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VIBWAY: A user-friendly computational tool for the prediction of railway-induced ground-borne noise and vibration

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ABSTRACT

This paper aims to introduce preliminary statement of methods of a computationally efficient and

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user-friendly toolbox, called VIBWAY, able to predict vibration and re-radiated noise levels in two situations. On the one hand, it can predict levels in existing buildings due to new lines or after the application of mitigation measures in existing operational railway infrastructures. Thus, it can be used to assess the performance of vibration countermeasures applied at the track, at the soil and/or at the building. On the other hand, it allows for the prediction of the response of new buildings to be constructed close to an existing railway line from vibration measurements in the surface of the ground where the building will be constructed. The VIBWAY toolbox is based on a non-interface 2.5D FEM-SBM approach for the wave propagation on the soil, on semi-analytical approaches for the track and the building and on rigid multibody dynamics modelling of the train vehicle.

1. INTRODUCTION

Urban and intercity railways has grown considerably the last decade. In cities, new lines have been constructed with the objective of reducing the urban traffic congestion, consequently mitigating the levels of air pollution. However, the growth of the railway urban networks also implies an increase of the noise pollution induced by the train operations. During the years, old at-grade lines has been transformed into underground systems, reducing the significance of the airborne noise induced problems in cities. In contrast, due to this shift from the at-grade to the underground space, the railway-induced ground-borne noise and vibration issue is rapidly arising, specially in heavily populated areas. Ground-borne noise and vibration induced by railway traffic may cause some severe annoyance on the residents of the surrounding buildings, it could induce malfunction of precision equipment and may even affect the integrity of structures such as old residential buildings and heritage structures. Thus, local authorities have implemented regulations to control this problem by imposing limits for noise and vibration levels in residential buildings, hospitals or other sensitive facilities. To assess the accomplishment of this noise and vibration regulations, reliable and practical predictive models are required: they should be flexible enough to deal with the main types of railway tracks, railway vehicles, soil profiles, buildings and facilities, and it is highly desirable that they avoid excessive both engineering and computational costs.

To build a prediction toolbox for railway-induced ground-borne vibration, several methods can be used to model the subsystems of a railway infrastructure, which are generally categorized as numerical, semi-analytical and empirical approaches [1]. This list should be lengthened by including hybrid approaches that combine experimental measurements with numerical modelling, which have been also proposed by numerous authors [2–5].

In the framework of numerical models, there are different existing modelling alternatives which can provide a reasonable degree of accuracy despite of the structural complexity of the problem [6–8]. However, the use of numerical approaches to model the full system under study in the context of a railway-induced ground-borne noise and vibration prediction toolbox has two main drawbacks: the computational costs and the need for an highly experienced user. Thus, alternative proposals has appeared during last years in which these numerical approaches are used indirectly to create a database of synthetic vibration data to be used for scoping modelling purposes. This approach has proposed by Connolly et al. [9] in the context of a prediction tool for high-speed railway lines. In that work, the database is constructed considering practical ranges for the values of the most dominant factors regarding the wave propagation problem in the soil. A machine learning approach based on this database allows for determining the response of the system in particular scenarios. Regarding the modelling approaches for railway subsystems, another alternative that stands out because of their computational benefits is the semi-analytical modelling. In this category, probably the most well-established models for at-grade and underground railways are the one presented by Sheng et al. [10] and the Pipe-in-Pipe (PiP) model [11, 12], respectively. These models are included in the prediction tool MOTIV [13].

In this paper, the last features of the recently developed VIBWAY tool are described. The tool has moved to a more numerical conceptualisation regarding the simulation of the wave propagation along the track embankment and the soil, discarding their previous fully semi-analytical nature [14]. Although this transformation could lead to a significant increment on the computational requirements of the tool, the use of meshless methods for the wave propagation simulation has allowed for mitigating this problem. Due to the new operational perspective, the flexibility and accuracy on the prediction of the tool has been enhanced, whilst keeping the computational efficiency at a reasonable level. Also, thanks to the new possibilities of the tool on modelling specific tunnel and embankment geometries, the practicality for technical users has been boosted. The VIBWAY software can deal nowadays with three types of situations: assessment of a new railway line to be constructed, prediction of the ground-borne noise and vibration levels on new buildings due to operational railway lines, and the assessment of vibration countermeasures such as track modification, vibration isolation screens and building base isolation.

2. MODELLING STRATEGIES

In the following, the global and particular modelling strategies considered in VIBWAY are explained. Dynamic models of the railway vehicle, the train, the track, the embankment or the tunnel (for at-grade or underground railway systems, respectively), the soil and the building are described, as well as the strategies to obtain the response of the train in the evaluation points defined by the used. Coupling conditions between models are also elaborated in order to provide a general view of tool.

