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3D HYBRID METHOD FOR ASSESSING RE-RADIATED NOISE INDUCED BY RAILWAY TRAFFIC: NUMERICAL VALIDATION

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ABSTRACT

In this study, a novel 3D hybrid methodology for assessing re-radiated noise induced by railway traffic is presented. This method combines numerical modelling techniques with experimental measurements to provide a comprehensive evaluation. Instead of fully modelling the train-track-ground system, the proposed methodology offers an innovative approach to accurately quantify, in a first step, the elastodynamic response of the building in the form of vibrations. Then, the structural velocities are used as input for a model based on the Method of Fundamental Solutions (MFS), enabling the assessment of the acoustic response inside the building's compartments. The ground-breaking aspect of the presented methodology lies in its ability to compute the dynamic response of the system without requiring any detailed information regarding the geometric or material properties of the track, rolling stock, and ground condition across the propagation path. The validation of this approach is achieved through a rigorous comparison between the results obtained using the hybrid method and those from a reference fully theoretical model of the system. The proposed hybrid methodology overcomes some of the limitations of traditional empirical models and offers a higher level of accuracy and flexibility in predicting railway-induced ground-borne noise.

Keywords: Building acoustics; Structure-borne noise and vibrations; building hybrid methodology

1. INTRODUCTION

One of the most common scenarios demanding a rigorous assessment of railway-induced noise and vibration occurs when planning the construction of new buildings near existing operational urban railway lines. In such instances, urban administrations typically require studies certifying that future buildings will comply with the noise and vibration regulations. Thus, predictive models for assessing railway-induced ground-borne noise and vibration levels within these buildings are imperative.

Over the past few decades, various theoretical models to assess railway-induced ground-borne noise and vibration in buildings have been developed to comprehensively address this issue, considering the entire system, including the railway infrastructure, the soil medium, and the target building. Early approaches, such as those by Balendra et al. [1,2] and Trochides [3], employed two-dimensional (2D) finite element method (FEM) modelling to assess train-induced vibrations. However, the transition to three-dimensional (3D) modelling approaches appearing in the literature has been motivated due to their enhanced accuracy in capturing complex wave propagation and precise representation of moving loads [4].

Empirical prediction models have also been widely used in engineering practice due to their simplicity and cost-effectiveness. The Federal Railroad Administration (FRA) and the Federal Transit Administration (FTA) introduced an empirical model for predicting vibration levels due to railway traffic [5], widely adopted for preliminary assessments. However, their limitations become evident when a detailed and highly accurate prognosis is required, as demonstrated by

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recent studies [6]. Furthermore, uncertainty in predictions due to the varying local subsoil conditions has been highlighted in several studies, underlining the need for probabilistic models [7-12]. To address these challenges, hybrid modelling approaches combining experimental data and theoretical models have emerged as promising alternative [13-15].

Concerning the acoustic field, only a few works can be found concerning the prediction of re-radiated noise due to railway traffic through numerical approaches [16-22]. Given the potential negative effects induced by a continuous exposition to re-radiated noise, an increase in the interest of the scientific community in this field is expected in the near future.

In this study, a novel methodology for predicting ground-borne vibrations and re-radiated noise in new buildings induced by railway traffic is presented. It is worth emphasizing that this methodology exhibits remarkable versatility as it can be employed across a wide spectrum of vibration sources. The present approach utilizes railway-induced ground vibrations measured at the building's future location to compute virtual forces representing the incident wave field from the nearby railway line. These forces are then applied to a theoretical model of the building-soil system to predict vibration levels throughout the structure. Once the vibration velocities of the building elements are determined, it becomes possible to predict the re-radiated noise within each of its compartments. This methodology, characterized by a weak coupling between the railway infrastructure and building structure, simplifies the traditional numerical process since it reduces the domain of the model and the need for some data that is sometimes inexistent or confidential, such as soil condition from the source to the building, source characteristics, etc… Given that the measurements taken in the initial step enable to fully characterize the vibration source and a substantial portion of the propagation path, this approach will substantially diminish uncertainties of the prediction. This hybrid methodology has been previously examined through a parametric study and a rigorous verification [23] using synthetic vibration measurements from a 2D and 2.5D perspectives.

In this paper, a verification of this hybrid method for re-radiated noise predictions is conducted also employing synthetic ground measurements. This verification comprises different scenarios involving a two-story building with shallow foundations on homogeneous soil. The primary aim of this study is to assess the accuracy of vibration predictions obtained through the hybrid methodology, along with the re-radiated noise prediction within the building.

