Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 19.6
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.19.6

On the Simulation of the Re-Radiated Noise Inside Buildings Using the Meshless Singular Boundary Method

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Abstract

This work presents a coupled vibro-acoustic framework designed to predict railway-induced re-radiated noise within nearby buildings subjected to train traffic. To evaluate the inferior sound pressure field, a three-dimensional acoustic singular boundary method (3D SBM) is deployed, where the enclosed room is represented as a structural subsystem with flexible plates formulated via thick plate theory. The global elastodynamic track-tunnel-ground-building system is established in the frequency domain using a weakly coupled approach across three distinct subsystems. Specifically, the track-tunnel-soil interaction is simulated using a two-and-a-half-dimensional (2.5D) FEM-SBM scheme, whereas the soil-pile foundation and structural building components are captured through an integrated 3D FEM-SBM framework. A key focus of this study is an investigation into how different soil–pile interaction modeling strategies influence the resulting interior vibro-acoustic responsein the building. Predictions derived from a semi-analytical approach employing a modified Novak pile model are compared against those from a numerical SBM-based formulation representation. This comparative analysis provides insights into the precision, computationally efficient and overall applicability of simplified foundation models for building vibration and interior noise forecasting.

Keywords: railway induced noise and vibration, re-radiated noise in buildings, coupled vibro-acoustic system, soil–pile interaction, 3D acoustic SBM, 2.5D elastodynamic FEM-SBM, modified Novak pile model

1 Introduction

Re-radiated noise in buildings occurs when structural vibrations, often induced by external sources such as railway systems, propagate through the building's structure and are subsequently transformed into airborne sound within interior spaces. This phenomenon is of particular concern in urban environments where underground transit systems or heavy machinery are located near residential or commercial buildings.

One of the key challenges in accurately modeling the vibro-acoustic response of buildings lies in capturing the floor-wall interaction and its influence on the overall behavior of the system. This complexity arises from the inherently intricate nature of real floor-wall interactions, making them difficult to be modeled. Traditionally, element-based computational methods, such as the finite element method (FEM) and boundary element method (BEM), have been widely employed for the analysis of re-radiated noise. These methods offer high accuracy for vibro-acoustic simulations; however, their computational efficiency is significantly influenced by the frequency of interest. For reliable results, FEM and BEM typically require at least 10 nodes per wavelength in each spatial direction [1]. This requirement leads to substantial computational costs, especially for large-scale acoustic problems, such as modeling re-radiated noise in complex building structures.

To address the limitations of conventional methods, recent research has explored numerical meshless methods, which do not rely on predefined domain or boundary meshes. Among these, the singular boundary method (SBM) has emerged as a promising boundary-type meshless technique to solve various boundary value problems, such as wave propagation analysis including acoustic, vibration and vibro-acoustic [2-13]. The SBM is a strong-form boundary collocation algorithm and has clear boundaries with the BEM and the method of fundamental solution (MFS). The key technique in the SBM is to replace the singularity at origin of the fundamental solution by the origin intensity factor (OIF). It is noted that the SBM is easily applicable to complex-shaped domain problems and it offers computational efficiency together with numerical stability, accuracy and robustness, making it particularly suited for large scale vibro-acoustic analyses involving re-radiated noise in buildings.

This study proposes utilizing the acoustic SBM in a three-dimensional (3D) framework to predict noise levels within an enclosed cavity, representing a room in a building subjected to train-induced vibration. The acoustic cavity is modeled as a subsystem within a coupled vibro-acoustic framework that incorporates the dynamic interaction between the building structure and the surrounding soil medium. The structural representation of the cavity is formulated on the basis of a previously developed soil-pile-building model reported in [14]. Extending this formulation, the enclosed cavity is modeled as part of the building structure, with its boundaries represented by flexible walls governed by thick plate theory. The elastodynamic track-tunnel-ground-building model is formulated in the frequency domain within a weakly coupled framework comprising three interacting subsystems: the track-tunnel-soil subsystem is modeled using a two-and-a-half-dimensional (2.5D) FEM-SBM approach, following the formulation in [4]; the soil-pile-building subsystem is represented using a 3D FEM-SBM model based on the methodology for soil-pile interaction developed in [9], coupled with a FEM model for building structure presented in [14]. Furthermore, the study examines the influence of different soil–pile interaction modeling strategies on the vibro-acoustic response of the enclosed cavity. In particular, predictions obtained using a semi-analytical approach employing a modified Novak model, are compared with those derived from a more rigorous numerical SBM-based representation of soil-pile interaction, thereby enabling an assessment of the accuracy and applicability of simplified foundation models for building vibration and interior noise prediction.

