of environmental evaluation.

2. Numerical Modeling

With the theoretical development in numerical techniques of structural dynamics and environmental acoustics, a number of well-developed commercial softwares are applicable to conventional linear analyses of acoustical-structural problems and permit accurate predictions for structure-noise radiation in sound field. To assess the structure-borne noise of a single-cell box-shaped bridge in vibration, a 3D finite element bridge model built by using the ANSYS software for the single-cell box-girder will be presented in this study. Then, the acoustical boundary element method in corporation with the LMS Virtual Lab software is combined with the FE bridge model to simulate the structure-radiated noise in spatial domain for a box girder subject to moving train loads. A detailed formulation of these numerical techniques will be described in the following subsections.

2.1 Finite Element Model of a Box Girder

Figure 1 depicts a typical section of a 32m PC box girder with single cell for elevated railway bridges in urban transit rail system of Nanchang City in China. With such sectional dimensions, as shown in Figure 2, a 3D-FE bridge model including slab track system of a single-span box girder is established by using the ANSYS software. In the ANSYS-FE bridge modeling, the single-cell box girder is discretized by the elastic shell elements of SHELL63 and the slab track system including CA mortar layer and concrete-bearing base by the solid elements of

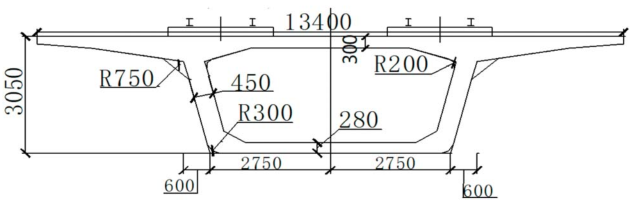

Figure 1. Sectional dimensions of the PC box girder (unit: mm).

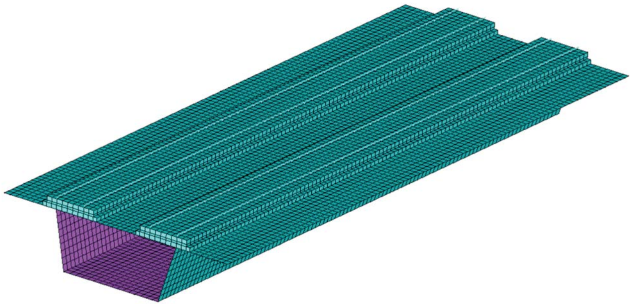

Figure 2. Finite element model of a single-room box girder with slab-tracks.

SOLID45. Here the standard gauge of 1,435 mm between two parallel tracks is also included in the FE slab-track modeling. The material properties of concrete used herein are given as follows: elastic modulus = 35.5 GPa, density = 2,500 kg/m^3, Poisson ratio = 0.2 and damping ratio = 0.02, respectively. The vertical stiffness and damping of the pad-fastener connecting the track with the non-ballasted slab are 4,107 N/m and 5,104 N-s/m, respectively. In this study, the interval of 0.64 m between two adjacent fasteners resting on sleepers is adopted. Then the matrix equations of free motion of the FE model for the single-cell box-girder can be expressed as

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+[K]\{u(t)\}=\{0\} \tag{1}$$

where ($\dot{\bullet}$) represents the differential with respect to time, ([M], [C], [K]) the mass, damping and stiffness matrices of the box girder and {u(t)} is the displacement vector, respectively. By solving the eigenvalue problem of $|[K] - \omega^2[M]| = 0$ for free vibration analysis using ANSYS software, the first vertical modal frequency of the box girder structure is 6.07 Hz, which is in agreement with the previous work [7]. Moreover, the first three vertical natural modes and corresponding frequencies have been plotted in Figure 3, respectively. Figure 3(a) is a typical single-bending mode shape of a simply supported beam. However, there significantly exist local vibration modes on the cantilever flanges in Figure 3(b) and on the top and bottom slabs in Figure 3(c), respectively. Such dynamic characteristics in local vibration modes of a PC box girder may play an exciting role of vibration sources to transmit bridge-radiated noise into surroundings of the bridge. This point will be implemented in section 3.

With the FE bridge modelling of the box girder shown in Figures 2 and 3, the train-induced vibration analyses of multi-span box-girders considering 1, 3 and 5 spans are carried out respectively. By regarding the train-induced vibration of the box-girders as the acoustical source of sound propagation in environmental noise radiation, the acoustic boundary element method will be introduced to analyze the sound pressure levels of environmental noise in the following section.