2. MODELLING APPROACH

2.1. General Description

The chosen modelling approach unfolds in two distinct phases: firstly, it involves calculating the induced vibration velocities of the building elements and, subsequently, it focuses on evaluating sound pressure levels inside the structure.

To validate the proposed methodology, sound pressure levels obtained through the hybrid model are compared with those derived from the reference model. Concerning vibrations, the reference model accounts for the entire system, taking into account the soil-structure interaction, directly computing the vibrations induced in the building due to the application of a point force on the ground surface. In the case of the hybrid approach, three essential models are employed: the soil model, which facilitates the acquisition of displacement fields at specified locations; the virtual force distribution as a model of the incident wave field; and the soil-building model, which enables the determination of the vibration transmitted to the building.

2.2. Vibration response

To compute the vibrations induced to the building, two modelling approaches have been employed: a hybrid methodology, and a Green-FEM 3D model, the latter representing the reference model.

The hybrid methodology for the assessment of the building response was firstly introduced by Arcos et al. [24], and its formulation is similar to the Method of Fundamental Solutions. This methodology is divided into three steps.

Step 1. To perform the experimental measurements of the vibration induced at the ground surface where the building structure will be constructed. In this work, synthetic responses will be used to verify the method and to study its accuracy. These artificial measurements have been obtained through a numerical model of the soil that includes the domain of collocation points, as shown in Figure 1 - Model 1.

Step 2. To determine the virtual forces, taking into account the "measured" response at the collocation points, transforming them from space-time domain into displacements in the frequency domain, collected in the vector $\mathbf{U}_c$. From those displacements, the virtual forces, $\mathbf{F}_v$, can be computed, according to Eq. (1).

$$\mathbf{F}_v = \mathbf{H}_{cf}^{-1}\mathbf{U}_c \tag{1}$$

The $\mathbf{H}_{cf}^{-1}$ is a square receptance matrix that relates the virtual forces and the collocation points response obtained with a local subsoil model of the existing ground, as visually exemplified in Figure 1 – Model 2.Step 3:

Step 3. Computation of the building/soil system response according to Eq. (2).

$$\mathbf{U}_b = \mathbf{H}_{bf}\mathbf{F}_v \tag{2}$$

where $\mathbf{U}_b$ represents the response of a set of evaluation points placed in the building/soil model and $\mathbf{H}_{bf}$ is the receptance matrix that relates the virtual forces and the evaluation points response. The $\mathbf{H}_{bf}$ matrix is obtained using the building-soil theoretical model specifically developed for the case study, as illustrated in Figure 1 - Model 3.

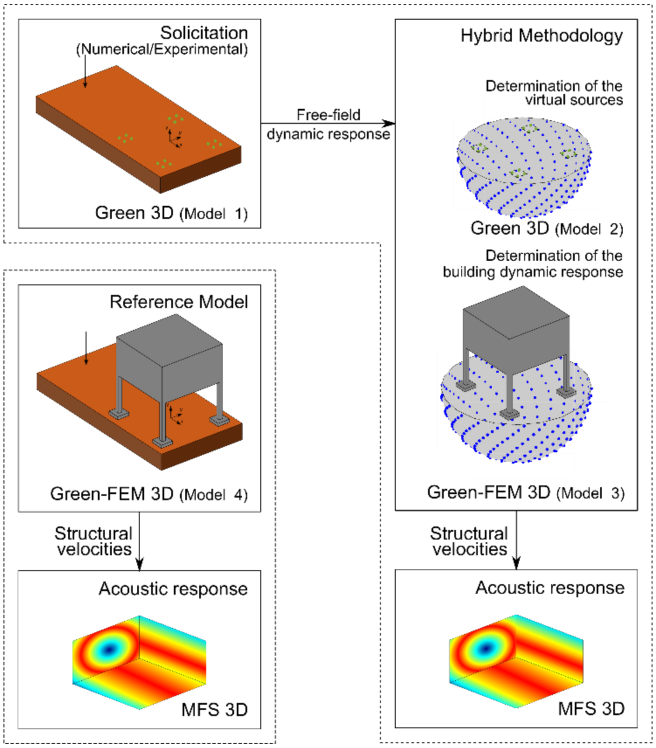

Figure 1. Representative scheme of the numerical modelling approach.

2.3. Acoustic response

For the determination of the acoustic response, an approach based on the method of fundamental solutions (MFS), previously validated by Colaço et al. [22] in an experimental context, is employed. The input parameters for the acoustic model are the vibration velocities of the structural elements of the building, obtained through the elastodynamic model of the building. Those vibration velocities are imposed as boundary conditions for the assessment of the sound pressure levels generated within the individual rooms of the building. This methodology corresponds to a collocation method that allows computing the response of the acoustic medium through a linear combination of the Green functions of the governing differential equation – the Helmholtz equation – considering a set of virtual sources positioned outside the propagating domain [25–28].

