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Mitigation of vibrations and re-radiated noise in buildings generated by railway traffic: a parametric study

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Abstract

In the last decades, the number of railway projects in urban environment has continuously increased. This rising requires a significant level of knowledge from the scientific and technical communities about the phenomena of generation and propagation of vibrations with emphasis on its interference in nearby buildings and the consequent nuisance of their occupants. In this context, a numerical model to predict vibrations and re-radiated noise in buildings induced by railway traffic is presented. The model is based in a sub-structuring approach, where the whole propagation media is considered, from the vibration source (vehicle-track interaction) to the receiver (building and interior acoustic media). The track-ground-building system is simulated by a 2.5D FEM-PML model, formulated in the frequency - wavenumber domain. The re-radiated noise evaluation is based on a 2.5D FEM-MFS model, where the FEM is used to obtain the structural response. The computed structural displacements are then used as vibration input to the Method of Fundamental Solutions (MFS) model in order to assess the acoustic response in the building's enclosures. Finally, a parametric-study focused in the evaluation of the influence of a mitigation measure in the reduction of the vibrations and re-radiated noise levels is presented.

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Keywords: Railway track; mitigation measure; vibrations; re-radiated noise; 2.5D FEM-PML model; 2.5D MFS model

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1. Introduction

Ground-borne noise and vibrations have become a major environmental concern in urban areas. The vibrations can arise from different sources and they are the reason for several complaints due to the annoyance to inhabitants of

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buildings located next to railway infrastructures [1]. In an attempt to better understand and contribute to the solution of this issue, there is a demand for efficient and comprehensive numerical tools in order to predict and mitigate pernicious effects induced by railway traffic that can annoy inhabitants in the vicinity of railway infrastructures. For the specific case of a railway line developed in a trench-like cross-section, the inhabitants' annoyance is perceived in terms of vibrations and re-radiated noise, since direct noise is prevented from reaching the buildings or, at least, significantly attenuated when noise barriers are installed. The complexity of the problem is high due to the dynamic interaction between different subdomains, with distinct behaviors, namely: the vehicle-track interaction; the track-soil-structure interaction; and the structure–acoustic medium interaction. In relation to the last subdomain, it should be emphasized that the re-radiated noise assessment has not yet received the same level of attention by the scientific community comparatively to the vibration assessment, Indeed, to the best knowledge of the authors, in the bibliography only few works can be found concerning the prediction of re-radiated noise due to railway traffic [2, 3]. The complexity of the problem is even increased taking into account the broad frequency range of interest: from 1 Hz to 80 Hz, for mechanical vibrations, and between 16 Hz and 250 Hz, when dealing with re-radiated noise [4]. The aim of the present paper is to present an integrated methodology that allows simulating the whole medium, from the vibration source (vehicle-track interaction) to the re-radiated noise inside buildings. Thus, the system track-ground-building is simulated by a 2.5D FEM-PML model, formulated in the frequency - wavenumber domain. The acoustic model to evaluate the re-radiated noise inside the building is a new feature compared to previous works of the authors [5-7] and it is based on the Method of Fundamental Solutions (MFS). After this global model presentation, a short parametric analysis is performed in order to show the capabilities of the present approach on dealing with the analysis of the efficiency of mitigation measures as, for instance, floating-slab-track systems.

2. Numerical Model

The problem to be solved consists of a mixed elastodynamic-acoustic problem, where the final goal is the assessment of the sound pressure level generated within the dwellings' compartments due to a nearby train passage. For this case, the train-track-ground-structure coupled system (elastodynamic) is firstly analyzed, followed by the solution of the acoustic part of the problem. Fig. 1 shows the main parts of the numerical model and their interaction. As can be seen, the numerical model considered for the analysis is modular, based on a substructuring approach. Special attention will be given to the last subdomain, where the acoustic sub model is described.

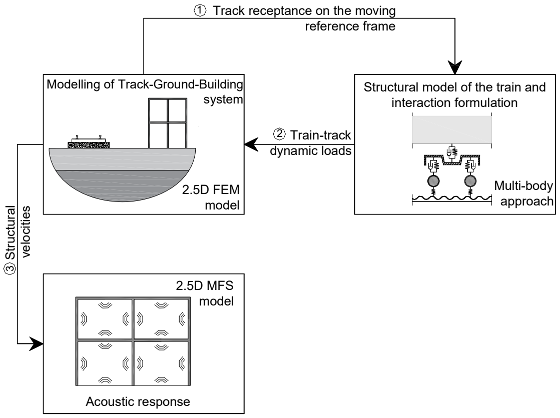

Fig. 1 – Representative scheme of the numerical modelling approach.