2.2 Acoustical Boundary Element Model in Spatial Domain

Since the structure-borne noise radiation induced by the vibration of multi-span PC box girders is of concern in this study, the acoustical boundary element meshes surrounding the box girder is modeled using LMS Virtual Lab software, as the profile plotted in Figure 4. The acoustic wave equation for sound pressure in three dimensions of space can be expressed as [11]

$$\left(\Delta^2-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)P(\mathbf{x},t)=S(\mathbf{x},t) \tag{2}$$

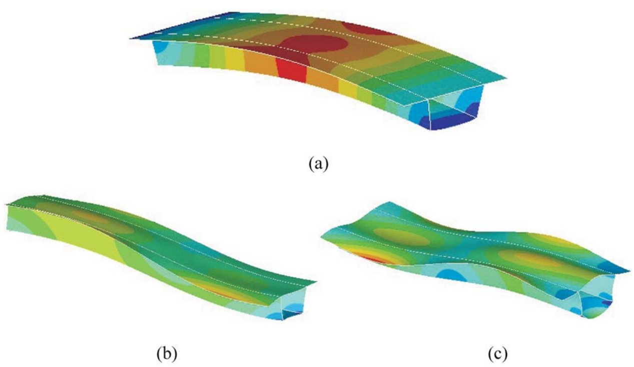

Figure 3. Modal analysis of a simply supported box girder. 1st bending mode (f_1 = 6.07 Hz); (b) 2nd bending mode (f_2 = 15.92 Hz); (c) 3rd bending mode (f_3 = 19.85 Hz).

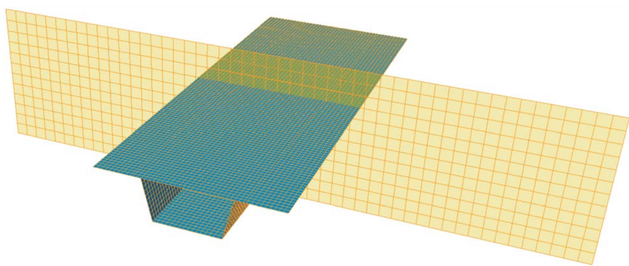

Figure 4. A sectional profile of acoustical boundary element model in spatial domain.

Here, Δ^2 = Laplacian operator, c = sound speed, $P(\mathbf{x}, t)$ = sound pressure and $S(\mathbf{x}, t)$ = acoustic source at location **x**. Let us consider a harmonic disturbance with the resulting pressure (p) in the outward normal direction on the surface of the box-shaped bridge structure (see Figure 5). Then the acoustic equation may satisfy the following Helmholtz equation

$$(\Delta^2 + k^2)p(\mathbf{x}) = s(\mathbf{x}) \text{ with } \frac{\partial p}{\partial v} = -i\rho\omega\upsilon_v \quad (3)$$

where $k = \omega / c$ = acoustic wavenumber, ω = circular frequency, υ_v = normal velocity on the surface of the bridge structure (see Figure 5), ρ = air density in room temperature. Equation (3) forms the boundary and interface between the acoustical BE model and the FE bridge model. By relating the acoustic pressure, normal velocity and normal impedance to the potentials of sound pressure, the boundary conditions for the BEM in acoustical model are defined and transferred to the corresponding nodes and elements meshed by the finite element model shown in Figure 5.

Based on the consistent conditions at the interface boundaries between the solid bridge structure and the sound field of the environment concerned, this study combined the dynamic finite element analysis of the box girders with the acoustic boundary element discretization of sound pressure to simulate the structure-borne noise radiation of multi-span box girders. In this study, the acoustic boundary element model was simulated using LMS Virtual Lab software, the size of the maximum boundary element unit should be designed as smaller than the shortest wavelength of the calculated frequency. Namely, the edge length (L) of the maximum unit shown in Figure 3 should satisfy the following condition:

$$L \le \frac{c}{6f_{\max}} \quad (4)$$

where $f_{\max}$ is the maximum characteristic frequency (= 226 Hz) and c the sound speed (= 343 m/s). In this study, the edge length L in the acoustic boundary element modeling is selected as 0.25 m.

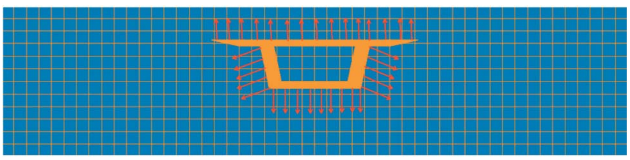

Figure 5. Schematic diagram of vibration sources of a box girder for structure-borne noise radiation.

