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Structure-borne low-frequency noise from multi-span bridges: A prediction method and spatial distribution

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ABSTRACT

Structure-borne noise from railway bridges at far-field points is an important indicator in environmental noise assessment. However, studies that predict structure-borne noise tend to model only single-span bridges, thus ignoring the sound pressure radiating from adjacent spans. To simulate the noise radiating from multi-span bridges induced by moving vehicles, the vibrations of a multi-span bridge are first obtained from a three-dimensional (3D) vehicle–track–bridge dynamic interaction simulation using the mode superposition method. A procedure based on the 2.5-dimensional (2.5D) boundary element method (BEM) is then presented to promote the efficiency of acoustical computation compared with the 3D BEM. The simulated results obtained from both the single-span and multi-span bridge models are compared with the measured results. The sound predictions calculated from the single-span model are accurate only for a minority of near-field points. In contrast, the sound pressures calculated from the multi-span bridge model match the measured results in both the time and frequency domains for all of the near-field and far-field points. The number of bridge spans required in the noise simulation is then recommended related to the distance between the track center and the field points of interest. The spatial distribution of multi-span structure-borne noise is also studied. The variation in sound pressure levels is insignificant along the length of the bridge, which validates the finding that the sound test section can be selected at an arbitrary plane perpendicular to the multi-span bridge.

1. Introduction

Low-frequency noise has considerable adverse effects on human health and well-being [1–3]. Vehicles crossing a bridge can induce low-frequency structure-borne noise with a long wavelength that is difficult to control. Thus, many researchers have focused their efforts on the problem of low-frequency structure-borne noise [4–10]. Some researchers have calculated the structure-borne noise by summing the infinitesimal spherical sources on the bridge surface [4,5], which may be not accurate enough for complex structures. The three-dimensional (3D) boundary element method (BEM) has been widely used for the simulation of structure-borne noise [6,8–10]. Zhang et al. [6] presented a numerical procedure to predict the noise from concrete bridges by applying the 3D BEM in the frequency domain and vehicle–track–bridge coupling analysis in

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the time domain, and conducted a series of experiments to investigate the noise characteristics [6,7]. Kozuma and Nagakura [8] used a hybrid method to predict the noise level of a concrete bridge. Bridge vibration was obtained by coupling the modal shapes and measured displacements of the bridge, while the structure-borne noise was simulated using the 3D BEM. Li et al. [9] simulated structure-borne noise using the modal acoustic transfer vectors (MATVs) method, which was efficient for the parametric analysis of various train types and train speeds. Recently, Zhang et al. [10] investigated the transient noise induced by highway vehicle-bridge coupling vibrations using the 3D BEM in the time domain.

It is generally extremely time consuming to apply the 3D BEM to compute the sound radiation from a bridge with a large superficial area. The 2.5-dimensional (2.5D) method, which has been extensively used in wave propagation research [11–18] for its high computation efficiency, can be applied to obtain a 3D solution of the model with a constant cross-section along one axis using a spatial wavenumber transform of the 2D solutions. Duhamel and Sergent [11], Hornikx and Forssén [12], and Nilsson et al. [13] used the 2.5D BEM to investigate the wave propagation problems in acoustic fields. Rieckh et al. [14] presented a 2.5D-Fourier-BEM model for simulating the vibrations of soil comprising layered anisotropic media in a tunnel. Costa et al. [15] used a 2.5D finite element method (FEM) and BEM model to predict the vibrations induced by train–track interaction, and validated the procedure by comparison with the in-situ measurements. Mazzotti et al. [16] proposed a combined semi-analytical FEM and 2.5D BEM approach to compute the dispersion properties of viscoelastic waveguides with an arbitrary cross-section. In our latest work [17], a 2.5D BEM was presented to calculate the MATVs of a single-span bridge with the same accuracy but much higher efficiency than the previous 3D method [9].

