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Using three-dimensional finite element analysis in time domain to model railway-induced ground vibrations

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ABSTRACT

For the prediction of ground vibrations generated by railway traffic, finite element analysis (FEA) appears as a competitive alternative to simulation tools based on the boundary element method: it is largely used in industry and does not suffer any limitation regarding soil geometry or material properties. However, boundary conditions must be properly defined along the domain border so as to mimic the effect of infinity for ground wave propagation. This paper presents a full three-dimensional FEA for the prediction of railway ground-borne vibrations. Non-reflecting boundaries are compared to fixed and free boundary conditions, especially concerning their ability to model the soil wave propagation and reflection. Investigations with commercial FEA software ABAQUS are presented also, with the development of an external meshing tool, so as to automatically define the infinite elements at the model boundary. Considering that ground wave propagation is a transient problem, the problem is formulated in the time domain. The influence of the domain dimension and of the element size is analysed and rules are established to optimise accuracy and computational burden. As an example, the structural response of a building is simulated, considering homogeneous or layered soil, during the passage of a tram at constant speed.

1. Introduction

Railway-induced ground-borne vibration has been the subject of many investigations over the last two decades. Many of these have focused on using prediction models, whereby the propagation of ground vibration waves is analysed considering different generation mechanisms (rail deflection, track irregularity, vehicle dynamics, etc.). However the problem of predicting the transmission of vibrations through the ground is complex. Three sources of complexity have been underlined by Gutowski and Dym [1]: the difficulty in precisely modelling the sources of vibration, the lack of understanding of the soil behaviour, and the difficulty in determining accurate values of soil properties. Additionally, in the railway case, the track transmits wheel/rail forces to the ground and must be taken into account.

The modelling of the vibratory source depends on many factors and is not straightforward. The simplest models reduce the vehicle to a set of moving constant loads [2,3]. Analytical developments are still used nowadays for predicting the effect of a moving load on an infinite beam resting on a flexible layer. Initially, models were studied by considering an elastic isotropic homogeneous half-space [4,5]. These works pointed out the harmful effect of train speed when close to the track/soil critical velocities. Advanced formulations have been recently proposed by Koziol et al. [6,7] and offer the possibility to extend this approach to various load configurations and to multilayer subgrade, using a compound wavelet method/coiflet filters. Special attention was paid to numerical optimisations to avoid up numerical instabilities and other calculation difficulties. Other authors, as Lombaert et al. [8], include the effect of the vertical track irregularity through a non-stationary random excitation. More sophisticated models, as those proposed by Garden and Stuit [9] or Costa et al. [10], take into account the dynamics of the vehicle.

The soil behaviour is generally considered as non-linear. Nevertheless, railway traffic generates ground vibration waves whose propagation generally induces small deformations: the shear strain is smaller than 10^{-5} in most practical cases. In this range of deformation amplitudes, the soil can be considered as an isotropic linear viscoelastic medium possibly composed of several homogeneous horizontal layers. This hypothesis was widely validated in literature (see, for example, the works of Sheng et al. [11], Lombaert and Degrande [12], Auersch [13] or Galvín and Domínguez [2]).

The choice of the numerical procedure used to model the soil must be able to efficiently represent infinity. The boundary element method (BEM) is based on an integral transformation that makes it possible to reformulate Navier's elastodynamic equations at the surface. The main difficulty is to determine a particular

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solution (Green's function) for the specific case of the problem (homogeneous or layered soil, loads at the surface or under soil, etc.). BEM is numerically efficient but it is practically limited to linear formulations and simple geometries. The finite element analysis (FEA) is by contrast able to model a soil with complex geometries, insofar as proper conditions are applied on the domain border. Another advantage is that FEA software is well adapted to non-linear problems and is widely used at an industrial scale. Non-reflecting conditions have been recently classified by Wang et al. [14] as elementary boundaries, local boundaries or consistent boundaries. The latter includes the infinite element formulation, which is frequently used in acoustics and is proposed more and more by commercial finite element software packages. In the case of railway, the FEA formulation is usually restricted to two-dimensional analysis (as proposed by Yang et al. [15] or by Yerli et al. [16]) to comply with available computational resources, but recently three-dimensional models have been found in literature. Kouroussis and his co-workers [17,18] have proposed a three-dimensional model using the well-known Lysmer and Kuhlemeyer viscous boundary [19] combined with infinite elements. Connolly et al. [20,21] showed the capabilities of three-dimensional FEA by applying their prediction model for a sensitivity analysis of track embankment or trenches on resulting ground vibrations. To limit the model size, a periodic finite element–boundary element formulation has been recently developed, combining the advantages of these two methods (boundary elements for subdomain infinite formulation, finite element for the studied structures) and applicable for geometry invariant along the track direction. Efficient examples have been proposed by Degrande et al. [22] and Chebli et al. [23] for studying the ground vibration generated by ballasted railway track or shallow tunnel track.