3. Response Analysis of the Box Girder

As a train travels over a bridge, in addition to interaction dynamics of the train-bridge system, the vibration-induced structure-borne noise problem is one of important topics in assessing environment impacts of noise radiations along the railway routes. In the following sections, a sequence of equivalent train loads including rail-irregularity to excite the PC box-girders will be modeled by using the wheel/rail contact mode, and the vibration acceleration level in decibels is defined and compared to verify its feasibility to assess the vibration level of the PC box girders. For numerical simulation, as shown in Figures 2 and 6, the 3D-FE model of the single-cell box-girder was established by using ANSYS software and the train car model (see Figure 6) simulated by SIMPACK software for response analysis of the moving train cars, respectively. A detailed description of the spectral analysis for the train-bridge interaction system based on modal analysis will begiven in section 3.1. Then the FEMBS identifiable file obtained from the SIMPACK software is used to excite the bridge on which the train travels for time-history response analysis of the train-bridge system, in which the flexible track model is taken into account in performing the dynamic interaction analysis between the two subsystems of the whole train-rail-bridge system. Thus one can compute the contact forces between the wheel and the rail. Then, the wheel-rail excitation forces calculated are transferred to the bridge through the slab-track model, as shown in Figure 2.

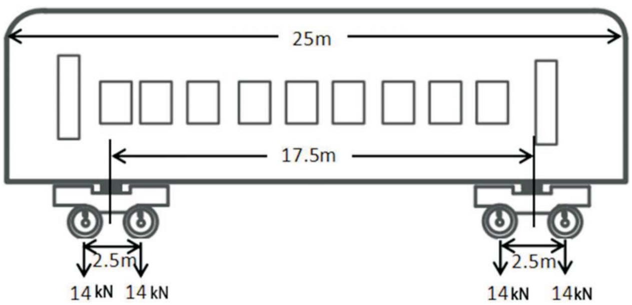

Figure 6. Schematic of the CRH2 train car.

3.1 Simulation of Train Loads by the Wheel/rail Contact Forces

Let us consider the CRH2 train car served in the urban rail transit system of Nanchang, as schematically plotted in Figure 6, the average equivalent axle-load acted on the wheel-set of a bogie is equivalently equal to 14 kN. On the other hand, the track irregularity and bridge deflection are two important factors to affect the dynamic response of the moving wheels over the supported rails. Since the 32 m PC box-girder is referred to as the standard bridge type of Chinese high speed rail system, it is designed much stiffer than conventional railway bridges for considerations of riding quality and running safety in operation. Thus if the operating speeds of a train running on the elevated bridges in the urban transit rail system is limited within 180 km/h, which is much less than the primary resonant speed ($v_r = f_1 * D = 6.07*25*3.6 = 546$ km/h) [12], the bridge deflection could be neglected in performing response analysis of the PC box girders. Thus the track irregularity is regarded as the main exciting source to stimulate the box-shaped bridges. By using the ANSYS FE bridge modeling with the SIMPACK multi-body dynamics software for the train-bridge system, the dynamic response analysis of the box girders under the action of the moving train loads is carried out using the direct integration with a tiny time step of 1.44×10^{-4} s in the following illustrated examples.

Moreover, the irregularities are characterized by the power spectral density (PSD) functions of Germany on rail quality [12].

$$S(\Omega) = \frac{A_v \Omega_c^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)} \quad (5)$$

where Ω represents the spatial frequency, Ω_c (= 0.8246 rad/m) and Ω_r (= 0.0206 rad/m) are the relevant constants depending on irregularity type, and A_v (= 1.08×10^{-6} m^{2}rad/m) relies on the irregularity type and rail quality. Figure 6 plots the time history of vertical wheel/rail contact force simulated and it is regarded as the exciting force of a moving axle-load to the box girders.

With the finite element model shown in Figure 2 and the vertical exciting force plotted in Figure 6, the structural equation of motion for the box girder bridge can be expressed as:

$$[M]\{\ddot{u}(t)\} + [C]\{\dot{u}(t)\} + [K]\{u(t)\} = \{F(t)\} \quad (6)$$

where $\{F(t)\}$ is the load vector induced by the track irregularity and the axle-loads. The train loads are regarded as a series of concentrated loads moving on the right side of the bridge deck, as shown in Figure 8. Then one can compute the dynamic response of the box-girder due to a series of moving train loads. The contact forces between the moving wheels and rails are obtained from the computational results of the SIMPACK software and they are regarded as a series of loading sources to excite the bridge through the slab-track systems laid on the bridge deck, as shown in Figure 2. Then the time-history response analysis of the ANSYS-FE-model was carried out by using conventional direct integration methods. In this study, the Newmark method is adopted to compute the dynamic response of the multi-span bridges.

