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A three-dimensional dynamic analysis scheme for the interaction between trains and curved railway bridges

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ABSTRACT

The present paper proposes an original scheme for the dynamic analysis of the vehicle–bridge interaction (VBI) between trains and curved in-plan bridges. Key features are the three-dimensional vehicle dynamics formulation, and the matrix statement of the equations which condense the VBI dynamics, making the scheme generic. The analysis brings forward the interaction along the radial and torsional sense of curved bridges, which are often neglected for straight bridges. Specifically, the study shows that the (centrifugal and Coriolis) forces generated due to the curved path govern the lateral dynamics of the vehicle–bridge system when the curvature and/or the velocity are high.

1. Introduction

Railway networks are expanding worldwide, and especially in China, to meet the increasing requirements for high-standard transportation. After ten years of constructing new high-speed railways and upgrading existing conventional railway lines, China now shares the world's longest (Fig. 1 [1]) high-speed railway (HSR). Compared with the conventional railway lines, HSR's have a higher percentage of bridges [2], mainly for reasons of safety, comfort and mitigation of noise pollution. For instance, the Beijing-Shanghai HSR line is 1318 km long, out of which 1059.4 km (80.5% of the whole line [3]) is on mostly viaduct bridges. Further, the operational speed for HSR trains in China has been limited from 350 km/h (in 2011) to 300 km/h [4] (in 2013). These unprecedented speeds trains operate, over an ever increasing length of railway bridges, create incentive to revisit their dynamic interaction to ensure safety and comfort during travel.

The VBI dynamics attracts the attention of researchers for almost a century [5]. As the field matured, the standard VBI model shifted, from the moving-force model [6–10], to the moving-mass model [11–14] and then to the sprung mass model [15–18]. Au et al. [16] compared the influence of five different vehicle models, on a cable-stayed bridge, and noted that the moving force and the moving mass models tend to underestimate the impact effect. During the last decades, the advent of personalized, high computational power enabled the consideration of more sophisticated models, for both bridges and vehicles. Most recent studies, e.g. [3,19–32], simulate the vehicle as an assembly of rigid-bodies (car body, bogies and wheelsets) connected with springs and dashpots representing the properties of the suspension system. For the purpose of a numerical VBI analysis, the response of bridges is captured either with integration in the time domain of the complete geometrical model [10,23,33–36] or with the modal superposition method [9,21,37–42]. Alternatively, the so-called VBI-element can be used which condenses (dynamically) the vehicle and the bridge subsystems (Yang and Lin [33]). Yang and Yau [34] refined the VBI-element approach taking into account the pitching effect of the vehicle, while Lou and Zeng [36] proposed a similar element considering a four-axle 10-DOF vehicle model with two-layer suspension systems. Very recently, Neves et al. [43] proposed a direct-method for the analysis of the nonlinear VBI along the vertical direction.

The majority of the VBI studies examine the problem solely in the vertical direction. Hence, despite the abundance of VBI studies, to the authors' knowledge, studies on the VBI of curved in-plan bridges (e.g. Fig. 2 [44]) are scarce. In particular, Yang et al. [45] derived closed-form solutions for a single-span, simply supported, horizontally curved beam subjected to pairs of moving vertical and horizontal (centrifugal) loads. Xia et al. [41] examined the lateral VBI dynamics of a 3D train model running on curved railway lines, supported on straight girders. Following a different approach than the one proposed herein, that study [41] concluded that in curved bridges, the centrifugal forces dominate the lateral dynamics, even over the effect of the hunting motion of the wheelset. The study further argued that no resonance is observed in the lateral VBI in

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curved bridges [41], and compared their numerical results with field experiments.

The primary motivation for this study is: (i) the expanding conventional and HSR networks worldwide, (ii) the ever increasing ratio of bridges comprising contemporary HSR lines, (iii) the unprecedented speeds trains operate, and (iv) the lack of published research on the dynamic VBI in the case of curved in-plan bridges. The present research deploys an original and versatile framework, for the simulation of the interaction dynamics between trains and curved, in-plan, railway bridges (Fig. 2).

2. Proposed approach

With the aim to avoid an ad hoc treatment of the VBI problem, the proposed approach deploys a matrix formulation, and results in a set of equations of motion (Eq. (23)) which are condensed and easily reproducible. For a different bridge and/or different vehicle-models or numbers of vehicles, one has only to implement the same matrix equations, presented later in Eq. (23), for the pertinent matrices.