2 Numerical methodology

The objective of this study is to assess structure-borne re-radiated noise in buildings induced by railway traffic. To this end, a comprehensive computational framework has been developed, as schematically illustrated in Figure 1. The framework comprises three main components: (i) a train-track interaction model, (ii) an elastodynamic model of the coupled track-tunnel-soil-building system, and (iii) an interior acoustic model.

The analysis is performed through a sequential coupling procedure. First, the dynamic responses of the vehicle and the track, obtained from a 2.5D FEM–SBM model, are used to determine the wheel-rail interaction forces. Second, these interaction forces are applied to the 2.5D FEM–SBM model of the track-tunnel-soil subsystem to compute the resulting vibration field within the supporting ground. Third, the responses obtained from the track-tunnel-soil model are employed as excitation inputs to a 3D model of pile-building, enabling the evaluation of the building's dynamic response. Finally, the structural vibrations of the building envelope are coupled with a 3D acoustic SBM model of the enclosed cavity to predict the resulting interior sound field and quantify the re-radiated noise levels, in the room, generated by railway-induced ground-borne vibrations.

As previously noted, re-radiated noise within a building is governed by a comprehensive, coupled vibro-acoustic process. While the detailed elastodynamic modeling of the train-track-soil-building system is outside the scope of this work (see [15, 16]), this paper focuses explicitly on the acoustic response.

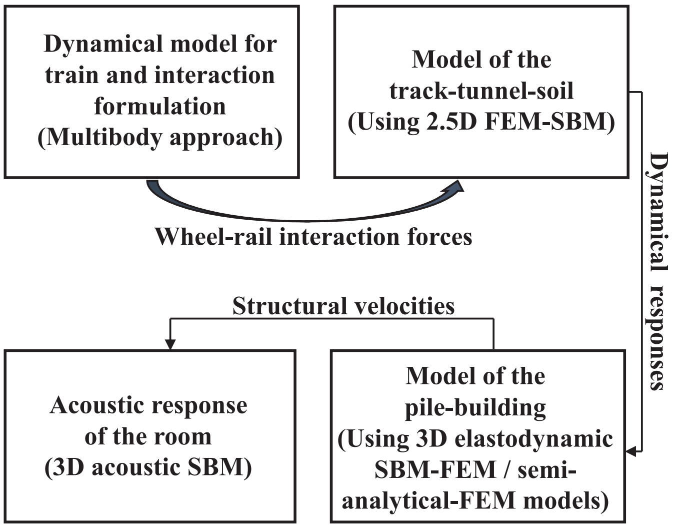

Figure 1: Schematic description of the methodology.

2.1 Acoustic analysis

The methodology presented utilizes the SBM for analyzing the acoustic pressure iside the enclosed cavity in combination with the a 3D FEM model for studying vibration of the building structure. The interaction between the acoustic and structural domains is considered in the basis of a weak coupling treating each domain independently while ensuring compatibility of particle velocities between them. In this decoupled framework, the structural velocity results obtained from the vibration analysis are used as input for calculating pressure levels in the acoustic domain. The acoustic pressure levels are computed using the proposed 3D SBM approach.

To maintain consistency, the collocation points for the SBM are selected to coincide with the nodal points from a selected room in the building, constructed via the FEM approach developed in [14], that defines the acoustic domain boundary. Explaining that the structural displacement data in this analysis has been obtained from the prior 2.5D elastodynamic model which serves as the excitation inputs for the 3D building model. Specifically, floor responses prescribe the vibrations of the upper and lower plates of the acoustic cavity, while the peripheral plates are driven by the column and floor displacements. These structural vibrations are subsequently coupled as boundary conditions into the 3D acoustic SBM model to evaluate the interior sound pressure field. Accordingly, the normal velocity $V_{\mathbf{n}}$ used as a boundary condition on the collocation points is computed from the normal displacement $U_{\mathbf{n}}$ obtained from the dynamic response of the building's structure as

$$V_{\mathbf{n}} = \mathrm{i}\omega U_{\mathbf{n}} \tag{1}$$

With the boundary conditions of the acoustic medium established, the procedure for determining the sound pressure levels using the SBM is presented in the following.