3.2 Simulation of Vibration Sources on the Box Girder

As the black dots marked on the box section of Figure 7, four particular locations (Point 1 at top slab, Point 2 at bottom slab, Point 3 at middle height of the right web, and Point 4 at the free end of the cantilever) at the mid-span of the PC box girders are selected as the measured vibration levels for simulate the acoustic source of bridge-radiated sound pressure in the following examples. The vibration acceleration level (A_{dB}) expressed in terms of the 1/3 octave band in decibels (dB) is defined as follows:

$$A_{dB}(\omega) = 20 \log_{10} \frac{a(\omega)}{a_{ref}} \quad (7)$$

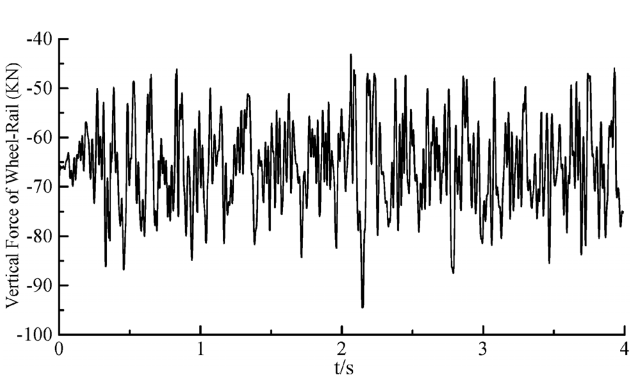

Figure 7. Time-history of the vertical wheel/rail contact force.

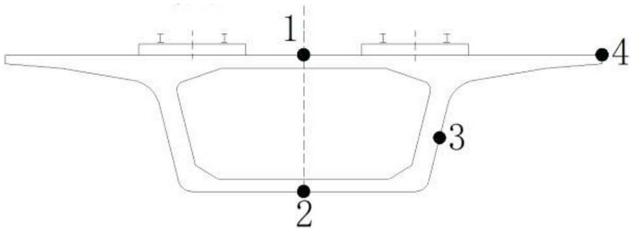

Figure 8. The response output of measured points on the box girder.

where $a(\omega)$ = the root mean square of measured acceleration level in frequency domain and a_{ref} (= 10^{-6} m/s^2) = the reference acceleration level. As a train travels on the box-girders, the vibration acceleration levels at the measured points (from Point 1 to Point 4 marked on the bridge section of Figure 8) are expressed in terms of acceleration, as shown in Eq. (7).

Let the CRH2 train travels on the right side of the mid-span box girders with constant speed of 180 km/h. The vibration acceleration levels in decibels vs. the measured frequencies at the measured points are plotted in Figure 9, respectively. As indicated, the dominant frequencies of the acceleration levels for all the measured points are within 40~80 Hz and the peak frequencies are close to 40 Hz for the web, 50 Hz for the bottom flange, and 63 Hz for the top flange and its cantilever end, respectively. Since the vertical stiffness of the web is much higher than that of the slabs and flanges, the highest vibration acceleration level takes place at the top slab (see Figure 7) but the lowest at the web. Such a conclusion is consistent with the measured results given in [10]. According to the numerical demonstrations shown in Figure 9, the present finite element modeling (see Figure 2) of the PC box girder computed by the ANSYS-FE software is feasible to predict structural vibration of the box-girder. In the following numerical investigations, the proposed approach incorporating the ANSYS-FE model for the box-girder structures with the LMS Virtual Lab acoustic boundary elements for the noise radiation in sound fields will be employed to explore the acoustic radiation phenomena of structure-borne noise induced by the vibration of multi-span box girders under the action of the moving train loads.

4. Bridge-radiated Noise Analysis

With the recent advent of powerful computers, FE and BE commercial codes have become widely applicable to vibrational or acoustical problems in bridge engineering. For structure-radiated noise analysis, the FEM can be used to simulate the dynamic characteristics of natural frequencies and mode shapes of solid structures and the BEM is more suitable for sound radiation problems with infinity conditions. Thus this study integrates the computational properties of the FEM and BEM to predict the structure-radiated sound pressure of rail bridges under the action of moving train loads. Moreover, an experimental setup for noise measurement will be carried out and compared with the present numerical simulation.

