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Influence of the vehicle model on the prediction of the maximum bending response of simply-supported bridges under high-speed railway traffic

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ABSTRACT

This investigation intends to contribute to the problem of train-bridge interaction in high-speed railway lines. For design purposes, most often a numerical model based on constant moving loads is used to reproduce the traffic action exerted on the structure. Since no vehicle–bridge interaction is considered, this simple model may overestimate the bridge transverse displacements and accelerations when resonance occurs, particularly in simply-supported spans. According to Eurocode 1 the reduction of the bridge response due to this phenomenon may be included either by means of a coupled vehicle–bridge analysis, for which several vehicle models can be employed, or by considering an additional amount of damping which depends on the bridge span. In this investigation the two approaches are addressed and the bridge response at resonance provided by both techniques is thoroughly compared; the comparison is carried out through various examples where the interaction phenomenon may have practical importance in the verification of the serviceability limit state of acceleration for ballasted tracks. Using a nondimensional formulation, the key parameters that determine the reduction of the bridge peak response in terms of accelerations and displacements due to train-bridge interaction are brought to light. The results of a subsequent extensive sensitivity analysis are presented and discussed. The main purpose is to decide whether, taking into account all potential train-bridge configurations, a conservative approach in the prediction of the response reduction caused by interaction can still be adopted.

1. Introduction

In the study of the dynamic behaviour of a railway bridge the choice of the vehicle model can have a significant influence that justifies the strong interest on the topic shown by scientists and engineers.

Conventionally, moving load models (MLM) have been used to solve the key problems in railway bridge dynamics [1–8] and are widely used for design purposes, according to the regulations existing in most modern countries [9]. Vehicle models of higher complexity, from the moving mass to those consisting of dozens of degrees of freedom (DOF), are found in the literature [3,10–15] whenever vehicle–bridge interaction (VBI) effects need to be captured.

Since the dynamic behaviour of the bridge and that of the moving vehicle are coupled through the wheel-rail contact forces, the degree of accuracy obtained with a MLM is sufficient whenever the inertial effects of the vehicles are of little importance, and therefore the contact forces can be approximated to the nominal axle load of the railway vehicle. This condition is met when the speed of the train does not approach a resonant loading condition [16,17], but must be questioned if resonance is attained and two factors contribute simultaneously: (i) the frequency of the suspended masses of the vehicle approaches the fundamental frequency of the bridge and (ii) the suspended mass is relatively large compared to the bridge mass [14,16,18–20]. Under these conditions the inertial effects of the railway vehicle play a major role and, if VBI is taken into account, reductions up to 30% of the bridge maximum vibration amplitude can be reached according to previous references.

This level of reductions reveals the potential influence of VBI in the verification of the serviceability limit states (SLS), which are

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List of acronyms

ADM	additional damping method
DIM	detailed interaction model
DOF	degrees of freedom
ERRI	European Rail Research Institute
LB	lower bound
MLM	moving load model
SIM	simplified interaction model
SLS	serviceability limit states
SS	simply supported
UB	upper bound
VBI	vehicle–bridge interaction

the most demanding requirements in a large number of situations and become crucial for the design of simply-supported (SS) high-speed railway bridges. The attention of the investigation is focused on the influence of VBI on the vertical acceleration of the deck. This choice is justified by the special relevance of the vertical acceleration as a determinant factor in the design of SS high-speed bridges: the maximum value of this magnitude must be kept under certain limits in order to avoid adverse consequences such as ballast destabilization, risk of derailment, deterioration of passenger comfort and a raise in the maintenance costs.