2.2 SBM approach applied to interior acoustics

The SBM approximates the solution to the governing governing differential, i.e., the Helmholtz equation, through a linear superposition of fundamental solutions. In this framework, the boundary conditions are discretized over a set of collocation points, with virtual sources positioned directly on the boundary surface. For optimal computational efficiency, the SBM typically employs a geometrically coincident arrangement, where the number and locations of the virtual sources correspond exactly to the collocation points. The strengths of these virtual sources are determined by enforcing the prescribed boundary conditions at each collocation point. Once these source strengths are resolved, the acoustic response throughout the domain can be evaluated. To address the inherent singularities of the fundamental solutions when source and collocation points coincide, the method utilizes the OIFs. Consequently, the acoustic pressure *P* and particle velocity *V* at an arbitrary point $\mathbf{x}$ are approximated by the collective contribution of N sources situated at positions $\mathbf{s}_j$ $(j = 1, 2, \ldots, N)$ as follows:

$$P\left(\mathbf{x}\right) = \sum_{j=1}^{N} \alpha_j \, G\left(\mathbf{x}, \mathbf{s}_j, k\right), \quad \mathbf{x} \in \, \Omega, \tag{2a}$$

$$\mathrm{i}\rho\omega V\left(\mathbf{x}\right) = \sum_{j=1}^{N} \alpha_j \, H\left(\mathbf{x}, \mathbf{s}_j, k\right), \quad \mathbf{x} \in \, \Omega, \tag{2b}$$

where α_j $(j = 1, 2, \ldots, N)$ represents the unknown source strengths and

$$G\left(\mathbf{x}, \mathbf{s}, k\right) = \frac{e^{\mathrm{i}kr}}{4\pi r}, \tag{3a}$$

$$H\left(\mathbf{x}, \mathbf{s}, k, \mathbf{n}_x\right) = \frac{\partial G\left(\mathbf{x}, \mathbf{s}, k\right)}{\partial \mathbf{n}_x} = -\frac{e^{\mathrm{i}kr}}{4\pi r^2}\left(1 - \mathrm{i}kr\right)\frac{\partial r}{\partial \mathbf{n}_x}, \tag{3b}$$

are the 3D fundamental solutions of sound pressure and particle velocity of the Helmholtz equation, respectively, and $\mathbf{n}_x$ is an arbitrary unit normal vector that represents the direction along which the particle velocity is calculated. Eqs. (2a) and (2b) can be transformed to evaluate the response at the mth collocation point, which is located at the position $\mathbf{s}_m$, as

$$P(\mathbf{s}_m) = \alpha_m G_{mm} + \sum_{j=1, j\neq m}^{N} \alpha_j \, G(\mathbf{s}_m, \mathbf{s}_j, k), \quad \mathbf{s}_m \in \, \Gamma, \tag{4a}$$

$$\mathrm{i}\rho\omega V_n(\mathbf{s}_m) = \alpha_m H_{mm} + \sum_{j=1, j\neq m}^{N} \alpha_j \, H(\mathbf{s}_m, \mathbf{x}_j, k, \mathbf{n}_b), \quad \mathbf{s}_m \in \, \Gamma, \tag{4b}$$

where G_{mm} and H_{mm} are defined as the OIFs of the fundamental solutions of the Helmholtz equation. Therefore, the source strengths resulting from the prescribed Dirichlet and Neumann boundary conditions can be obtained, respectively, as

$$\alpha = \mathbf{G}^{-1}\mathbf{P}_b, \tag{5a}$$

$$\alpha = \mathbf{H}^{-1}\mathbf{V}_b, \tag{5b}$$

where $\mathbf{G}$ and $\mathbf{H}$ are the SBM interpolation matrices that consolidate the information in Eqs. (4a) and (4b) in a matrix form, α is the vector that collects all source strengths, and $\mathbf{P}_b$ and $\mathbf{V}_b$ are vectors that collect the imposed boundary conditions evaluated at all collocation points. Once the source strengths have been computed, the acoustic responses at an arbitrary field point in the medium are obtained by means of Eqs. (2a) and (2b).