4.1 Experimental Setup of Acoustical Measurement

To carry out an in-site noise measurement of the urban-transit line in Nanchang, the experimental setup of acoustic measurement is referred to the free field condition, as shown in Figure 10. The bridge has a span length of 32 m, and its sectional depth and width are 3.05 m and 13 m, respectively. On the bridge deck, the ballast-less track of CRTS I is laid. Under the box girder that crosses the traffic lane (see Figure 10(a)), there exist 4 m wide pavement along the direction of the bridge. Thus there is no background noise to affect the present noise measurement. The experimental train of CRH2 EMU type is used to excite the target bridges with the moving speed of 180 km/h. The microphone receivers are of the free-field type GRAS AM0069 with sampling rate of 20 kHz. The experimental procedure for the field-test of sound-level mea-

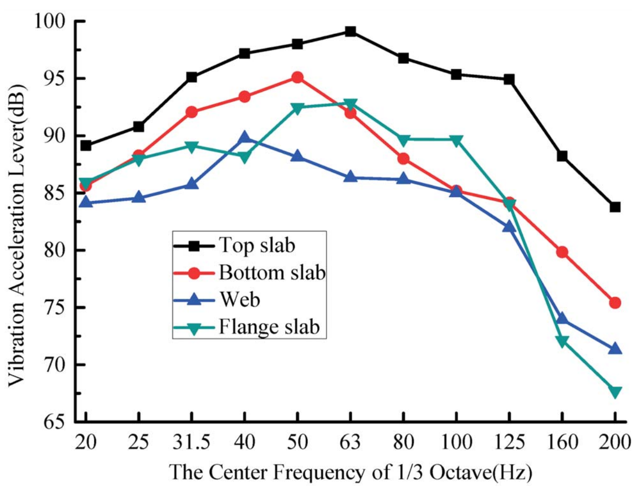

Figure 9. Vibration acceleration levels at the measured points.

(a) (b)

Figure 10. Photograph of in-situ noise measuring equipment and the test box-girder bridge: (a) Microphone receivers and experimental setup; (b) data acquisition system.

surement are summarized as follows:

(1) The acoustic microphone arrays are designed as noise receivers and deployed at 25 m along the cross direction of the bridge (see Figure 10(a));

(2) The sound-level data measured from the microphone arrays are collected by the Head Recorder with the sampling rate of 48 kHz;

(3) The collected data are then transferred to Head Recorder software package to perform acoustic analysis in frequency domain for the following procedure of data interpretation.

To measure the sound pressure levels radiated from the vibrations of the box girders induced by the moving train loads, as shown in Figure 11, two upper locations with 1.5 m from the ground are selected, namely, the near field point is denoted as N1 beneath the bottom of the mid-span of the middle bridge and the far field point N2 has a distance of 25 m from the measured point N1.

4.2 Computational Procedure of Bridge-radiated Noise Analysis

Based on the solid-sound consistent conditions, this study combined the dynamic finite element analysis of the box girders with the acoustic boundary element simulation in sound field to predict the bridge-radiated noise from the multi-span box girders in vibration.

To accurately estimate the sound pressures caused by the bridge-radiated noise in low frequencies, this study adopts an un-weighted linear sound pressure level to assess the structure-borne noise level on the measured points from the box girders [13], in which the vibration velocity level (v_{dB}) expressed in terms of the 1/3 octave band in decibels (dB) is defined as follows:

$$v_{dB}(\omega) = 20\log_{10}\frac{v(\omega)}{v_{ref}} \tag{8}$$

where $v(\omega)$ = the root mean square of measured velocity in frequency domain and v_{ref} (= 10^{-9} m/s) = the reference velocity.

To assess the acoustical characteristics on free-field noise radiation, both the spectrum curves and the sound pressure level are adopted in this study [12]. Let us adopt the microphone-receivers deployment at the measured stations perpendicular to the railway line shown in Figure 11 of section 4.1. Then, we can carry out the in-situ noise measurement using the experimental procedure described in section 4.1. With the in-situ noise measurement procedure shown in section 4.1 and the computational model of acoustical radiation described in section

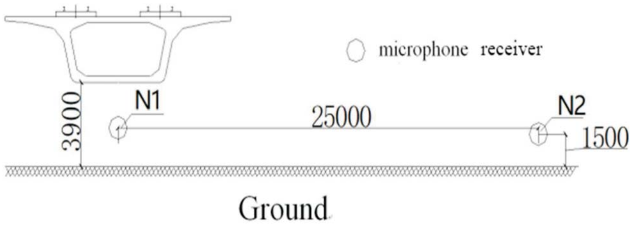

Figure 11. Layout of measured points at N1 and N2 (unit: mm).