2.1. Track-tunnel-soil or track-embankment-soil model

Due to the complexity of the wave propagation problem in the soil due to railway tunnels or at-grade tracks, the model of these subsystems is the most expensive one in terms of computational effort. Thus, it plays a central role in VIBWAY. The modelling strategy considered in the software to deal with this phenomenon is based on the finite element method (FEM), to model the structure, and the singular boundary method (SBM), to model the soil in where it is embedded. This method is formulated in the two-and-a-half-dimensional (2.5D) domain and receive the name 2.5D FEM-SBM [15]. For underground railway infrastructures, the structure is referred to the tunnel structure together with the track embankment, whilst for at-grade tracks the structure is just the track embankment. Ballasted and direct slab tracks are included on these structures and they are consequently modelled with the 2.5D FEM. Only the rails and floating slabs are considered differently. Rails are modelled by infinite Euler-Bernoulli beams that are attached to the rest of the system using a coupling strategy presented in [16]. Floating slab tracks are also modelled independently of the FEM-structure by considering a longitudinally infinite plate with two rails attached.

To simplify the experience of the user, the FEM mesh of the embankment or the tunnel structure is generated using the Delaunay-based mesh generation algorithm presented in [17]. Thanks to that, the user define those structures by simply their basic dimensions and properties. For example, a circular tunnel is just defined by the tunnel external radius, the thickness of the tunnel wall and the height of the tunnel invert. Figure 1 shows automatically generated meshes for a circular and a cut-and-cover tunnels, the two types of tunnels considered within the tool.

2.2. Building model

In order to model the building and its coupling with the ground, VIBWAY employs a modular strategy to construct the building model simply based on Euler-Bernoulli beams and flexural plates. Again, the objective is that the user could define the complete geometry of the problem in hands only using values of various basic geometrical parameters. The basic modelling strategy for the building is described in Clot et al. [18]. The idea is to construct the building model using rectangular plates

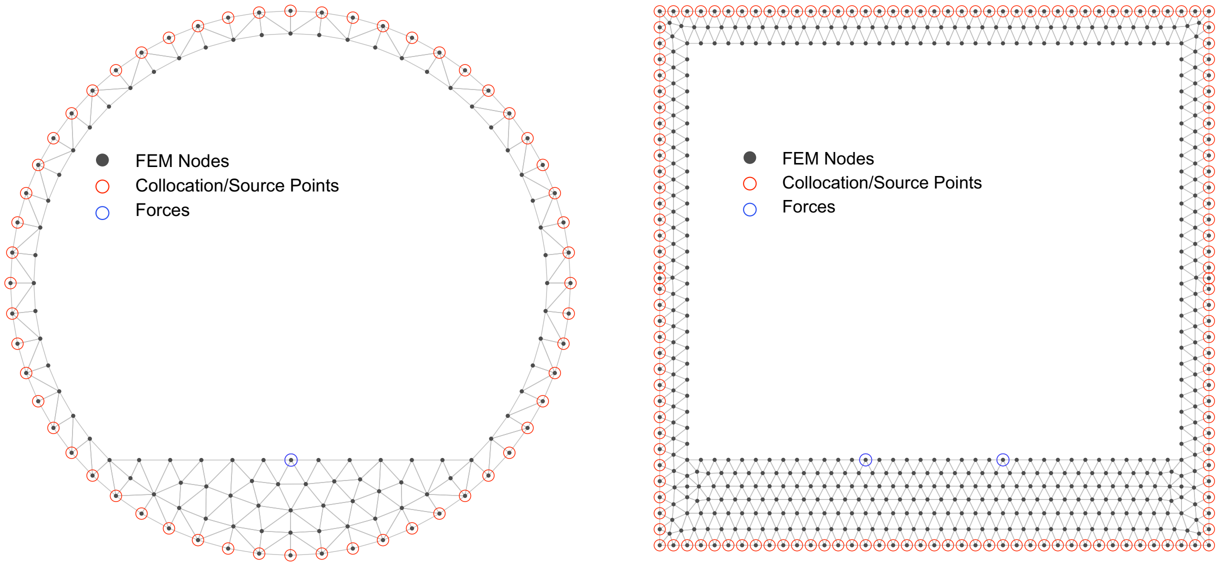

Figure 1: Examples of automatically created meshes for the case of a circular tunnel (left) and a cut-and-cover tunnel (right).

as models of the floors connected between them by a regular distribution of columns. Three new features are included in the building model of VIBWAY with respect to the Clot's proposal. On the one hand, interaction moments between the columns and the floors are accounted for. On the other hand, primary and secondary beams are incorporated in the model. Furthermore, VIBWAY also incorporates the option of determining the re-radiated noise in the rooms of the building if the user defines the type of building enclosures to be installed.