Regarding the modelling strategy for the train-track interaction, two components of the load are considered: i) the static load, resulting from the movement of the dead loads corresponding to the weight of the train; ii) the dynamic load, due to the dynamic interaction between the train and the track. For the latter component, which requires simulation of the train-track dynamic interaction, a compliance approach is adopted, fulfilling the requirements of equilibrium and compatibility between the train and the track [8-10]. To simulate the track-ground-building system, a 2.5D FEM-PML model is adopted. This 2.5D formulation assumes the linearity of the problem and the invariance of the system (mechanical and geometrical) along the development direction. Additional information about this procedure can be found in [5, 11, 12]. However, despite the advantages provided by a finite element approach, a topic of particular relevance is the formulation of special procedures to treat the boundary effects inherent to the truncation of the domain associated with the finite element discretization. In order to avoid this spurious reflection of waves, a 2.5D PML approach is adopted, as described in Lopes *et. al* [6, 12].

From this 2.5D FEM-PML model, it is possible to compute structural dynamic response along the structure-acoustic medium interface. This dynamic response will be used as input data for the acoustic model, i.e., an uncoupled formulation is adopted, assuming that the acoustic response does not affect the elastic dynamic response of the building. The results computed in terms of structural vibration velocities along the structure interface, which limits the acoustic space, are then imposed as boundary conditions for the assessment of the sound pressure levels generated within the closed space (an acoustic compartment). For this case, the relevant governing equation is the well-known Helmholtz equation, which can be written, at frequency ω, as

$$\nabla^2 p + k^2 . p = 0 \tag{1}$$

in which p is the acoustic pressure, $k=\omega/c$ is the wavenumber, and c is the sound propagation velocity. To solve this equation, the Method of Fundamental Solutions (MFS) is used, following the scheme presented in Fig. 2.

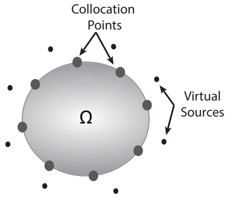

Fig. 2 – Schematic representation of an MFS model for the acoustic domain Ω.

The MFS approximates the pressure field within a given domain by a linear combination of fundamental solutions (Green's Functions) of the governing differential equation – the Helmholtz equation (eq. (1)) [13]. The acoustic response at a generic point x is then reproduced considering the effects of *NS* virtual sources located outside of the analysis domain, as expressed in equation (2).

$$p(x, k_a) = \sum_{m=1}^{NS} A_m G^{2.5D}\left(x, x_0^{(m)}, k_a\right) \tag{2}$$

where $G^{2.5D}\left(x, x_0^{(m)}, k_a\right)$ corresponds to the Green's function of the 2.5D sound pressure field. To complete this process, it is necessary to impose boundary conditions (normal velocities, in this case) at a set of collocation points, giving rise to a linear system of equations that allows determining the unknown amplitudes of the virtual sources A_m [14, 15].

3. Case study

3.1. General description

The selected case study corresponds to a railway line, with longitudinal development along a trench cross section, located in an urbanized environment. In the vicinity of the railway line, the existence of buildings in both sides was assumed, allowing modelling just half of the cross-section of the track-ground-structure system due to the symmetric condition of the problem. It should be noted that this assumption implies the consideration of the same unevenness profile for both rails, being that such simplification can influence the prediction of the ground-borne vibration [16]. Fig. 3 gives an overview of the problem geometry and configuration.

This figure also presents the mechanical properties assumed for the building, the diaphragm wall and the concrete slab. In relation to the properties adopted for the ground, these are compatible with an evolution over depth of S wave velocity from 200 m/s at the ground surface to 300 m/s at 13,5 m depth (ν=0.35; ρ=1950 kg/m^3; ξ=0.04).

In what concerns to the railway track, a continuous floating slab-track system is assumed with different values for the mats beneath the slab track, as depicted in Table 1. These floating slab systems are usually implemented for the control of the phenomena of excessive vibration and re-radiated noise inside the buildings. The effectiveness of this kind of mitigation measure is related with the introduction of a new resonance frequency of the system, i.e., by changing the dynamic behaviour of the railway track, as indicated in Table 1.

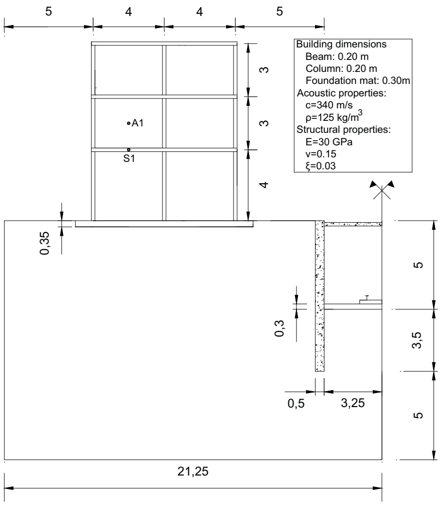

Fig. 3 – Geometrical properties of the case study (dimensions in m).

Table 1 – Properties of the different mats assumed.