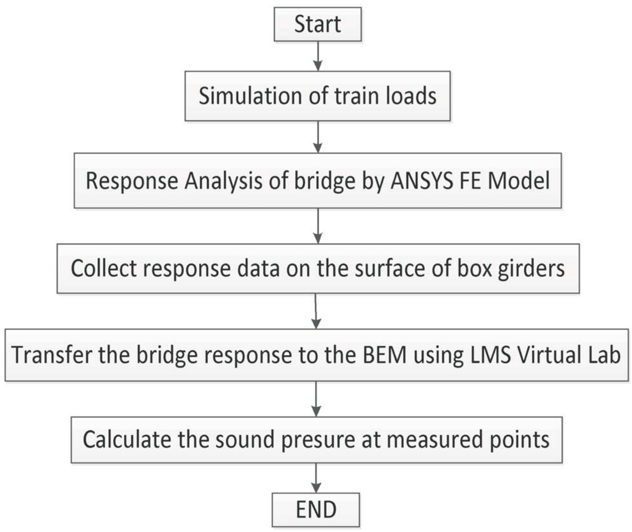

Figure 12. Computational flowchart of structure-borne noise.

3, both the experimental measurements and numerical results of the linear sound pressure level under 1/3 octave band in decibels for the points N1 and N2 shown in Figure 11 have been plotted in Figures 13(a) and 13(b), respectively. First, for a single-span PC box girder, as shown in Figure 13, the peak frequency of the sound pressure at Point N1 (near field) is close to 40 Hz and the Point N2 in the vicinity of 63 Hz, which are quite different from the measured results. Next, let us consider the bridge with 3-span PC box girders, the peak frequencies of sound pressure at Points N1 and N2 are close to 63 Hz. Finally, considering the bridge with 5-span PC box girders, the peak frequency of the sound pressure at Point N1 is 50 Hz and at Point N2 is 63 Hz, which are quite close to the measured results.

Table 1 lists the sound pressure levels computed and measured from the present study. As indicated in Table 1, at Points N1 (near field), the peak sound pressure levels computed using 1-, 3- or 5-span PC box girders are quite close to the measured ones. However, for Point N2 (far field), the sound levels predicted by the single-span box girder are significantly smaller than the measured ones. Moreover, from the sound pressure spectra plotted in Figure 13(b), there exists a significant underestimation of the sound pressure levels at the peak frequency (63 Hz) of Point N2 in comparison with the measured ones. Such a dynamic phenomenon indicated that the vibration of the multi-span box girders may increase the noise radiating area of the bridges excited. Obviously, the multi-span effects of the PC box girders on evaluation of the sound pressure levels in low frequency should be taken into account.

4.3 Panel Acoustic Contribution Analysis

With the acoustical boundary element meshes shown in Figure 4, a box girder can be divided into 6 components [14,15]. For illustration, only the 3-span PC box girders are considered in this example. As shown in Figure 14, the middle span box girder with red-colored characteristic arrows has been divided into 6 panels, in which Panels 1 and 2 represent the top and bottom slabs, Panels 3 and 4 the web slabs, and Panels 5 and 6 the overhanging flanges, respectively. Similarly, another sets of panel numbers are also shown on the right-side span with Panels 7−12 and the left-side span with Panels 13−18, respectively.