This building model is coupled to the soil through the foundations of the building. For shallow foundations, the proposal of Bucinskas and Andersen [19] is adopted, whilst for piled foundations, a novel methodology based on a Euler-Bernoulli model of the pile embedded in the soil is employed (see Figure 2). The main particularity of this methodology is that it accounts for the interaction moments between the pile and the soil and that it considers the SBM to account for the soil system, resulting in an accurate and efficient method.

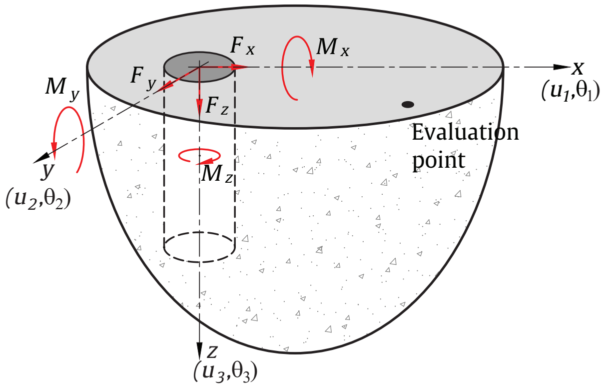

Figure 2: Model of a single pile embedded in a half-space subjected to external points loads and bending moments.

2.3. Modelling of the vehicle and the train-track excitation

The dynamic model of the vehicle used in VIBWAY is a three-dimensional (3D) rigid multi-body system. The quasi-static excitation induced by the static component of the moving loads applied by the train to the track and the dynamic excitation caused by the rail unevenness are considered as excitation sources. The dynamic wheel/rail interaction forces are modelled using linearised Hertz contact. Both, moving train forces [20] and pull-through roughness [12] modelling strategies for the determination of the response of the system to the passage of trains are included in VIBWAY, whilst the pull-through roughness strategy is recommended to control the computational cost.

3. SIMULATION AND USER-INTERFACE STRATEGIES

As previously mentioned, the computational tool can deal with three main types of problems. Depending on the problem to be solved, the operating schemes of the tool are different. The problem types and simulation schemes are outlined below, together with a description of the user experience in each of the situations.

3.1. New infrastructures to be constructed in urban environments

In these cases, the full system should be modelled, and the software requires the user to fill the information of the mechanical and geometrical parameters of the main subsystems: the vehicle, track, embankment/tunnel, soil and building. In practical situations, engineers do not have at hands all needed parameters required to properly characterize each subsystem. In order to solve this common situation, VIBWAY holds a database of parameters for typical systems that the user can use to complete the missing data. However, it is important to note that the imperfect knowledge of the input parameters of the system could lead to very large uncertainty levels of the prediction results. In this regard, the later described hybrid modelling options, when feasible, are always a better option. In terms of user experience, due to the automatic meshing adopted in the embankment/tunnel-soil modelling and the modular concept for the building model construction, all information required are values of the different mechanical and geometrical parameters, whilst no drawing, meshing or complex interface interaction are required.

3.2. New buildings to be constructed close to existing infrastructures

Recently, VIBWAY has preliminary incorporated a novel experimental/numerical hybrid methodology for the assessment of railway-induced ground-borne for this type of problems [5]. This methodology models the incident wave field induced by the railway infrastructure through a set of virtual forces applied in the soil, which would be obtained from vibration experimental measurements in the surface of the ground where the building will be constructed. These virtual forces can be then applied to a model of the building-soil system to determine the vibration levels to be induced by the existing railway infrastructure to the studied building. A simple example is here presented, where the response on four shallow squared foundations of 1 m side and 0.5 m depth is numerically assessed with the hybrid method in comparison to a reference numerical model of the foundations-soil system. In both models, the excitation is applied within the system of coordinates (x, y, z) at the point $(-4.5, 0, 0)$ m and the centres of the four squared foundations are located at $(2.5, -2.5, 0)$ m, $(2.5, 2.5, 0)$ m, $(-2.5, 2.5, 0)$ m and $(-2.5, -2.5, 0)$ m. The soil properties are: shear wave speed of 150 m/s, Poisson's ratio of 0.49, density of 1900 kg/m^3 and damping of 0.03. The distribution of collocation points (blue dots) and virtual forces (red dots) is shown in Fig. 3a, where it can be seen that just four measurement points (collocation points) for each foundation are considered. Within these assumptions, the hybrid method is capable to reproduce accurately the response of the shallow foundations when they are subjected to the same excitation until 150 Hz, as shown in the comparison presented in Fig. 3b for one of the foundations.

