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Track-ground vibrations induced by railway traffic: experimental validation of a 3D numerical model

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ABSTRACT

This paper presents a numerical model that can be used to perform a fully three-dimensional analysis of problems involving vibrations induced by railway traffic, taking into account the dynamic interaction of the vehicle-structure-ground system. The structure and the vehicle are modelled with finite elements, while the behaviour of the ground is described by its Green's functions. It is a particular case of a FEM/BEM coupling, in the time domain, wherein the structure modelled with finite elements lays on the surface of the ground. The dynamic analysis of the system results from the direct and efficient calculation of a single system of equations. The validation of the proposed model is based on the results of an experimental campaign developed in a stretch of the Portuguese railway network. The vibrations generated by one passage of the Alfa Pendular train are analysed and a good agreement between measured and calculated responses is achieved.

1. Introduction

Due to its several benefits, such as economic, social and environmental [1], railway systems are actually one of the most efficient transportation systems. Despite these benefits, some problems associated to its implementation and operation must be considered. Among this range of issues, it is important to point out the vibrations generated by railway traffic. In fact, these vibrations propagate through the surrounding ground and may affect the buildings in the vicinity of the track. While the occurrence of building damages is not expected (at least not in structural terms), the impact of vibrations on occupant comfort and on the operation of sensitive equipment has caused some concerns, partly as a result of an increasingly demanding society.

Thus, the study of the vibrations induced by railway traffic is extremely important, especially when the construction of new lines or the renewal of existing lines is planned. Such analysis requires the development of adequate tools, which allow the timely identification of problematic situations and the study of appropriate mitigation solutions.

Over the past two decades, the technical and scientific community has paid a special attention to this issue, which enabled the development of several models: empirical, semi-analytical and numerical, occasionally supported by experimental works.

The empirical models usually provide good results [2,3]. Nevertheless, they present a certain lack of versatility, since their field of application is normally limited to scenarios that are similar to those for which they were developed.

The analytical or semi-analytical models are quite useful, as a result of: i) their efficiency from a computational point of view; ii) their potential in the identification of the key parameters involved in the phenomenon as well as their influence [4–7]. Nevertheless, the application of these models still presents some limitations from a practical point of view, due to their difficulty in simulating real scenarios.

The versatility of the numerical methodologies often allows overcoming some of the limitations of the semi-analytical formulations and studying the phenomenon in a more realistic way. In this manner, a significant progress has been observed in recent years in what concerns the development and application of these tools, for which the fast growth of available computational resources has greatly contributed.

The developed methodologies are often based on the Finite Element Method (FEM), a very popular and attractive tool, which enables the analysis of systems with complex geometries. However, despite its extreme usefulness, the FEM presents some limitations in the simulation of undefined mediums. In these cases, some additional caution at the artificial boundaries (resulting from the impossibility to model the entire domain) is needed, in order to prevent the occurrence of spurious reflections that may disturb the response of the modelled part. The problems associated with spurious reflections can be minimized (but not fully solved) through local methods, such as: absorbing

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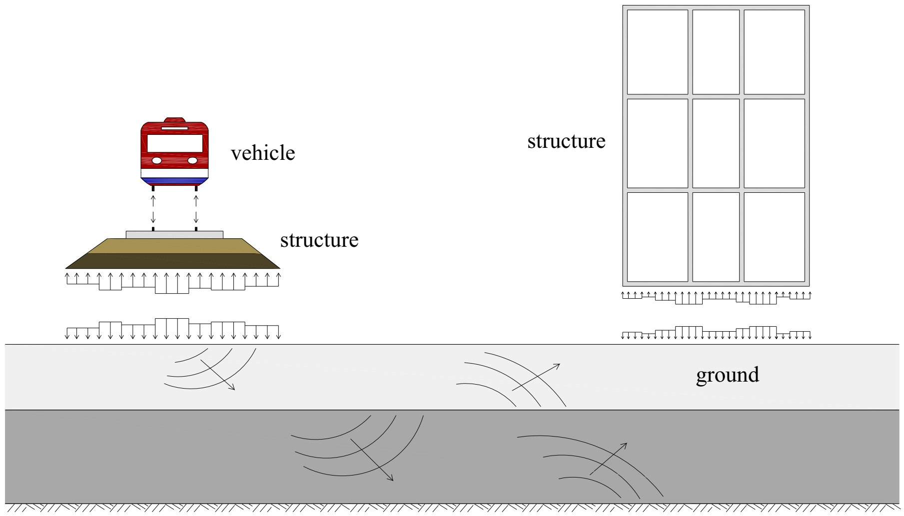

Fig. 1. Vehicle-structure-ground system.

boundaries [8,9], infinite elements [10] or absorbing layers, namely PML [11–13]. Alternatively, this problem can be solved in a more accurate and sophisticated way, using general procedures such as the Boundary Element Method (BEM) [14].