To date, only minor attention has been paid to the accurate prediction of structure-borne noise at far-field points. For instance, only near-field sound pressure was calculated in Refs. [4–6]. The numerical results in Refs. [8,9,17] agree well with the measured results at near-field points. Nevertheless, the computed sound pressures were smaller than the measurements at far-field points, and the discrepancy increased as the distance between the bridge and the receivers increased. The measured sound pressures can be much larger than the simulated pressures when the distance between the bridge and the receivers exceeds the bridge span length, as shown in Refs. [8,17]. The main reason for the discrepancy is that a single-span bridge model was developed in the abovementioned studies, and the sound radiation from adjacent spans was thus neglected. However, the noise level at far-field points is an important indicator in environmental assessments. For instance, the sound pressures at field points 25 m away from the track center should be measured according to the ISO 3095:2005 standard [19]. Thus, an effective method of predicting the structure-borne noise at far-field points is needed, especially for field points near residential buildings.

In this paper, we first extend our latest 2.5D BEM framework to realize the prediction of far-field structure-borne noise from multi-span bridges excited by moving vehicles. Then, the MATVs of 3-span, 5-span, and 11-span U-shaped rail transit bridges are obtained using the 2.5D BEM, and the dynamic responses of the vehicle–track–bridge system are calculated. Finally, the sound pressures from the single-span and multi-span bridge models are calculated and compared with the measured pressures. A spatial distribution analysis of the noise along the longitudinal axis of the track is also conducted to investigate the effect of microphone location on the measurement.

2. Vehicle–track–bridge interaction analysis

Li et al. [20] proposed a computer-aided method to simulate the dynamic interaction problem between the vehicle, track, and bridge subsystems. The nonlinear Hertz contact theory was used to model the wheel–rail contact force normal to the contact zone, and the Kalker creepage theory modified by Shen et al. [21] was used to simulate the wheel–rail creeping force. The nonlinear wheel–rail contact forces, linear/nonlinear spring elements, and dashpot elements in the coupled vehicle–track–bridge system were treated as pseudo forces [20,22] so that the vehicle–track–bridge subsystem could be modeled separately.

The dominant frequencies of the structure-borne noise from concrete bridges mainly range from 40 Hz to 80 Hz, which can be described as the natural frequency of a single wheel adhering to an elastically supported rail [23,24]. Thus, the total vehicle model, comprising the car body, bogies, and wheelsets, can be reduced to a simplified sprung mass model [23,24] to enhance computing efficiency. In this study, however, the car body, bogies, and wheelsets are still modeled as rigid bodies, and the suspension systems connecting these components are modeled by spring and dashpot elements, to enable the use of the program developed by Li et al. [20].

The motion equation of a railway vehicle with multiple elements can be generally expressed in terms of modal coordinates [20] as

$$\begin{cases} \ddot{\mathbf{q}}_v + 2\boldsymbol{\xi}_v\boldsymbol{\omega}_v\dot{\mathbf{q}}_v + \boldsymbol{\omega}_v^2\mathbf{q}_v = \boldsymbol{\Phi}_v^T\mathbf{f}_v, \\ \mathbf{f}_v = \mathbf{f}_{vp} + \mathbf{f}_{vc}, \end{cases} \tag{1}$$

where $\mathbf{q}_v$, $\boldsymbol{\Phi}_v$, $\boldsymbol{\omega}_v$, $\boldsymbol{\xi}_v$, and $\mathbf{f}_v$ stand for the modal coordinate vector, modal shape matrix, modal frequency matrix, modal damping matrix, and force matrix of the vehicle, respectively; $\mathbf{f}_{vp}$ is the pseudo-force vector generated by the nonlinear part of the springs and all parts of the dashpots; $\mathbf{f}_{vc}$ is the wheel–rail contact force vector applied on the wheel, which is determined by the motions of the vehicle, the responses of the track–bridge system, and the wheel–rail combined roughness; and the superscript T is the matrix transpose operation.