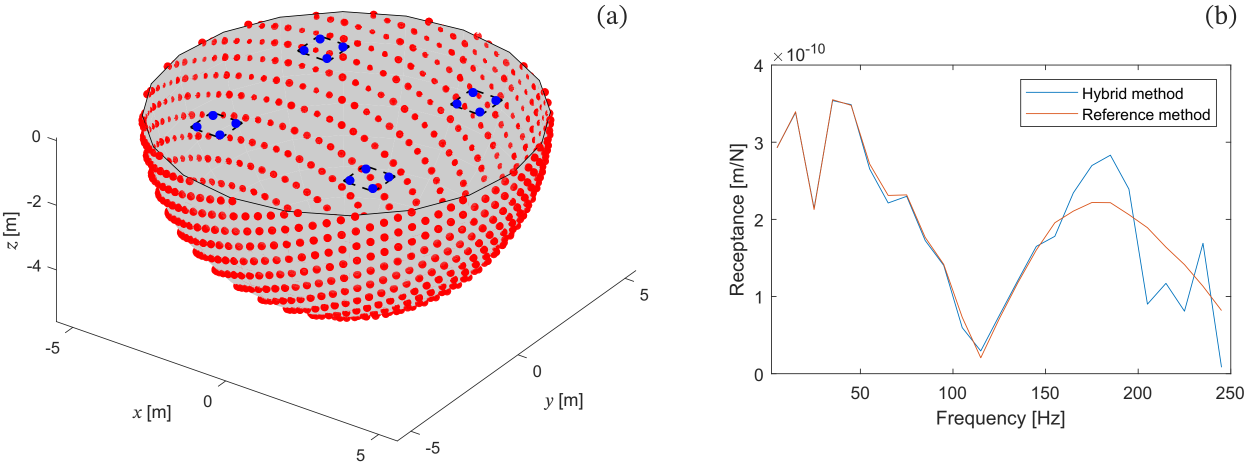

Figure 3: Numerical demonstration of the hybrid methodology in a simple example.

3.3. Assessment of the efficiency of vibration mitigation measures to be applied in the context of operating railway systems

In this case scenario, hybrid concepts accounting for experimental data of the existing infrastructure can be also applied, as proposed in [2] and in [16]. This feature is still in process of implementation and inclusion in the VIBWAY tool.

4. CONCLUSIONS

In the last two decades, the industrial sector in Europe has been demanding computational tools for the prediction of railway-induced ground-borne noise and vibrations. An easy-to-use but accurate and efficient software could be of great help to decision makers in the railway sector to tackle assessment studies of noise and vibration annoyance. VIBWAY software is a proposal in this direction, trying to meet demands as high flexibility (being able to compute a large variety of scenarios), user-friendly interface (to reduce the expertise degree required to the user) and low computational times. As detailed in the present paper, the VIBWAY tool tries to match these requirements through various features and characteristics:

- The use of an internal meshing engine for the 2.5D FEM modelling of the track embankment or the railway tunnel brings benefits on accuracy with respect to semi-analytical modelling whilst keeping the demands to the user at the minimum.

- The use of a modular strategy for the building modelling provides again a simple definition experience to the user, who is, however, restricted to model the building with rectangular floors and a regular distribution of the columns.

- VIBWAY incorporates databases of mechanical parameters for typical vehicle, track, tunnel, soil and building systems in order to help the user on completing the missing information about them.

- Hybrid modelling is a novel feature of VIBWAY that enhances accuracy of the simulation, although requiring an experimental measurement campaign in the specific site under study.

Here, the existing and potential applications of the VIBWAY computational tool in the field of railway-induced noise and vibration and related topics are outlined:

- To predict the vibration levels that a new railway line, either at-grade or underground, will generate on the nearby buildings.
- To predict the vibration levels that an existing line will induce on a new building or facility to be constructed on the surroundings of the infrastructure.
- To evaluate the efficiency of building base isolation systems as countermeasures to address railway-induced vibration problems.
- To evaluate the effect of retrofitting existing tracks to the induced levels of vibration and re-radiated noise.
- To perform comparative studies between different types of tracks.
- To accurately predict rail deflection and other parameters associated to the quasi-static excitation.

An open topic in the simulation of railway-induced ground-borne noise and vibration is the quantification of the prediction uncertainty. Due to the complexity of the problem that needs to be addressed, the consequent amount of parameters involved and the uncertainty associated to some of them, the quantification and control of the prediction uncertainty is a must. Thus, a future line of research in this context is to propose, develop, implement and test methods to quantify the parametric and non-parametric uncertainty of ground-borne noise and vibrations predictions at the source (train-track), at the receiver (building-soil) and when designing vibration mitigation countermeasures.

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