By using LMS Virtual Lab software, the sound pres-

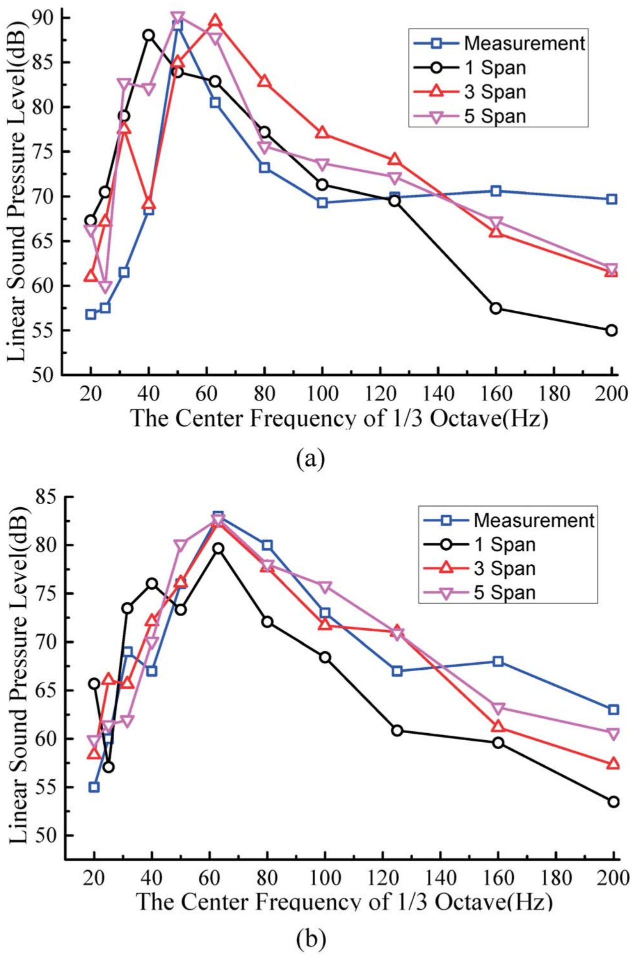

Figure 13. Sound pressure spectrum at the near (N1) and far (N2) field points (a) at the measured Point N1; (b) at the measured Point N2.

Table 1. Comparison of sound pressure at N1 and N2

Span	N1 (dB)		N2 (dB)	
	Measurement	Simulation	Measurement	Simulation
1-span		88.05		79.67
3-span	89.12	89.60	83	82.31
5-span		90.20		82.71

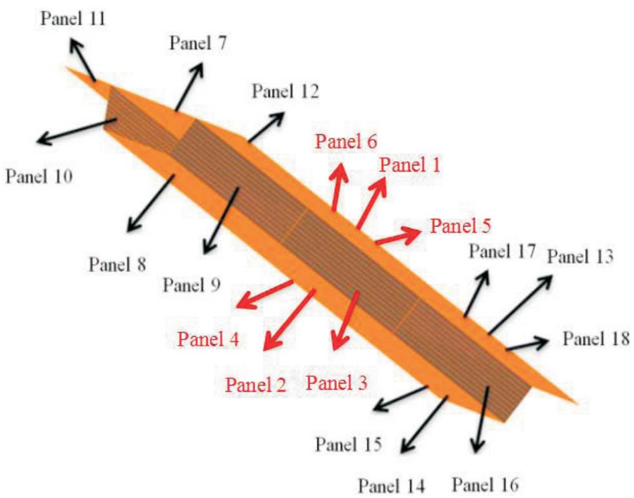

Figure 14. Distribution of panels along the 3-span box girders.

sure contributions of the panels to structure-borne noise at Points N1 and N2 can be computed respectively. For illustrations, the sound pressure contribution factor (D_c (ω)) of the target panel to the structure-borne noise radiation at the measured point is defined as follows:

$$D_c(\omega) = \mathrm{Re}\left(\frac{P_t P^*}{|P|^2}\right) \tag{9}$$

Here, Re(•) means to take the real part, P represents the total sound pressure at the measured point, P^* the complex conjugate of the pressure P, and P_t the sound pressure generated by the target panel. If the positive value of D_c means the panel vibrations of the box girders can give contribution to sound pressure at the measured points. In contrast, the negative value of D_c provides negative sound pressure for the measured points. In the following numerical demonstrations, the sound pressure contribution factor defined in Eq. (9) will be used to assess the sound pressure level of structure-borne noise radiation due to the panel vibrations of the box girder.

As the numerical results computed in section 4.2, the peak amplitude of the bridge-radiated noise from the 3-span box girders takes place at the frequency of 63 Hz. In the following examples, the dominant frequency of 63 Hz is regarded as the upper-bound frequency of the prominent factor for panel acoustic contribution analysis in evaluating the bridge-radiated sound pressure level. Figure 15 plots the panel acoustic contribution coefficients corresponding to the measured Points at N1 and N2 under the frequency of 63 Hz, respectively. As can be seen from Figure 15(a), Panels 1–6 at the middle span provide positive sound pressure contributions to the sound pressure at Point N1, but Panels 7, 8, 12, 13, and the remaining panels at side-spans give negative contributions to Point N1. On the other hand, for the measured Point N2, Panels 1–8, 10, 11, 12, 13 and 14 at side-spans produce positive contribution but the other panels lead to negative contributions. Table 2 lists the proportions of sound pressure contribution of each box girder to the measured points at the near- (N1) and far-field (N2) points, respectively.

