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A fast random method for three-dimensional analysis of train-track-soil dynamic interaction

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ABSTRACT

A fast computation method that can be used for efficient analysis of full scale three-dimensional random vibrations induced by railway traffic is presented in this paper. The method uses the pseudo-excitation method (PEM) for random analysis and the proposed multi-point synchronous algorithm (MPSA) for solution of the large sparse linear equations of the train-track-soil coupled system (TTSCS). A mixed two- and three-dimensional TTSCS model is established firstly. Based on the linear Hertzian wheel/rail contact relationship, the time-dependent equations of motion of the TTSCS are deduced. This formulation leads to a global system of equations that can be solved in a directional manner without the need for iterative processes. By means of the PEM, the self-excitation induced by the random track irregularity is transformed into a series of deterministic harmonic excitation vectors. To accelerate the computation, a fast computation strategy is proposed. In the numerical example, the proposed method is validated through comparison with field measured results. Comparison of the results of the MPSA with those of the triangular factorization algorithm and ANSYS is undertaken to evaluate the efficiency of the MPSA. It is confirmed that the MPSA can result in a five- to tenfold increase in computation efficiency.

1. Introduction

With the development of high-speed railways and urban rail transit systems, the impact of induced environmental vibrations on working and living environments is considered a critical social issue [1]. Thus, study of the vibrations induced by railway traffic is important, especially during the design and planning stages for new lines or the renewal of existing lines.

Over the past decades, various models have been developed to predict the generation and propagation of ground vibration due to a moving train. Most of the early work was based on analytical [2] or semi-analytical [3] approaches to the solution of ground vibrations induced by moving loads, with unavoidable simplifications. In fact, many of these solutions did not permit the derivation of general formulations capable of dealing with the complex geometries usually encountered in practical applications [4]. With the rapid development in computation technologies, numerical approaches have been developed based on the finite element method (FEM) [5–9], the finite/infinite element method [10–12], the boundary element method (BEM) [13,14], the hybrid FEM/BEM and the finite difference method [15,16] to solve the combined dynamic interaction of a train and railway substructure. Various numerical models have been developed in this regard, including 2D models [11,17], 2.5D models [10,18] and 3D models [12,15,16]. Although 2D and 2.5D models require less computation effort, their application is limited to cases in which it is reasonable to assume longitudinal invariance or periodicity of the track-soil system [19].

As an alternative, 3D models can take into account local soil discontinuities, underground constructions such as underpasses, as well as coupling with nearby structures that break the uniformity of the geometry along the track line [16]. In this regard, a track-embankment-ground system was modeled by Hall in [5] using a 3D FEM and the numerical results were compared with field measurements for a high-speed train within different speed ranges. A 3D finite element (FE)

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analysis was presented by Powrie [9] to investigate the stress path of a soil unit beneath a ballasted railway track during train passage. However, static or moving point loads were used as train loads in these studies and therefore it was not possible to consider the wheel-rail dynamic interaction. O'Brien et al. [6] and Galvín et al. [16] used a coupled 3D FEM/BEM approach in which the track was modeled using FEM and the unbounded domain was accounted for by BEM to predict ground vibration. However, the BEM submodel was dependent on the Green's function of the medium, such that only a limited range of soil characteristics could be considered. Two-stepped numerical procedures using a 3D finite element/infinite element model were presented by Kouroussis et al. [20], El Kacimi et al. [7], and Zhai et al. [8] to predict the free field vibrations caused by high-speed trains. Although this approach was capable of simulating quasi-static and dynamic excitation mechanisms, the models were solved independently and therefore only first order interaction effects were accounted for. More versatile, implicit 3D FE models were proposed by Connolly et al. [4] and El Kacimi et al. [7] to investigate the propagation and transmission of ground vibration induced by high-speed trains. In this review, a common challenge of 3D FE approaches was the large amount of computation, especially for a coupled train-track-soil system. It was reported that, to model train-induced ground vibrations, a 3D FE analysis in the time domain based on the commercial software ABAQUS, PLAXIS, and ANSYS requires at least 30 h for each simulation scenario, using a personal computer.

