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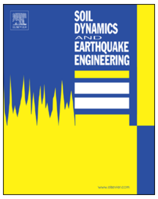

Prediction of railway ground vibrations: Accuracy of a coupled lumped mass model for representing the track/soil interaction

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ABSTRACT

Recent advances in railway-induced ground vibrations showed that the track/soil interaction plays an important role in the low frequency range. This paper contributes to the numerical analysis of train/track/foundation dynamics by presenting the accuracy of a coupled lumped mass (CLM) model devoted to the railway foundations and to the track/soil coupling. Following a summary of the background and the advantages of the CLM model, the coupling strategy is quantified through two application cases. Firstly, the dynamic track deflection is calculated for different railway lines considering various degrees of complexities of foundations. Then, the foundation responses are compared depending on whether detailed coupling is introduced or not. The benefit of the proposed model is emphasized by presenting free-field ground vibration responses generated by a tram and a high-speed train, obtained by a revisited two-step prediction model developed by the authors.

1. Introduction

Research in railway-induced ground vibration models intensified in the past, pressed by the so-called “supercritical phenomenon”, which appears when the vehicle speed is close to the Rayleigh ground wave speed. Abnormal high vibration amplitudes are associated to this phenomenon and corroborated by measurement records in Sweden [1] and in other European countries [2]. More precisely, this phenomenon is relatively uncommon [3] compared to other ground vibration types (e.g. tramway with singular rail surface defect [4]) but it brought out the necessity of taking into account the track/soil coupling in prediction schemes.

The study of track/soil coupling and of the associated degree of dynamic coupling is not recent. The analytical work of Sarfield et al. [5] and Rücker [6] first focused on the possible interaction between the sleepers and the soil of a railtrack without intermediary elements (such as ballast). Their findings were that a coupling effect was observed in track/soil compliance functions, which had several local maxima in relation to the number of sleepers taken into account in the formulation. Several years later, Knothe and Wu [7] proposed a similar study considering a two-layer model, including the ballast as elastic rods. They concluded that track receptances are better predicted at low frequencies when the soil is modelled using a half-space solution rather than Winkler foundation (represented by spring elements). However, the Winkler formulation was used to predict the vibrations generated by high-speed trains (HSTs) with reasonable accuracy [8,9]. This “anomaly” can be explained by the fact that the track is modelled as a continuously supported beam in the Winkler formulation. In the case of tracks defined as discretely supported beam models, no strong coupling is obtained, because the coupling between sleepers is incomplete. To reproduce the full effect, two mechanisms must be allowed (Fig. 1): (i) the transfer of vibrations between sleepers through the rail (top coupling, generally provided in track models) and (ii) the transfer of vibrations through the soil (bottom coupling). In the Winkler formulation, the soil flexibility beneath the sleepers (direct coupling) is included but not the bottom coupling (indirect coupling).

The success of half-space medium, which provides bottom coupling, demonstrates that an accurate prediction model of ground vibrations needs a full coupling between the track subsystem and the subgrade subsystem. Galvín et al. [10] proposed a time domain model that used a coupled finite element/ boundary element method for the three-dimensional analysis of high-speed track–soil dynamic interaction. The same approach was proposed by other authors [11–14] in the frequency domain, which is adapted for the boundary element formulation. To avoid spurious reflections with finite element models, specific boundary conditions were implemented [15–19]. More detailed models include a vehicle. El Kacimi et al. [20] used an in-house coupled train/track/soil model to determine the dynamic response of ground during the passing of

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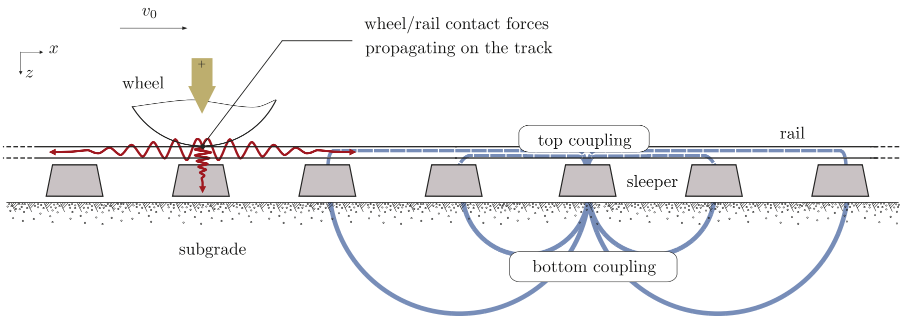

Fig. 1. Two transfers of vibration between sleepers.

a HST. Connolly et al. [21,22] used a similar approach with the commercial finite element software ABAQUS by defining the moving load effect using a subroutine into the main finite element model.

