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A mixed space-time and wavenumber-frequency domain procedure for modelling ground vibration from surface railway tracks

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ABSTRACT

This paper presents a methodology for studying ground vibration in which the railway track is modelled in the space-time domain using the finite element method (FEM) and, for faster computation, discretisation of the ground using either FEM or the boundary element method (BEM) is avoided by modelling it in the wavenumber-frequency domain. The railway track is coupled to the ground through a series of rectangular strips located at the surface of the ground; their vertical interaction is described by a frequency-dependent dynamic stiffness matrix whose elements are represented by discrete lumped parameter models. The effectiveness of this approach is assessed firstly through frequency domain analysis using as excitation a stationary harmonic load applied on the rail. The interaction forces at the ballast/ground interface are calculated using the FE track model in the space-time domain, transformed to the wavenumber domain, and used as input to the ground model for calculating vibration in the free field. Additionally, time domain simulations are also performed with the inclusion of nonlinear track parameters. Results are presented for the coupled track/ground model in terms of time histories and frequency spectra for the track vibration, interaction forces and free-field ground vibration. For the linear track model, the results from the mixed formulation are in excellent agreement with those from a semi-analytical model formulated in the wavenumber-frequency domain, particularly in the vicinity of the loading point. The accuracy of the mixed formulation away from the excitation point depends strongly on the inclusion of through-ground coupling in the lumped parameter model, which has been found to be necessary for both track dynamics and ground vibration predictions.

1. Introduction

The numerical modelling of ground vibration from surface railways has been the focus of much research over the years. When linear parameters are used for the track and ground, the modelling can be readily done in the frequency-wavenumber domain. Sheng et al. [1] studied ground vibration generated by a stationary harmonic load acting on a railway track using a

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transformation into the frequency-wavenumber domain. The track was modelled as infinite layered beams that are coupled to a horizontally layered ground. This methodology was applied to the case of a load [2] and a train [3] moving along a railway track. These models are based on the assumption that the track geometry is longitudinally invariant, in addition to the assumption of linearity.

However, when complex irregular geometries are to be modelled, more complex approaches such as Finite Elements (FE) and Boundary Elements (BE) are necessary for this problem. These approaches include the so-called two-and-a-half dimensional (2.5D) approach [4–6], widely used to discretise the cross-section of track and ground, with the longitudinal dimension modelled in the wavenumber domain. Fully three dimensional FE models or coupled FE-BE models in the time domain [7] are required when nonlinear track or soil components [8] are to be included. The use of FE and BE methods in numerical analyses can be very costly in terms of the computational hardware and the time required for the simulations. This is mainly due to the large number of elements required to discretise the ground, particularly in the 3D case.

An alternative, which is widely used in soil-structure interaction problems, e.g. the vibration of machine foundations on a half-space or layered ground [9], is to represent the ground by approximate lumped parameter models consisting of spring, dashpot, and in some cases mass elements. This approach has been applied to ground vibration from surface trains in [10,11]. The lumped parameter model was formulated based on Lysmer's analogue fitting which, due to its simplicity, is mostly accurate for modelling the asymptotic values of the dynamic stiffness at low and high frequencies, without capturing mid frequency fluctuations. Triepaischajonsak and Thompson [12] presented a hybrid modelling approach for predicting ground vibration from trains, whereby the track is modelled in the time domain and the ground in the frequency domain. The transfer mobilities of a layered ground were calculated using the dynamic stiffness method [13] for a harmonic load distributed over a circular area at the surface. The effect of the ground was incorporated into the track model by connecting the sleepers to a series of equivalent spring-dashpot systems, the properties of which were obtained by curve fitting the combined ballast/ground dynamic stiffness that makes use of the ground mobilities. In this study, however, the effect of through-ground coupling was not considered. Another hybrid model was presented by Nielsen et al. [14] for predicting ground vibration due to discrete wheel-rail irregularities. The DIFF model [15], which is based in the time domain, was used to obtain the transient wheel-rail contact force and the TRAFFIC model [16], formulated in the frequency-wavenumber domain, utilised this as input to predict the track and ground vibration. The ground was included in DIFF using discrete spring-dashpot-mass systems tuned to minimise the differences in the track receptance computed using DIFF and TRAFFIC.

Wolf [17,18] presented a systematic procedure for formulating consistent lumped parameter models with real frequency-independent coefficients to represent an unbounded soil medium. In this method, each dynamic stiffness component in the frequency domain, e.g. the vertical stiffness due to a vertical load, can be represented in discrete form as a rational fraction. This is subsequently decomposed into singular, first- and second-order regular parts, depending on the nature of the roots of the rational fraction. These models can provide a high degree of accuracy when sufficiently high order of approximating polynomials are used. They also have the advantage that they can be incorporated into standard FE/BE routines for soil-structure interaction, allowing nonlinear parameters to be readily included in the structure. Damgaard et al. [19,20] applied this approach to study the dynamic soil-structure interaction of offshore wind turbines on gravity footings and monopiles.

The main purpose of this paper is to develop a procedure for studying railway track dynamics that makes use of both space-time and wavenumber-frequency techniques. The railway track is modelled in the space-time domain using the FE method, whilst the ground is modelled in the frequency-wavenumber domain. The railway track and ground are coupled through a series of rectangular strips located at the surface of the ground; their vertical interaction is described by a frequency-dependent dynamic stiffness matrix whose elements are represented by discrete lumped parameter models [17,18]. The framework for deriving this dynamic stiffness matrix is developed, and an iterative curve-fitting routine is adopted to obtain the parameters required to formulate the lumped parameter models. Through-ground coupling in the track/ground model is included within this framework, and the effect of this on ground vibration is also investigated. The mixed formulation is assessed using both frequency and time domain analyses and for linear and nonlinear track parameters. Subsequently, the interaction forces at the ballast/ground interface are calculated in the space-time domain, transformed to the wavenumber domain, and used as input to the ground model for calculating the vibration in the free field.

The dynamic stiffness matrix is derived in Section 2 while the corresponding discrete lumped parameter models that represent it are systematically formulated in Section 3. Section 4 presents an example application of the lumped parameter model to study the dynamic interaction between three rectangular strips. The FE track model is introduced in Section 5 and the procedure for calculating the ballast/ground interaction force is described in Section 6 together with the wavenumber domain transformation and subsequent use as input for free-field ground vibration calculations. A frequency domain analysis is conducted in Section 7 with results presented as frequency spectra for the track vibration, interaction forces and free-field ground vibration. Finally, to demonstrate the application of the mixed formulation, time domain simulations are performed in Section 8 for both linear and nonlinear track models.

2. Wavenumber-frequency domain modelling of the ground

The ground vibration due to a harmonic load distributed over a rectangular strip at the ground surface was studied by Jones et al. [21]. In this section, this formulation will be extended to account for the interaction between multiple rectangular strips.