The examined dynamical system consists of the vehicle subsystem and the bridge subsystem. The two subsystems are coupled through the contact forces between the vehicle wheels and the rails. The study simulates the, straight or curved in-plan (horizontally), bridges with the finite element method (FEM), and models the vehicles as multibody assemblies. The solution of the global equations provides the response of both the bridge and the vehicle simultaneously. The mass matrix, the stiffness matrix, the damping matrix and the loading vector of the global (coupled vehicle–bridge) system become time-dependent. The paper accounts for the self-excitations, such as the elevation and alignment rail irregularities, the hunting motion of the wheelset, and the subsequent rolling rotation due to the conicity of the wheels. The study also considers the track eccentricity (offset) with respect to the shear center of the deck's section and the effect of the cant angle. It is assumed that all deformations remain small and that the linear elastic theory applies. Numerically, the proposed framework is realized with MATLAB [46].

Fig. 2. A continuous curved in-plan railway bridge of the Lan-wu line, in China. (Image CC from CRCC [44]).

2.1. Vehicle modeling

The train vehicles are modeled as multibody assemblies comprised of (Fig. 3(a)): (i) one car body, (ii) two bogies and (iii) four wheelsets of each vehicle, which are all considered as rigid bodies. Fig. 3(a) presents the typical, 27 degrees of freedom (DOF's), 3D vehicle model [45] utilized in this study. The car body, the front and the rear bogies are assigned five DOF's each: the vertical and the lateral displacements, the yawing, the rolling, and the pitching rotations (Fig. 3(b)). For each wheelset, only three DOF's are designated: the vertical and the lateral displacements, and the rolling rotation.

Following [47], the study employs three systems of reference to formulate the equations of motion of the vehicle: an inertia (space-fixed) system O–XYZ, a moving trajectory system O'–$X^{ti}Y^{ti}Z^{ti}$, and a body-fixed system O^{ir}–$X^{ir}Y^{ir}Z^{ir}$ (Fig. 4).

The definition of the moving trajectory system O'–$X^{ti}Y^{ti}Z^{ti}$ requires only a time-dependent coordinate, the arc length, s^i (Fig. 4). The orientation of the trajectory system is then defined using three Euler angles: ψ^{ti} (yawing), ϕ^{ti} (rolling) and θ^{ti} (pitching)

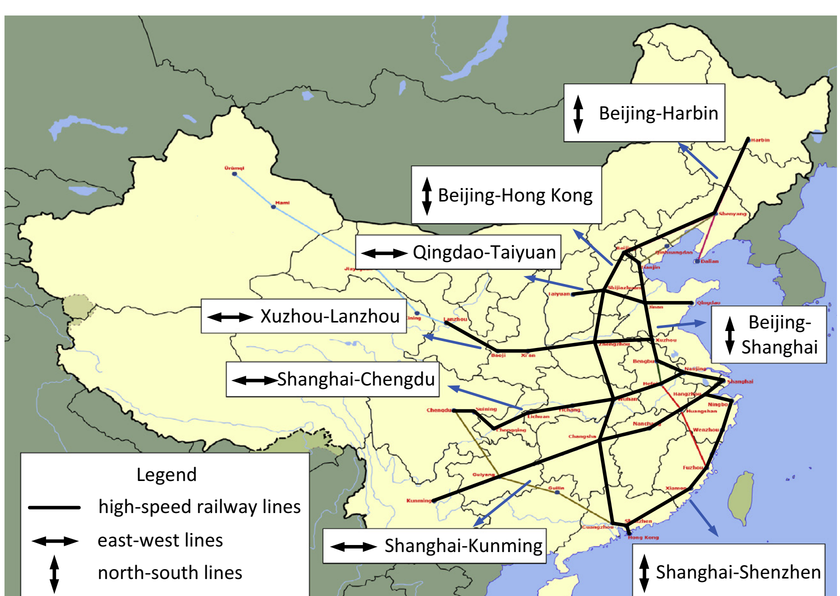

Fig. 1. The blue print of the planned high-speed railway network in China for 2020. The total envisaged length for 2020 is 50,000 km. (Image CC from Alancrh [1]).