The aforementioned studies have mainly focused on deterministic problems of dynamic responses in which both the system models and the loads are given in prescribed forms. Actually, the moving loads produced by trains are associated with random characteristics due to track irregularity and other uncertainties, and hence the vibration at any specific ground location induced by a moving train is a nonstationary, random process [21]. Track irregularities are generally regarded as one of the most important sources of railway induced ground vibration and often as the only excitation mechanism considered in addition to quasi-static excitation [22]. It is noted in other study [23] that track irregularity can generate high-frequency vibrations and such vibrations cannot be ignored in design practice. Therefore, a reasonable simulation of the wave propagation behaviors of soils induced by moving trains requires the inclusion of the dynamic contact or interaction forces generated by the train wheels moving over rails with irregular surface. To solve such problems is quite challenging, especially in 3D cases, and the computation efficiency is very low for obtaining the second-order statistics of the random responses by conventional computational methods such as the Monte Carlo method [21]. For this purpose, the pseudo-excitation method (PEM), as an efficient and reliable random vibration method, is well established to analyze the responses of system under stationary or nonstationary random excitations [24]. In the PEM, the stationary random vibration analysis is translated into a harmonic analysis and therefore the nonstationary random vibration analysis is transformed into a deterministic transient analysis that can be solved using direct dynamic integration methods [25]. The PEM has been successfully applied in train-structure coupled random vibration analyses and it has been demonstrated that computational efficiency is improved by 1–2 orders compared with the Monte Carlo method [26–29]. Although a few studies have investigated solving stochastic dynamic responses of soil subjected to moving trains [3,21,26,30,31], these works are either based on analytical/semi-analytical solutions or treat the geometry of the track and soil homogeneous along the track. There are very limited works concentrated on random ground vibration by using the 3D models.

Considering the flexibility of the FEM for the 3D coupled train-track-soil system and the computational efficiency of the PEM, these two methods are integrated for nonstationary ground stochastic vibration analysis. However, the strategy of integrating FEM and PEM is still generally challenging for personal computers because of the large-scale degrees of freedom (DOFs) of the 3D model and the large number of equations of motion of the TTSCS under different frequency points. This becomes the main difficulty in the application of the 3D coupled train-track-soil model in nonstationary random response analysis. The objective of this paper is to present an efficient computation strategy for combining 3D FEM and PEM in the prediction of random vibration of the TTSCS. The contributions and advantages of the proposed efficient stochastic analysis in this paper include:

1) A method used for calculating the nonstationary random ground vibration caused by a moving train is proposed based on the 3D FEM, which can take into account local soil discontinuities, underground constructions such as underpasses, as well as coupling with nearby structures that break the uniformity of the geometry along the track line.
2) A fast calculation algorithm is proposed which make the 3D random ground vibration could be implemented in a personal computer. It is time consuming for random ground vibration analysis by using the 3D approach. In order to save computational effort, an efficient random vibration theory – PEM is adopted to derivate the TTSCS random vibration formulation. Moreover, a multi-point synchronous algorithm (MPSA) for the solution of the large sparse linear equations of motion for the TTSCS is proposed, which could save the calculational effort to a large extent.
3) Taking a CRH3-type train traveling across a slab track-embankment-ground section in China as an example, the proposed method is validated through comparison with field measured results. Comparison of the results of the MPSA with those of the triangular factorization algorithm (TFA) and ANSYS is undertaken to evaluate the efficiency of the MPSA.

2. Modeling and formulation for the TTSCS

The ground vibration induced by moving trains includes a variety of excitation mechanisms: the quasi-static contribution (forces generated by moving axle loads), the parametric excitation due to discrete supports of the rails, the transient excitation due to rail joints and wheel flats, and the excitation due to wheel and rail roughness and track unevenness [32]. In the context of ground railway transportation, a train-slab track-embankment-ground analysis model is shown in Fig. 1, where the TTSCS consists of two subsystems, the train subsystem modeled by simple-rigid-body dynamics theory and the track-soil subsystem simulated by FEM. The two subsystems are coupled as an integrated system through the linear wheel-rail interaction relationship.

2.1. Train model

As shown in Fig. 2, a railway train can in most cases be modeled as a series of identical 4-wheel vehicles moving along a track with random track irregularity at a constant speed v. Each vehicle is treated as a simple-rigid-body model consisting of a car body, two bogies, four wheelsets, four primary suspensions, and two secondary suspensions. The car body and two bogies are connected through the secondary suspension, and two wheelsets are linked with the same bogie through

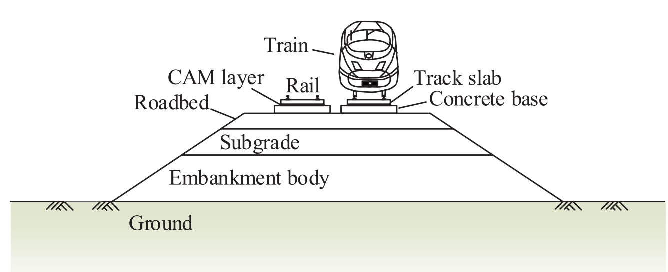

Fig. 1. Train-track-soil coupled model.