The previously introduced OIFs G_{mm} and H_{mm}, associated with the SBM fundamental solutions for sound pressure and particle velocity, respectively, are evaluated using two distinct procedures. The coefficient G_{mm} is obtained through an empirical formulation, whereas H_{mm} is derived via a desingularization strategy based on the subtracting-and-adding-back (SAB) technique. Detailed derivations of these approaches can be found in [2,3]. Consequently, the following formulations are obtained

$$G_{mm} = \frac{1}{4\pi}\left(\frac{\pi^4}{25\sqrt{A_m}} + \frac{(\ln\pi)^2}{S}\right) + \frac{\mathrm{i}k}{4\pi}, \tag{6}$$

$$H_{mm} = \frac{-1}{A_m}\sum_{j=1, j\neq m}^{N} A_j \,\frac{\partial G_L(\mathbf{s}_m, \mathbf{s}_j)}{\partial \mathbf{n}_{s_j}}, \tag{7}$$

where A_j is the influenced area surrounding the j-th source point, S denotes the surface area of the 3D object and $G_L = \frac{1}{4\pi r}$ represents the 3D fundamental solution of Laplace equation.

3 Results and discussions

The present methodology is applied in the investigation of the re-radiated noise generated by train traffic inside nearby buildings. The dynamic response of the track-tunnel-soil system is evaluated using the coupled 2.5D FEM–SBM formulation described in [4]. To model the transmission of vibrations from the ground to the superstructure, the 3D FEM–SBM framework for soil–pile interaction, originally proposed in [9], is integrated with the FE building model developed in [14]. In this study, the FE model of the enclosed cavity is formulated based on the structural building model, with the cavity boundaries represented by flexible plates governed by thick plate theory. This coupled approach enables the prediction of the structural response of the complete soil–pile–building system. The resulting structural vibrations are subsequently used to excite the 3D acoustic SBM, which is employed to determine the sound field within the building interior. Particular attention is given to the role of foundation modeling in the prediction of interior vibro-acoustic performance. To this end, results obtained using a semi-analytical formulation based on the modified Novak model are contrasted with those derived from a numerical SBM representation of the soil–pile interaction system presented in [9].

In this simulation, a train operating speed of 90 km/h was prescribed, and the resulting structure-borne noise induced by structural vibrations was evaluated within a

3 m $\times$ 3 m $\times$ 3 m room. Following the spatial configuration presented in [14], this room is located on the first floor and spans the coordinate intervals of $x \in [3.5, 6.5]$ m and $y \in [3.5, 6.5]$ m and $z \in [3, 6]$ m. The sound pressure level (SPL) induced by the structural vibrations was computed using the 3D SBM, where the SPL is defined by

$$\text{SPL} = 20 \log_{10} |\frac{P}{P_{ref}}| \text{ (dB)} \tag{8}$$

where P_{ref} takes the value of 2×10^{-5}. In the simulation conducted, the acoustic medium is characterized by a sound speed of $c = 340$ m/s and an air density of $\rho = 1.24$ kg/m^3, assuming negligible hysteretic damping.

The resulting SPLs, computed using the proposed 3D acoustic SBM and accounting for the two soil–pile interaction models, namely, the semi-analytical modified Novak formulation and the numerical SBM scheme, are presented in Fig. 2. From a general perspective, a good agreement is observed across the entire frequency range between the acoustic responses predicted by the two modeling approaches. Nevertheless, noticeable discrepancies arise within specific frequency bands. Furthermore, the results demonstrate the capability of the SBM to predict re-radiated noise within buildings, highlighting its potential as an efficient and robust numerical framework for the analysis of complex vibro-acoustic problems. The validity and accuracy of the reported results are currently under further investigation and will be addressed in future work.

4 Concluding remarks

A comprehensive computational framework has been developed for the prediction of railway-induced re-radiated noise in buildings, integrating vehicle-track interaction, ground-borne vibration transmission, structural dynamics, and interior acoustics within a unified vibro-acoustic modeling environment. The proposed methodology combines a 2.5D FEM–SBM formulation for the track–tunnel–soil subsystem with a 3D FEM–SBM representation of the soil–pile–building system, while the interior acoustic field is evaluated using a 3D acoustic SBM. The enclosed room is modeled as an acoustic cavity bounded by flexible structural elements governed by thick plate theory, enabling the simulation of structural–acoustic coupling effects associated with vibration-induced sound radiation.

