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A case study of interior low-frequency noise from box-shaped bridge girders induced by running trains: Its mechanism, prediction and countermeasures

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ABSTRACT

A side effect of high-speed railway and urban rail transit systems is the associated vibration and noise. Since the use of concrete viaducts is predominant in railway construction due to scarce land resources, low-frequency (20–200 Hz) structure-radiated noise from concrete bridges is a principal concern. Although it is the most commonly used bridge type, the mechanism of noise emission from box-shaped bridge girders when subjected to impact forces from moving trains, which sounds like beating a drum, has not been well studied. In this study, a field measurement was first made on a simply-supported box-shaped bridge to record the acceleration of the slabs and the associated sound pressures induced by running trains. These data indicated that a significant beat-wave noise occurred in the box-shaped cavity when the train speed was around 340 km/h, which arose from the interference between two sound waves of 75.0 Hz and 78.8 Hz. The noise leakage from the bridge expansion joint was serious and resulted in obvious noise pollution near the bridge once the beat-wave noise was generated in the cavity. The dominant frequency of the interior noise at 75.0 Hz was confirmed from the spectrum of the data and the modal analysis results, and originated from the peak vibration of the top slab due to resonance and the first-order vertical acoustic mode, which led to cavity resonance, amplifying the corresponding noise. The three-dimensional acoustic modes and local vibration modes of the slab were calculated by using the finite element method. A simplified vehicle–track–bridge coupling vibration model was then developed to calculate the wheel–rail interaction force in a frequency range of 20–200 Hz. Numerical simulations using the boundary element method confirmed the cavity resonance effect and the numerical results agreed well with the data. Based on the calibrated numerical model, three noise reduction measures, i.e., adding a horizontal baffle in the interior cavity, narrowing the width of top slab by reducing the inclination angle of the webs, and using a softer fastener on the track, were found to be effective and practical for reducing the noise generated by high-speed trains.

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1. Introduction

In addition to the common noise that arises from wheel–rail interactions, structural noise radiated from vibrating bridge components when a train runs across a bridge is another important source of noise [1]. Bridges constructed with steel material radiate middle- to high-frequency noise ranging from 400 Hz to 1000 Hz, which can be distinctively heard due to high levels comparable to wheel–rail noise. The steel bridge noise induced by trains has been extensively investigated. Various prediction models and control measures have been proposed [2–4]. Similar to a steel bridge, trains running across a reinforced concrete bridge also generate noise, but in a lower frequency range. Compared to the noise from a steel bridge, train-induced noises arising from vibrations of reinforced concrete bridges have been less studied. As a result of rapid economic development and urbanization, many reinforced concrete bridges have been and are still being built close to densely populated residential and metropolitan areas. Moreover, people are becoming increasingly less tolerant to low-frequency noise (20–200 Hz) radiated from concrete bridges because of its long-term adverse effects on physical and mental health and they have higher expectations of more environmentally-friendly surroundings in cities [5]. Therefore, investigations of low-frequency noise emanating from concrete bridges and the search for methodologies to mitigate such noises have been attracting more and more research attention.

The box-shaped bridge is the most commonly used type of concrete bridge because of its good mechanical properties, its simple shape, and low weight-span ratio. Nowadays, a large number of box-shaped girders are being used in China with the rapid growth of high-speed rail and urban rail transit networks. The West Rail in Hong Kong was the first practical engineering project that encountered the noise problem from concrete box-shaped bridges because of Hong Kong's strict noise control requirements and the high level of noises generated due to the interaction between structure-radiated noise and other noises arising from the rails, trains and floating slabs [6]. Some researchers have conducted experiments and field measurements of noises from concrete bridges. Ngai and Ng [7] studied the dominant frequency components of noises radiated from a vibrating concrete box structure with a single-box double-cell cross-section, and concluded that the dominant frequency of noise and vibration of the concrete viaduct was between 20 Hz and 157 Hz, and the resonance frequencies were 43 Hz and 54 Hz and had significant tonal noise characteristics. Lee et al. [8] used a steel hammer to excite a small-sized cement viaduct model to acquire vibration responses and mode shape data. The results showed that the web vibration can increase the input impedance, resulting in less sound radiation. Li et al. [9] carried out in-situ measurements of noises from two box-shaped viaducts, measuring and analyzing noises underneath the box-girder, far from the bridge, and near the bridge gap as trains passed by. The frequencies corresponding to the peak noise radiated from the bridge and the noise tonal characteristics were 50 Hz and 63 Hz for a double-track and single-track box-shaped viaduct, respectively.

Besides experimental studies and field measurements, numerical methods to predict the noise emanating from bridge structures induced by trains have also been developed. These include the boundary element method [10,11], modal acoustic transfer vectors [12], power flow [13], and the finite element method [14]. These numerical approaches predict the effects on bridge-radiated noise of structural parameters (plate thickness and the angle of the web), the bridge type (box-shaped or U-shaped girder), ground reflection (present or absent), and the train speed.

These studies have helped to optimize the design of box-shaped bridges to minimize the bridge-borne noise level. However, it should be noted that a box-shaped bridge girder has a large cavity and thin slabs (i.e. top slab, bottom slab, web and flange).When a moving train imposes impact forces on a box-shaped girder, it sounds like beating a drum (see Fig. 1(a)). The girder generates a unique noise which has not been considered in previous studies. Differently than other structures such as U-shaped or T-shaped bridge girders, the structure-radiated noise from a box-shaped girder is susceptible to amplification as a result of cavity resonance. Moreover, the expansion joint of a simply-supported railway bridge is usually 0.1–0.2 m wide and there are no closed transverse diaphragms at the beam ends (see Fig. 1(b)), therefore the noise leakage from the expansion joints increases the noise field alongside the bridge, which has been reported in several cases [15].

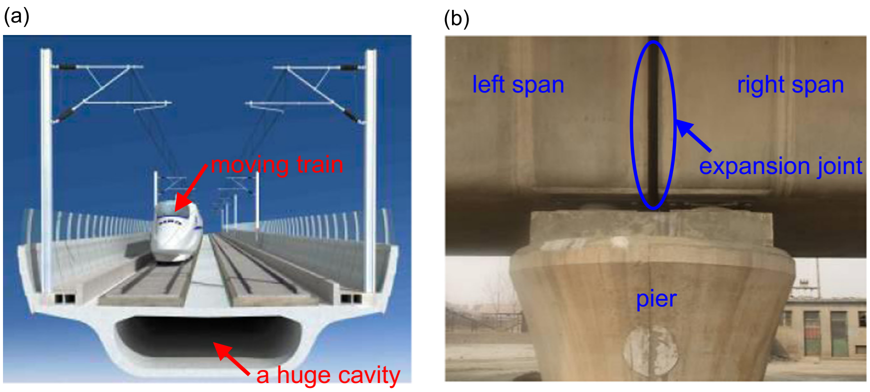

Fig. 1. Noise from (a) dynamic train loads acting on a box-shaped bridge girder and (b) the bridge expansion joint.

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