As an alternative to a coupled vehicle–bridge analysis, Eurocode 1 [9] provides the so-called additional damping method (ADM) in order to incorporate VBI effects in constant load models by increasing the bridge damping in a suitable amount given as a function of the span length. The ADM was formulated by the D-214 Committee of the European Rail Research Institute (ERRI D214) on the basis of the response of an ensemble of SS bridges to the ICE 2 and Eurostar trains; these trains were modelled as series of pairs of single-DOF oscillators, each pair thus representing the effect of one bogie travelling over the bridge. In this vehicle model, referred to as the *simplified interaction model* (SIM), the oscillation of the car-bodies masses is neglected, and the fraction of the bogie mass proportional to each wheelset is assumed to vibrate in a vertical axis on top of the wheel (which implies an approximated representation of the pitching motion of the bogies). The dynamic effects of the car-bodies as well as a proper representation of the bogie pitching motion are both taken into account in the *detailed interaction model* (DIM), in which the bogies and the car-bodies are represented by means of rigid bodies with translational and rotary inertia (see Fig. 1). The DIM is therefore able to reproduce some VBI phenomena which, conversely, are not captured by the SIM, and using the former model is mandatory whenever the riding comfort evaluation of the passengers is required.

The choice of the SIM instead of the DIM for the analysis of a railway bridge usually relies on the absence of dynamic coupling between the car-body and the bridge, derived from the low natural frequency of the first compared with that of the second in most real SS structures [21] (particularly when the focus is on short or medium-span bridges). While this is a reasonable assumption, to date no complete sensitivity analysis has been carried out in order to validate the suitability of each vehicle model. Therefore, an in-depth analysis is required where a wide, representative ensemble of vehicle–bridge combinations is considered and different resonance situations are taken into account.

The aim of this investigation is to come up with meaningful conclusions regarding the conditions under which the bridge response computed with a moving load model may differ significantly from the one computed with a vehicle model of higher complexity. Specifically, this purpose is to be achieved by examination of two principal questions: the first one concerns the deduction of a safe (or *lower bound*) estimation of the interaction benefit; the second one is to determine if the associated reduction of the response is significant enough as to justify the consideration of VBI effects for design or retrofit purposes. The influence of the ballasted track, which also affects the dynamic behaviour of the bridge [22–24], has been taken into account only by means of the associated dead mass added to that of the bridge. This simplification, which is in line with common design practices, is necessary to determine the lower bound estimation of the interaction benefit with the same bases adopted by the ERRI D214 in the formulation of the ADM, and thus allowing a direct comparison of the results. Only the contribution of the bending modes has been considered in all the analysis performed. Therefore, the results of the investigation are restricted to all those structures in which the maximum response can be computed disregarding the contribution of the three dimensional modes. According to Eurocode 1, this

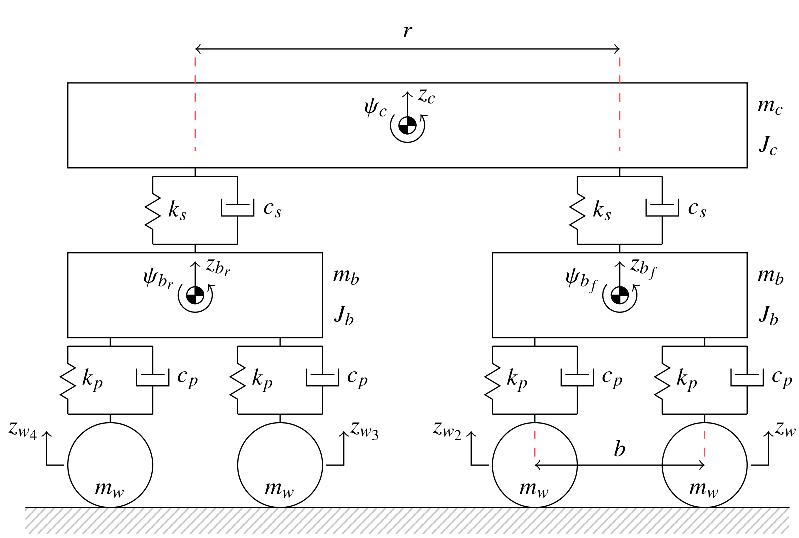

Fig. 1. DIM of a conventional coach.