Particular attention has been devoted to assessing the influence of soil–pile interaction modeling on the predicted interior acoustic response. To this end, a semi-analytical modified Novak formulation has been compared with a numerical SBM-based representation of the soil–pile system. The results indicate a generally good agreement between the two approaches over the investigated frequency range, suggesting that simplified foundation models may provide reasonable estimates of interior noise levels for certain applications. However, discrepancies observed within specific frequency bands highlight the sensitivity of vibro-acoustic predictions to the adopted

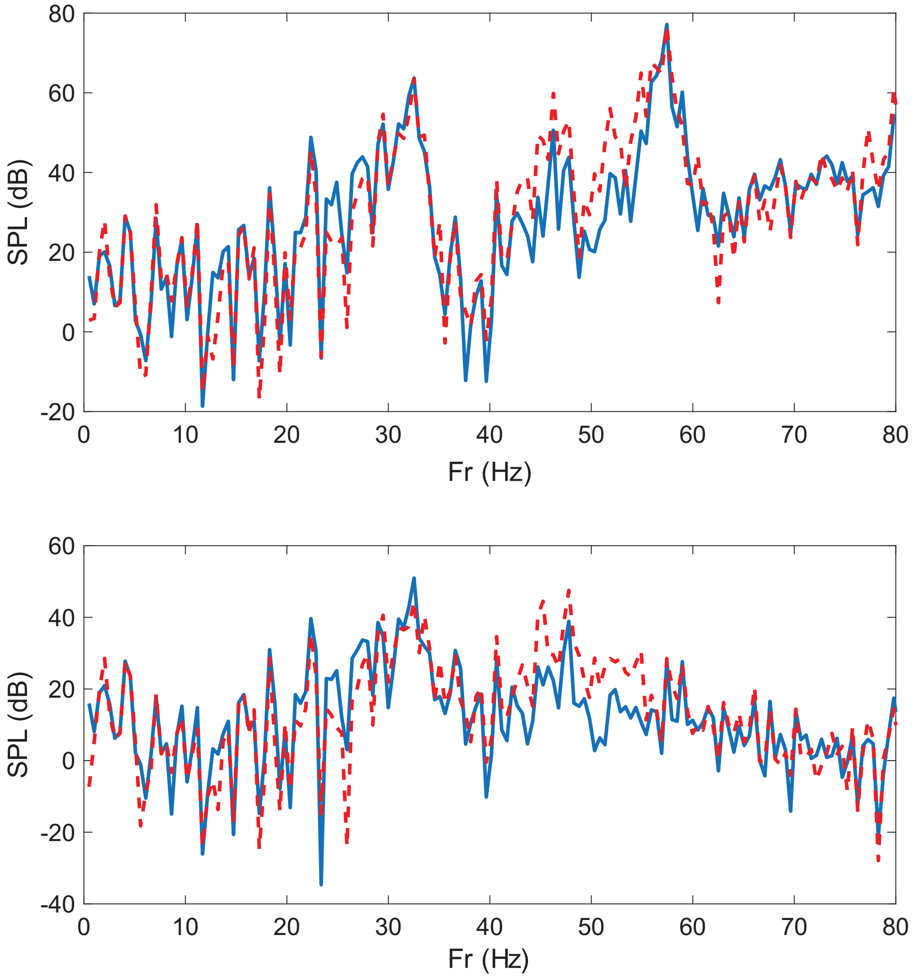

Figure 2: SPL computed using the proposed 3D acoustic SBM for two evaluation points within the cavity: (a) (0.1, 0.1, 0.1) m and (b) (1.5, 1.5, 1.5) m in local coordinate. Blue lines depict the acoustic response induced by considering the numerical 3D SBM pile-soil interaction model, while red dashed lines correspond to the ones induced by the semi-analytical modified Novak model scenario.

soil–foundation representation and underline the need for careful model selection.

Overall, the findings demonstrate the feasibility and potential of the acoustic SBM as an efficient and robust tool for the analysis of complex coupled vibro-acoustic problems involving railway-induced ground-borne vibration and re-radiated noise in buildings. Further work will focus on the validation of the proposed framework and on a more detailed assessment of the accuracy and applicability of the different soil–pile interaction models in practical engineering scenarios.

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