Both frequency and time domain numerical models are challenged by important computational run times, implying that it is difficult to take into account simultaneously all the aspects of ground vibration. Decoupling techniques provide an interesting solution since they calculate the vehicle/track and track/ground responses separately. Gardien and Stuit [16] proposed a specific technique consisting of different modules (or submodels) for each specific application (track static deflection, track dynamic response and ground wave propagation). Another option was presented by Kouroussis et al. [23]. This last one envisions that the vehicle is a complex mechanical system which could influence the track deflection. Proposed as an extension of vehicle dynamic simulation, the methodology relies on a two-step approach: first, the vehicle/track subsystem provides the vertical forces acting on the soil surface and, second, the response of the soil subsystem is determined. Although the soil subsystem needs the use of a commercial finite element software, the vehicle/track simulation can be easily performed within EasyDyn [24], an in-house framework dedicated to dynamic simulations. The model was validated in the case of a tramway [4] and in the case of a high-speed line [25]. However, there is still a need to improve the track/soil coupling which is nearly non existent, since multibody simulation (in vehicle/track subsystem) and the finite element model (soil subsystem) is in effect a decoupled approach. A Winkler hypothesis was considered as a minimal solution but it is well known that it is not effective if the foundation stiffness is low compared to the ballast one [7,23]. However, Winkler and generalized Winkler models are used in many geotechnical applications, and Kouroussis et al. [26] used it as inspiration to develop a spring–damper–mass model, called the coupled lumped mass (CLM) model, in order to more faithfully encompass the track/soil coupling.

This paper presents the revisited model that builds upon [23], adding a CLM model, to improve the prediction of vibration levels. The paper is organized as follows: the next section will briefly introduce the revised two-step approach including the CLM model; then, first simulations of track defection are performed depending on whether flexible foundation is introduced or not; a similar approach is proposed for the track/soil interaction. Finally, the transmission of vibration is analysed in the tramway and in the HST cases.

2. Modelling approach

The two-step railway vibration prediction model [23] aims to predict vibration levels across large sections of track taking into account the vehicle dynamics. It can be used in vehicle design and to identify areas likely to be affected by elevated vibration levels. The simulation is split between the vehicle/track and the track/soil submodels. Detailed vehicle dynamic analyses are possible in the first submodel, which combines a multibody approach for the vehicle and a finite element analysis for the track. The motion is simplified in the vertical plane. The multibody approach is clearly different from the basic principle of describing the soil dynamic behaviour, at least for the generation of equations of motion, which are not necessary to be defined as linear. For these reasons, the second submodel is based on the finite element approach only and calculates ground wave propagation, born from the forces acting on the soil surface (representing the ballast reaction). The latter are calculated in the first step. A more detailed explanation of these submodels can be found in [27]. Fig. 2 summarizes the procedure for the evaluation of ground vibrations. The two subsystems are successively used and solved in the time domain: the vehicle/track simulation considers that the vehicle rides on a flexible track with the foundation being taken into account by the CLM model [26]. The available results comprise all displacements of the vehicle and the track, and forces acting on the foundation. They are the input to the second subsystem modelling the soil (ground waves propagation simulation). Information needed for the simulations is provided by the train constructor (vehicle) and the railway operator (track and soil). If the latter are unavailable, in situ measurement may be performed in order to determine the corresponding dynamic parameters. Notice that parameters needed for the CLM model can be obtained by updating the track receptance or by condensation of the soil coupling, as proposed in [26]. Compared to other works dedicated to vehicle/track simulation (e.g. [28–32]), the proposed track model presents a compact and efficient way to include the track/soil interaction and to fill the error provided by the track/soil decoupling.

Regarding the value of integrating the vehicle dynamics into the ground vibration simulation, several authors recently showed the importance of a detailed vehicle model. In [33], an increase in vibration level was pointed out for stiff primary suspensions and heavier unsprung masses. Kouroussis et al. [34] showed that ground vibration spectra caused by a passing tram presented peaks corresponding to the vehicle bounce and pitch mode eigenfrequencies. Costa et al. [35] advised the consideration of unsprung and semi-sprung (bogies) masses of a train in a prediction model, for a better accuracy of the numerical results. Alexandrou et al. [36] proposed a detailed model of the vehicle and wheel/rail interaction to study the flat wheel effect on ground motion.

Another important question is the choice of a suitable interface for the division into two submodels. Grouping track and soil together might seem convenient due to the ease of connecting two finite element models. However, it is preferable to avoid a split at the wheel/rail interface due to the stiff and moving contact. Additionally, multibody/finite element coupling is quite common in railway dynamics, with various methods (co-simulation [37,38], direct coupling [39,40] or model order reduction [41]).