3. CASE STUDY

The primary objective of this case study is to compare the acoustic responses obtained inside a room of a building due to the application of a force on the ground surface, 7.5 meters away from the geometrical centre of the building. This comparison will verify the correctness of the hybrid method and confirm its suitability for determining the vibration velocities of structural elements, which subsequently enable the prediction of re-radiated noise.

To streamline the parameter analysis, a homogeneous geotechnical scenario is considered, with properties listed in Table 1.

Table 1. Mechanical properties of the building-soil system, where E represents the Young's modulus of the material, ρ its density, ν is Poisson's ratio and η the material damping

Designation	E [GPa]	ρ [kg/m^3]	ν [-]	η [-]
Soil	0.325	2000	0.3	0.03
Masonry walls	1.2	1200	0.2	0.03
Concrete	30	2500	0.2	0.02

The building structure was considered to be a reinforced concrete structure comprising two floors. To maintain simplicity, given the academic nature of this study, the building stands at a total height of 6 m with a footprint area of 5x5 m^2. Structural elements, including beams and columns, maintain regular dimensions of 0.2x0.4 square meters and 0.2x0.2 square meters, respectively, while the slab thickness measures 0.2 m. Masonry walls, of 0.15 meters thick, are integrated into the structure, and their mechanical properties are also detailed in Table 1. Four shallow foundations, each measuring 1x1 square meters with a thickness of 0.25 m, support the building. Additionally, Table 1 provides the mechanical properties of the concrete used in this structure.

Both the hybrid method and the acoustic model demand the definition of some deployment characteristics. In the case of the hybrid method, this entails defining the placement of the collocation points and virtual forces, while for the acoustic model, it involves choosing the virtual forces locations. In the context of the hybrid method,100 virtual forces uniformly distributed within a semi-sphere with a radius of 4.5 meters are considered, surrounding the building foundations and centred at the building symmetry axel. This choice of virtual forces quantity adheres to the empirical guideline established, stating that the spacing between consecutive virtual forces should be smaller than the wavelength of S-waves in the medium for the frequency of interest, $d < \lambda_S$. In terms of the number of collocation points, an amount of four per foundation is adopted, totaling 16 collocation points. In Figure 2, it can be observed the position of the collocation points and virtual sources with respect to the location of the building foundations.

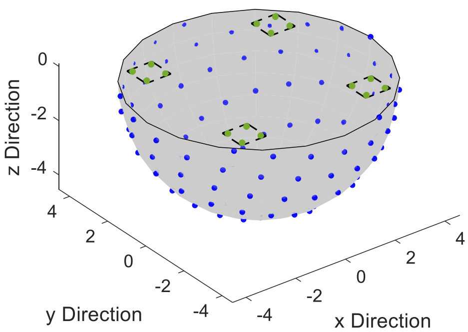

Figure 2. Representative scheme of the collocation points (green) and virtual forces (blue) with respect to the building foundations domains (dashed lines).

For the acoustic model, the collocation points were placed based on the locations of the building FEM model nodes, while the virtual forces were positioned with a one meter offset from the collocation points domain, as illustrated in Figure 3.

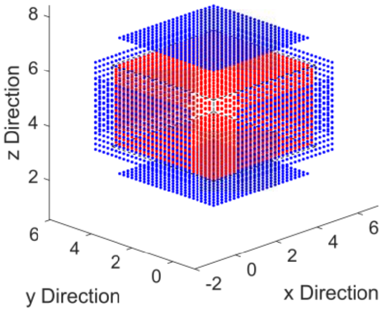

Figure 3. Representative scheme of the collocation points (red) and virtual forces (blue) of the re-radiated noise model.

4. RESULTS

In alignment with the initially defined primary objective of this study, the numeric computations were proceeded in two phases. First, the predicted displacements at each point within the domain were determined through the hybrid method and, simultaneously, through a direct approach, used as the reference model. Then, in the second part, the sound pressure levels within the building room under analysis were computed based on the vibration velocities of the building structural elements. Three evaluation points were chosen to compute and compare the response. The evaluation points were situated 0.5 meters away from the corners of the room, as illustrated in Figure 4.

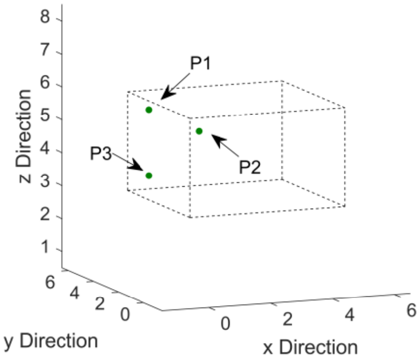

Figure 4. Location of the evaluation points.

