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Discrete modelling of vertical track–soil coupling for vehicle–track dynamics

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ABSTRACT

This paper presents a coupled lumped mass model (CLM model) for the vertical dynamic coupling of railway track through the soil. The well-known Winkler model and its extensions are analysed and fitted on the result obtained numerically with a finite–infinite element model in order to validate the approach in a preliminary step. A mass–spring–damper system with frequency independent parameters is then proposed for the interaction between the foundations, representing the contact area of the track with the soil. The frequency range of track–soil coupling is typically under 100 Hz. Analytical expressions are derived for calibrating the system model with homogeneous and layered half-spaces. Numerical examples are derived, with emphasis on soil stiffness and layering. The dynamic analysis of a track on various foundation models is compared with a complete track–soil model, showing that the proposed CLM model captures the dynamic interaction of the track with the soil and is reliable to predict the vertical track deflection and the reaction forces acting on the soil surface.

1. Introduction

Dynamic models of railway track are widely used for various applications such as the assessment of stresses on track components, noise emission calculation, or the prediction of ground-borne vibrations. Knothe and Grassie [1] provide a detailed description of these models and a useful classification still applied up to the present time. The assumption of uniform subgrade (railpads and ballast supposed to be continuous along the track) or discrete supports, the adoption of an Euler–bernoulli beam, Timoshenko beam, or a 3D representation define the degree of complexity of the model, depending on the application. For example, the replacement of discrete supports by a continuous layer allows to faithfully to establish the vertical rail deflection solution, whereas the discrete disposition has a non-negligible influence on the definition of the soil loads (sleeper excitation frequency depending on vehicle speed). This particularity has been underlined by Krylov in his ground vibrations prediction model [2].

Another aspect of track modelling is the recognition of the track–soil coupling. Naturally, the dynamic response of the track is largely affected by soil foundation, and track models with rigid foundations cannot be considered accurate. In the case of continuous subgrade, Winkler foundation is totally sufficient. For example, Dieterman and Metrikine [3] propose a continuous model for the rail, using an equivalent elastic foundation for both the ballast and the soil. A forward Fourier transform along the track is adopted to evaluate the coupling between the track and the soil, the latter being modelled as a homogeneous half-space. An equivalent stiffness is derived, showing its dependence on frequency for high-speed loads. Winkler foundation is also used in discrete supports. Zhai and Sun [4] have proposed a detailed model for vertical vehicle–track dynamics, with a complex representation of the ballast, but considering the soil as a Winkler–Voigt foundation. Sarfield et al. [5] and Rücker [6] were the first to study the interaction between the sleepers and the soil through a simple model, without taking into account the ballast. The sleepers were directly connected to the ground, and the importance of such coupling was emphasized for high-speed lines. Analysing the influence of the number of sleeper couplings and soil configuration, Knothe and Wu [7] established that track–soil coupling essentially intervenes in low- and mid-frequency ranges, typically up to 100 Hz. The main conclusion is that the Winkler foundation cannot be used as a half-space model to represent the subgrade in the track model.

Winkler and generalized Winkler models are used however in many geotechnical applications, especially for the dynamic impedance of foundations. Gazetas [8] demonstrated the real efficiency of single degree-of-freedom systems for soil–foundation interaction problems. Advanced representations have been afterwards proposed, as for example the models developed by De Barros and Luco [9], their main difficulty being the identification of model parameters, often performed by fitting results from numerical models or experimental studies. Ju [10] proposed a least-squares

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