According to the proportional analysis of panel acoustic contribution to bridge-radiated noise, as listed in Ta-

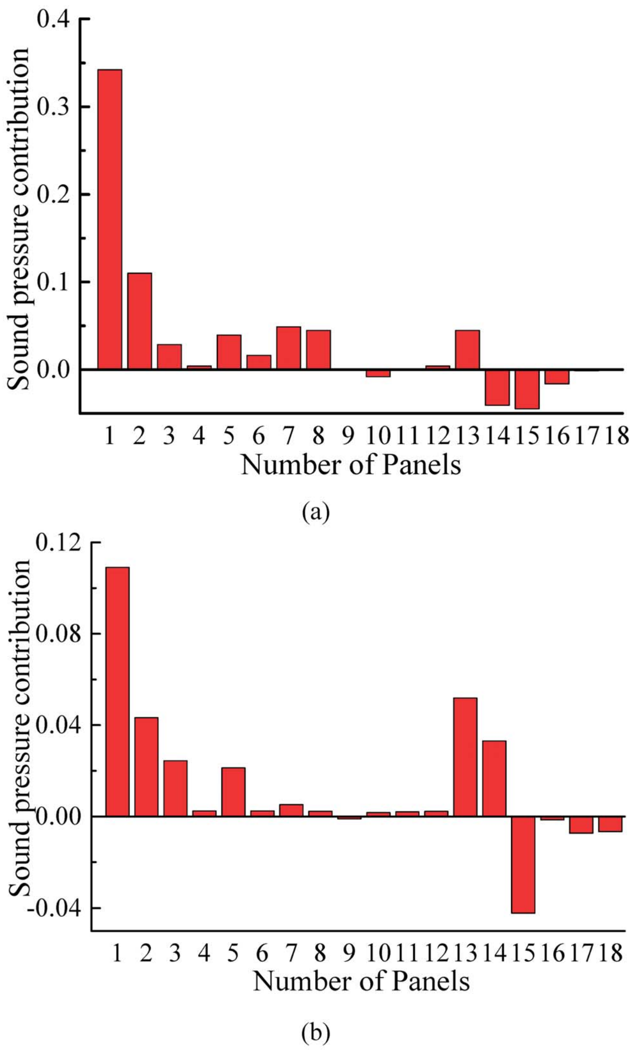

Figure 15. Sound pressure contribution of panels to the points N1 and N2: (a) Point N1 (near field); (b) Point N2 (far field).

ble 2, there are 94.6% of sound pressure at Point N1 (near-field) is contributed from the noise radiation of the panels on the middle span box girder but only 5.4% from the side-spans. It means that such a noise contribution to the near-field points can be neglected. However, for the far-field at Point N2, 83.5% of the sound pressure levels is radiated from the middle span and 16.5% from the side-spans, which means the radiation noise cumulated by the side-spans of the multi-span bridges cannot be neglected in evaluating sound pressure. This point also explains why a single-span bridge model usually underestimates the sound pressure level at far field in numerical simulations.

Table 2. Contribution and proportion of sound pressure

Position / Panel No.		Middle Span / 1–6	Side Span 1 / 7–12	Side Span 2 / 13–18	Summation
N1		0.540	0.089	-0.058	0.571
N2		0.203	0.012	0.028	0.243
Proportion	N1	94.6%	15.6%	-10.2%	100%
	N2	83.5%	5.2%	11.3%	100%

5. Conclusions

This study combined ANSYS-FE bridge modeling with LMS Virtual Lab software to simulate the structure-borne noise radiation analysis for the train-induced vibrations of single-cell railway bridges with PC box-girders. The proposed hybrid FE-BE approach not only reserves the computational performance in dealing with the dynamic response analysis of bridges using ANSYS software but also integrates the computational ability of acoustic boundary element analysis by LMS Virtual Lab software to simulate the structure-borne noise radiation of elevated bridges subject to moving train loads. With the present study, the following conclusions are addressed:

(1) Since the box-girder is simulated as a 3D FE model including all components, such as cantilever flanges, web slabs, top and bottom slabs, the contributions of local vibration modes of the box girder to noise radiations can be taken into account in simulating the acoustic sources when performing the bridge-radiated noise analysis.

(2) From the present noise-radiation analysis of a single-span box girder, the sound pressure level at dominant frequencies of far-fields would be underestimated in environmental noise evaluation. Thus, the sound pressure levels induced by multi-span box girders should be taken into account in assessing sound pressure levels at far-fields of railway viaducts using numerical simulation for acoustics.

(3) By the proportional analysis of panel acoustic contribution factor for the multi-span box girders, the sound pressure at near field (Point N1 in Figure 11) is mostly contributed by the single box-girder above it. Thus, for this case, the noise contribution by multi-span bridge girders can be ignored. For the far field (Point N2 in Figure 11), however, the noise contribution from the multi-span bridges to environmental sound levels should be taken into account in performing bridge-radiated noise analysis.

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