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Structure-borne noise of railway composite bridge: Numerical simulation and experimental validation

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ABSTRACT

In order to investigate the characteristics of the noise from steel–concrete composite bridges under high-speed train loading, a model used to predict the bridge-borne noise is established and validated through a field experiment. The numerical model for noise prediction is developed based on the combination of spatial train–track–bridge coupled vibration theory and Statistical Energy Analysis (SEA). Firstly, train–track–bridge coupled vibration is adopted to obtain the velocity time history of the bridge deck vibration. Then, the velocity time history is transferred into frequency domain through FFT to serve as the vibratory energy of SEA deck subsystems. Finally, the transmission of the vibratory energy is obtained by solving the energy balance equations of SEA, and the sound radiation is computed using the vibro-acoustic theory. The numerically computed noise level is verified by a field measurement. It is determined that the dominant frequency of steel–concrete composite bridge-borne noise is 20 – 1000 Hz. The noise from the bottom flange of steel longitudinal girder is less than other components in the whole frequency bands, while the noise from web of steel longitudinal girder is dominant in high frequency range above 315 Hz. The noise from concrete deck dominates in low-frequency domain ranges from 80 Hz to 160 Hz.

1. Introduction

Modern high speed railways have to maintain relatively smooth line geometry and pass over rivers, valleys or existing motorways. As a result, bridges often make up a considerable proportion of the railway line, especially for the high-speed railway network in China. When a train is travelling through a bridge, both wheels and rails will radiate rolling noise directly because of the wheel/rail interaction. Besides, bridge components will also generate rumbling noise after excited by the vibratory energy that is transmitted to them. The excited steel components of a bridge will generate higher vibration level and thus will radiate more noise. Compared with the normal track, the overall noise level of a composite bridge with ballast track is about 0 – 5 dB higher and a steel bridge with ballast track can have the noise increase of 5 – 10 dB. In cities, regions near high speed railway bridges usually become hot spots in noise maps. Although sound barriers are effective to shield the

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noise above the bridge deck, their usefulness is limited in reducing bridge-borne noise. This provides the impetus for this study to investigate the structure-borne noise emitting by railway bridges.

With the development of computers, FEM (Finite element method) and/or BEM (Boundary element method) is applied to the calculation of concrete bridge vibration and noise. Crockett and Pyke [1] developed a FEM model of the structure, trackform and vehicle to determine the structural vibration levels under moving train load. An analytical model took these vibration levels as input and determined the wayside structure-radiated noise. Xie et al. [2] developed a grillage model of a highway bridge which is updated using a genetic algorithm to investigate the low–frequency noise of a steel continuous bridge with two separate box girders. The dynamic response of the bridge derived from vehicle–bridge coupling vibration was calculated as a sound source and sound pressure due to bridge vibration was estimated according to sound propagation theories. Li [3] adopted BEM to investigate the noise radiated by U-shaped pre-stressed concrete girder, and the numerical simulation agreed well with the measured results. Wu and Liu [4] used the forces in the rail pads from vehicle–track interaction as the excitation to viaducts which were modeled by finite element software and compared the sound emission between box-section and U-section railway concrete viaducts. Li and Zhang [5,6] investigated the noise of 32 m simply supported pre-stressed box girder from field experiment and hybrid FEM–BEM. Herron [7] conducted waveguide finite element method to investigate the vibration response of a railway bridge that has a uniform cross-section along its length. Because three-dimensional BEM is time-consuming, Li et al. [8] presented a two-and-a-half dimensional BEM-based procedure for simulating bridge-borne low-frequency noise with higher efficiency.

Practically, finite element model is not suitable for the vibration response of the bridge with the audible frequency range owing to the high modal density of structure. If acoustic FEM or BEM is employed, mesh dimension has to be fine enough to ensure the analysis precision and the amount of elements increases rapidly. Consequently, the acoustic calculation is too expensive to be solved in this situation. Statistical Energy Analysis (SEA) is another approach to solve the dynamic response in high modal density of large scale structures by broad band excitation. Manning et al. [9] applied the concepts used in SEA to carry out the energy flow calculations in coupled structures and developed a simple analytical model. Remington and Wittig [10] presented an analytical model for the generation of noise from a deck plate girder steel bridge, in which SEA techniques were used to compute vibration transmission from the rail to the ties and the girders. University of Southampton’s ISVR (Institute of Sound and Vibration Research) has carried out systematic investigation on railway vibration and noise [11]. Janssens and Thompson [12] determined the input power of a bridge from the real part of the bridge point mobility and the forces acting on the bridge via the rail fasteners. The ratio of the velocity levels of the various bridge parts was derived using SEA. The bridge was assumed a homogeneous structure, and then the mobility of bridge is derived according to I-shaped girder’s formulae. Harrison et al. [13] carried out SEA to assess the noise from a steel–concrete composite bridge. Subsequently, Thompson and Jones [14] developed a model called NORBERT to predict the noise radiated by railway bridges. Using the combined wheel and rail roughness, vibrations of rail and wheel are calculated from the rail and wheel mobility at a certain train speed. Bewes [15–17] improved the calculation model by developing the coupling between the rail and bridge at low frequencies and the mobility of the support girder at high frequencies. Poisson and Margiocchi [18] studied the vibro-acoustic of a steel bridge using FEM in the low-frequency range and SEA at higher frequencies respectively.

In general, steel–concrete composite bridges generate higher noise level than all-concrete bridges. For composite or steel bridge–borne noise, existing studies mainly employed SEA method and drawn some meaningful conclusions. However, the coupled vibration between train and bridge is typically not taken into account, and the bridge with complex geometry in SEA is highly simplified in existing studies about this field. One of the main difficulties with SEA is the estimate of the vibration power transmitted from the track into the bridge structure. Very limited research about the noise mechanism of high-speed railway composite bridge can be found. In order to address these issues, this paper presents a noise prediction method for steel–concrete composite bridge by combining spatial train–track–bridge coupled vibration with SEA considering the bridge geometry. An on-site noise measurement of a continuous steel–concrete composite bridge in service is conducted and the proposed method is validated by comparing the computed sound pressure levels (SPLs) with the measured ones. Then the mechanism of noise radiated by the composite bridge is investigated.

2. Bridge-borne noise prediction method

The noise radiated by steel girder is up to several hundred Hz and even higher, which directly relates to high-frequency local vibration. As a result, the finite element mesh for steel components must be refined enough to capture higher frequency vibrations. This is extremely computationally intensive and is not practical. However, the vibratory dominant frequency of concrete deck is much lower than the steel girder. Even if the element size is larger, the computed dynamic response of bridge deck is reasonable. Based on the fact, this paper proposes that the vibratory velocities of bridge deck may be calculated using hybrid beam–shell FEM in train–track–bridge coupled analysis and used as the vibratory energy of SEA deck subsystems. Then the vibration responses can be derived by solving the power balance equations in frequency domain. Finally the noise emission is calculated by vibro-acoustic theory. The procedure of predicting the structure-borne noise is presented in Fig. 1.