In fact, the phenomenon under study is clearly three-dimensional. However, despite the potential of currently available computers, its study using fully 3D formulations is still extremely difficult from a computational point of view. Alternatively, some authors propose the use of methodologies based on an invariance along the longitudinal direction of the track, which are usually called 2.5D [15]. Noteworthy in this context are the methods based on the use of the 2.5D FEM, in which the treatment of the boundaries often achieved through the coupling with the BEM [16,17] or through the introduction of infinite elements [18] or PML [19]. Some other authors suggest the consideration of a periodicity of the system in the longitudinal direction of the track, which leads to a study based on a reference cell [20,21].

Both referred formulations lead to efficient and appealing procedures from a computational point of view. However, their application is limited to the study of problems where it is reasonable to assume such invariance or periodicity. The study of scenarios where this is unreasonable requires the use of three-dimensional models.

In what concerns 3D approaches, the attempts of [22] and [23] appeared at a time when the available computers did not allow the application of these tools to real scenarios. Later on, Galvin presented relevant works, based on a FEM/BEM coupling formulated in time domain: at first, taking into account only the quasi-static component of the excitation [24] and, later on, also considering its dynamic component [25]. More recently, several models have been proposed by other authors, often based on the FEM and using different solutions for the treatment of artificial boundaries [26–28].

The experimental evaluation of the vibrations induced by railway traffic is fundamental for a better understanding of the phenomenon as well as for the validation of the developed models. In fact, it is possible to find some case studies in the literature [29–34] but the complete information that is needed for the correct simulation of the problem is not always available.

This paper presents a numerical model that allows a fully three-dimensional analysis of problems involving vibrations induced by railway traffic, taking into account the dynamic interaction of the vehicle-structure-ground system. The presented model is based on the proposal from [22] and consists on the description of the ground through Green functions and on the simulation of the structure and the vehicle using finite elements. This is a particular case of FEM/BEM coupling, formulated in the time domain, where the structure that is modelled with finite elements lays on the surface of the ground. On one hand, the presented model enables the opportunity to study the ground in a more realistic way (as a layered halfspace) and to consider the dynamic interaction between vehicle and structure using a very efficient procedure. On the other hand, the evolution of the available computational resources enables its application to a case study.

In order to validate the proposed model, a detailed experimental campaign was performed in a renovated section of the Portuguese railway network: Carregado test site [35]. The experimental work consisted of three components that complement each other: i) the characterization of the ground; ii) the characterization of the track; iii) the measurement of the vibrations induced by railway traffic. The characterization of the track-ground system was essential at a first stage, simplifying the development and allowing the calibration of the model used in the simulation of the case study. Once the model was calibrated, the study of the vibrations generated on the track and at the surface of the ground by the passage of an Alfa Pendular train was performed. The comparison between measured and calculated results enabled the experimental validation of the numerical model.

2. Model for the analysis of the vehicle-structure-ground interaction

2.1. Generalities

The proposed model enables a three-dimensional analysis of problems involving vibrations induced by railway traffic, taking into account the dynamic interaction of the vehicle-structure-ground system (Fig. 1).

The model is based on the description of the behaviour of the ground through its Green's functions and on the simulation of the structure and the vehicle using the finite element method. This is a particular case of a FEM/BEM coupling, formulated in the time domain, where the structure modelled with finite elements lays on the surface of the ground [22]. Note that, in this work, the term structure represents any motionless system set on the surface of the ground. Therefore, it can correspond to the track, as well as to any building or structure in its vicinity.

The simulation of the vehicle and the structure using finite elements is justified by the possibility to develop models with different complexities, according to each problem. On the other hand, the description of the dynamic behaviour of the ground through the fundamental solutions allows an appropriate reproduction of its response, taking into account the radiation conditions at infinity.