Notably, the evaluation points P1 and P2 exhibit symmetry with respect to one of the problem symmetry axis, implying that their responses should be equivalent. Subsequently, the assessed sound pressure levels at each of these three evaluation points, are presented in Figures 5 to 7.

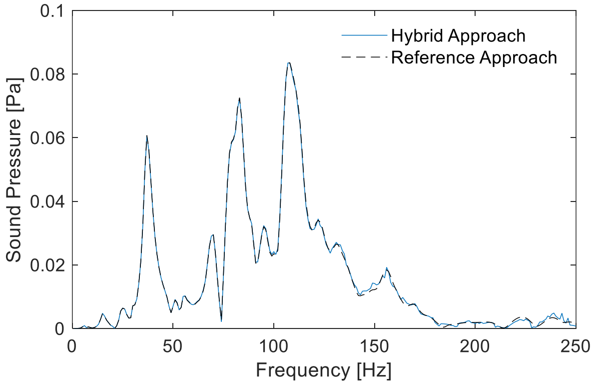

Figure 5. Acoustic pressure level calculated at Point P1, derived from vibrations obtained using the hybrid method (blue line), and through the reference model (black dashed line).

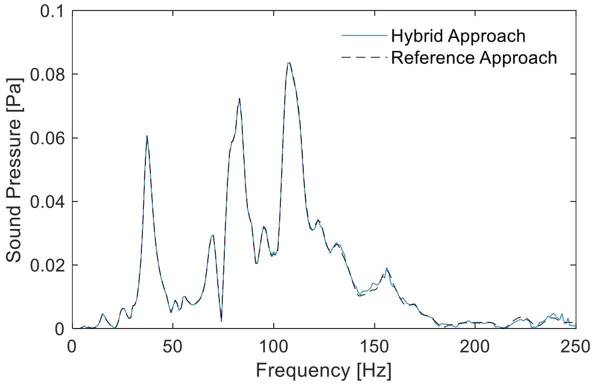

Figure 6. Acoustic pressure level calculated at Point P2, derived from vibrations obtained using the hybrid method (blue line), and through the reference model (black dashed line).

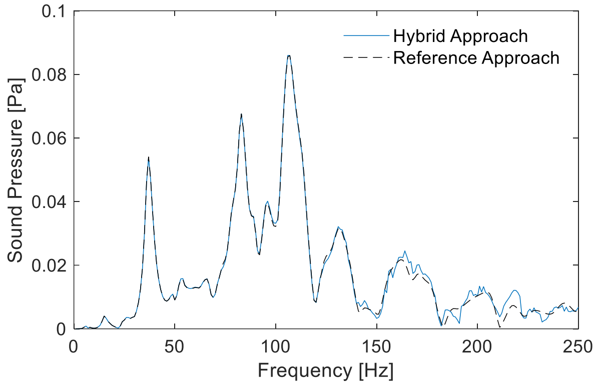

Figure 7. Acoustic pressure level calculated at Point P3, derived from vibrations obtained using the hybrid method (blue line), and through the reference model (black dashed line).

5. CONCLUSIONS

As observed in the obtained results,
it should be highlighted the significant overall agreement between the sound pressure levels computed on each evaluating point through the two different approaches, for all the range of frequencies adopted in this study. The strong agreement observed emphasizes the capabilities of the hybrid methodology to accurately estimate the acoustic responses inside a room of a building. Notably, the differences between the responses become slightly higher at higher frequencies, which can be effectively mitigated by considering a larger number of collocation points on the ground surface. An increase in the amount of virtual forces can also produces slightly better results.

In conclusion, this hybrid methodology represents a substantial step forward to effectively deal with ground-borne vibrations and reradiated noise problems in buildings to be constructed near to vibration sources. The methodology can be used to develop accurate assessment studies that not only enhance living conditions but also play a pivotal role in ensuring regulatory compliance regarding exposure limits, thereby safeguarding the well-being of the occupants of the buildings affected by this issue.

By combining experimental measurements with numerical models, this approach offers a practical and reliable tool applicable to multiple scenarios. It not only provides precise predictions of vibration and noise levels but also reduces the levels of uncertainty in the final predictions, allowing for detailed studies of diverse types of mitigation measures. These studies empower stakeholders, especially infrastructure managers to choose the most effective mitigation measures for addressing the issue, allowing for the selection of solutions based on their cost-effectiveness.

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