Most often, despite the importance of the vehicle dynamics, only the track/soil configuration is considered. This approach makes it possible to understand the soil behaviour but cannot be used by the train constructors to verify the influence of some vehicle components. Moreover the possible coupling between the subsystems is neglected in the analyses. Kouroussis et al. [17] presented a comprehensive study of vehicle/track influence with the aid of a compound vehicle/track/soil model. Special attention was paid to the excitation mechanism, considering the track and the vehicle behaviour on the forces transmitted to the soil. The results showed that the ground vibration level strongly depends on the vehicle configuration. It was also recognised that soil layering induces soil surface vibrations that can be completely different from those obtained in the case of a homogeneous half-space.

This paper is an updated and revised version of the conference paper [24]. The use of this finite/infinite element model is discussed. Some properties of non-reflecting boundaries are presented. Viscous boundaries are analysed in order to demonstrate their efficiency on soil modelling and to show the conditions that lead to the best wave absorption. Rules in frequency and time domain analysis are also given, before presenting the detailed implementation of the model. Practical applications are presented, based on the passing of a tram on a singular defect. Free field responses are analysed, as well as the structural response of a building placed near the track, illustrating the possibilities of the proposed methodology and the interest of the FEA.

2. Soil dynamics – considerations

The simulation of unbounded domains in numerical methods is a very important topic in dynamic soil–structure interaction and wave propagation problems. The frequency range depends on the purpose of the problem. If the dweller's comfort or structural integrity is of interest, frequencies up to 80 Hz are important with a particular attention in the range between 5 and 20 Hz, according to the standard references. Higher frequencies are attenuated by the soil.

When the soil is modelled as an elastic, homogeneous and isotropic medium, the wave field can be expressed as a superposition of plane waves [1], of two types: longitudinal waves (or *P*-waves) where the particle motion takes place in the direction of wave propagation, and shear waves (*S*-waves), moving perpendicularly to their propagation direction. The wave velocities c_P and c_S are given by

$$c_P = \sqrt{\frac{2G(1-\nu)}{\rho(1-2\nu)}} \tag{1}$$

and

$$c_S = \sqrt{\frac{G}{\rho}} \tag{2}$$

where G, ν and ρ are the shear modulus, the Poisson's ratio and the density of the medium, respectively. Along the surface, additional waves, called Rayleigh waves, can develop in the case where shear waves reflect free surface. These waves propagate in the horizontal direction and their amplitude decreases exponentially with the depth. It is known that the *P*-wave is the fastest, followed the *S*-wave, itself a bit faster than the Rayleigh wave. In terms of transmitted energy, it is the opposite: in the case of a vertical concentrated load acting on the soil surface, the Rayleigh wave transports 67% of the total energy [25].

In the case of layered media, reflection and refraction increase the problem complexity. Each layer can be defined by the body waves but the surface waves in layered media are dispersive. The frequency dependent phase velocities of the different vibration modes of the layered medium are therefore considered, depending on the configuration and the thickness of each layer. For this configuration, the use of numerical tools becomes necessary.

3. General description of the proposed model

A prediction model [26] has been developed, working in two successive steps (Fig. 1). The first step is based on the philosophy adopted by the train constructor where the vehicle is modelled using a classical multibody approach. Carbodies and bogie frames are defined as rigid bodies linked by interconnecting elements (springs and dampers) representing the suspension. As the vertical motion has a significant effect on ground vibrations, a two-dimensional model of the vehicle is sufficient at this stage. It is connected to the track, itself modelled by a classical 2D and 2-layer model, in accordance with the reviews of Grassie et al. [27] and Knothe and Grassie [28]. The rail is discretely supported by rigid sleepers. The flexible rail, defined by its Young modulus E_r, its geometrical inertia I_r, its section A_r and its density ρ_r, is described using the finite element method. A spacing L of the sleepers has been considered, with a discretization of N_n elements for one sleeper spacing. Railpads and ballast are characterised by springs and dampers (k_p and d_p for the railpad, k_b and d_b for the ballast). Each sleeper is defined as a lumped mass m. The vehicle/track interaction is characterised by the contact law, defined as non-linear. The defect on the rail surface is also considered as a local unevenness and/or an overall roughness and can be represented by any kind of deterministic functions. The integration of the equations of motion is performed with the home-made C++ library, EasyDyn, dedicated to second-order differential equations and multibody problems [29,30].

The second step considers the reaction forces of the ballast as the loads acting at the surface of the soil. It uses FEA to calculate