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Dynamic response of arch bridges traversed by high-speed trains

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Abstract

A mechanical model describing the planar elasto-dynamics of arch bridges with general arch profiles is presented. The model is amenable to analytical or semi-analytical treatments and is effective for parametric studies, design of control systems or structural optimizations. The Ritz's energy approach is employed to calculate the solutions of the vibration eigenvalue problem—natural frequencies and mode shapes—and the forced responses to external excitations, namely those induced by the passage of trains. A closed-form solution of the bridge dynamic response to the transit of trains with arbitrary load distributions and running speeds is found and the train-induced resonances are accordingly discussed. In particular, three European high-speed trains—the French TGV, the Italian ETR 500, and the German ICE—traversing a lower-deck steel arch bridge are considered and the ensuing responses are investigated.

1. Introduction

The dynamic response of bridges traversed by trains is a subject of interest in structural engineering due to the increasing train speeds which will become significantly higher with the next-generation magnetically levitated trains. From a structural point of view and the passenger comfort, the noise disturbance and bridge vibrations cause undesirable effects that need to be dealt with and become more serious during the train acceleration phases.

Early studies considered the bridge as a simply supported beam and the train as a moving load with constant speed. Later, Bolotin [1] studied a beam subject to an infinite sequence of equal loads uniformly spaced by a distance d and moving at constant speed $\bar{V}$. In his study, the period of the moving loads, $d/\bar{V}$, was identified as the key parameter. Along the same lines, Fryba [2] concluded that the forced steady-state vibratory response will attain its maximum when the time interval between two successive loads is equal to or is an integer multiple of some natural periods of the beam in free oscillations. Besides straight beams, also the dynamic response of circular arches subject to a concentrated load moving along the circumferential direction has been recently studied in Ref. [3].

A few investigations [4] have considered the nonlinear resonances that can be excited by a single load traversing a bridge, modelled as an Euler–Bernoulli beam resting on nonlinear visco-elastic supports, and have

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shown that, in addition to the primary resonances of the bending modes, when the forcing levels are high there are many secondary resonances exciting responses that can be significantly more complex compared with those exhibited by the linear model.

Recent studies have investigated the dynamic behaviour of railway bridges employing detailed models of the bridges and passing trains. For example, Au et al. [5] used five models of moving vehicles to study the impact effects on a cable-stayed bridge under railway train loading. The rail irregularities and the geometric nonlinear behaviour of the cable-stayed bridge were taken into account.

Yang et al. [6] presented a closed-form solution of the dynamic response of simply supported Euler–Bernoulli beams subjected to the passage of high-speed trains where the phenomena of resonance and cancellation were identified, along with optimal design criteria. Klasztorny [7] presented an iterative algorithm for solving vertical vibrations of a multi-span steel bridge, induced by a fast passenger train, moving at a speed of 120–360 km/h. Xia and Zhang [8] studied the dynamic interaction between a high-speed train and the bridge by theoretical analysis and field experiments. Each vehicle was described by 27 degrees of freedom whereas the bridge was modelled by the modal superposition technique. They showed a good agreement between the calculated results and the in situ measured data.

In recent years, the dynamic behaviour of high-speed railway bridges has been extensively investigated mainly via field tests aimed at improving the design of high-speed railways. Xia et al. [9] reported the experimental results—deflections, accelerations, strains—relating to a prestressed concrete bridge, the Gouhe River Bridge, traversed by the China-Star high-speed train (design speed of 270 km/h) that reached the peak speed of about 320 km/h. Kwark et al. [10] conducted experimental and theoretical studies to determine the dynamic behaviour of bridges crossed by the Korean high-speed train (KHST). For running speeds close to the critical speed (i.e., the train speed at which one of the bridge modes is excited), greatly amplified dynamic responses compared with the static responses were observed. They adopted three-dimensional (3D) models to represent the dynamic interaction between the articulated bogies train and the bridge and showed reasonable agreements.

Most of the referenced theoretical and experimental investigations relate to simply supported single- or multi-span straight bridges. Nonetheless, steel or prestressed concrete arch bridges are typical structural schemes in the medium-/long-span bridge category, normally constructed in mountain areas. A good number of works dealt with 2D elastic and inelastic modelling of upper-deck steel arch bridges to investigate the in-plane bridge responses to earthquakes (see, e.g., Ref. [11]). Only a few studies have considered the dynamic behaviour of lower-deck arch bridges under train loads. In Ref. [12], the vibration characteristics of steel arch bridges traversed by high-speed trains were investigated. Two simple criteria were determined to predict the train–bridge resonance effects and validated the predictions employing finite element (FE) analyses.

In the present work, the dynamic response of arch bridges is investigated employing a mechanical parametric model, based on pertinent kinematic assumptions, and suitable to describe the structural elasto-dynamic responses to general planar excitations and, in particular, to the passage of trains. The distributed-parameter (DP) model allows efficient parametric studies as well as the effective design of vibration control schemes aimed at improving the structural integrity and passenger comfort which is the main focus of an accompanying paper. Employing the proposed mechanical model, the elasto-dynamic responses to the passage of arbitrary trains are obtained in closed form along with the train-induced primary resonances of arbitrary bridge modes.

In Section 2, the arch bridge analytical model is presented. In Section 3, the semi-analytical computational strategy is discussed. In Section 4, the closed-form bridge response to the passage of an arbitrary train is shown; the resonance speeds are discussed in Section 5. In Section 6, the main results relating to a steel arch bridge traversed by three European high-speed trains are reported. In Section 7, the main conclusions are drawn.

2. Equations of motion for arch bridges

In this section, the DP model describing planar elasto-dynamic responses of arch bridges with general arch profiles of the lower- or upper-deck type is illustrated. To the best of the author's knowledge, this approach has not been employed in former studies on arch bridge dynamics. The model (see Fig. 1a) comprises three