Scenario	Stiffness per meter in longitudinal direction k (N/m^2)	Viscous damping per meter in longitudinal direction c (Ns/m^2)	Fcut-on (Hz)	Fcut-off (Hz)
Softer mat	0.040x10^9	5.5x10^4	18.7	26.4
Intermediate mat	0.153x10^9	5.5x10^4	26.4	37.3
Stiffer mat	0.283x10^9	5.5x10^4	37.3	52.8

Independently of the mat adopted, a continuous concrete slab track with 0.3 m thickness and 2.5 m width is assumed, with a longitudinal bending stiffness of 1.62x108 N/m^2 and a mass of 2800 kg per unit of length. The rails, materialized by UIC60 profiles, are continuously supported by railpads with a stiffness of 2.5x108 N/m^2 and a damping coefficient of 6x104 Ns/m^2. For the rolling stock, the passage of the Portuguese "Alfa-Pendular" train, at a running speed of 40 m/s, is considered.

3.2. Vibrations induced by traffic

In order to evaluate the effect of the introduction of the resilient mat bellow the track slab, Fig. 4 presents a comparison of the vertical velocity observed in point S1 (located at the 1st floor of the building), between a non-isolated railway track and an isolated railway track (with different resilient mats).

a) b)

Fig. 4 – Frequency content of the vertical velocity at Point S1: a) one-third octave bands; b) Insertion loss curves (dB-ref 10^{-8}).

The introduction of the resilient mat bellow the track slab gives rise to a new resonant frequency of the system, implying an amplification of the response for frequencies around the resonant frequency of the track-slab and an attenuation of the energy transmitted from the track to the ground in the frequency content above the cut-off frequency [6, 17]. As can be seen, the benefit of this mitigation measures is only noticeable for frequencies larger than the cut-off frequency. This effect is accompanied by an increase of the vibration levels in the frequency range around the cut-on frequency, which is as much lower as softer is the mat beneath the track-slab. From the time domain records (Fig. 5) it is evident that the frequencies where the dynamic response is amplified have a relevant contribute for the response, since the presence of the mat is giving rise to larger peak values of the vertical velocity of the slab.

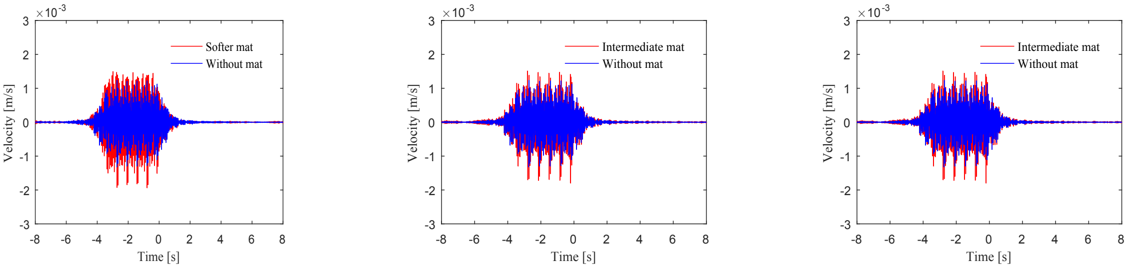

Fig. 5 – Vertical velocity at Point S1 for the different railway track solutions.

3.3. Re-radiated noise induced by traffic

In terms of acoustic response inside the building, a great contrast is verified as function of the mat adopted for the railway track. Analysing the results obtained for point A1(see Fig. 6 and Fig. 7), just the softer mat solution has a clear benefit in the reduction of the re-radiated noise levels, as can also be seen in the time record presented. This result is essentially due to the frequency content of the computed acoustic field, where the maximum values of sound pressure levels are shifted to the right compared to the frequency content of the structural response, as can be seen in Fig. 7. This condition combined with softer mat cut-off frequency (lower natural frequency and, consequently, lower cut-off frequency), gives rise to an effective reduction of the response.

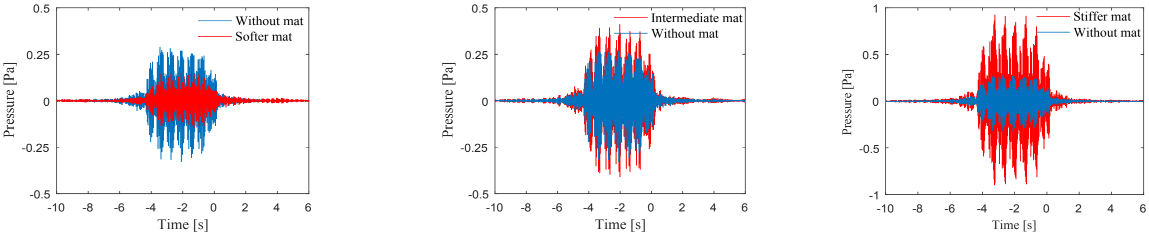

Fig. 6 – Time history of acoustic pressure for point A1 in the interior space, for different resilient mats.

In contrast, the other floating slab-track systems have a similar behaviour with that observed in structural analysis. Thus, and unlike the track solution with a flexible mat, where the clear benefit comes from the positive conjugation between the dominated frequency content of the response and the natural frequency introduced by the track solution, for the stiffer solution (and intermediate one) the natural frequency is close to the frequency range with a higher frequency content, justifying the observed amplification. On the other hand, when the reduction of the sound pressure level due to the application of the resilient mat starts to occur, the frequency content is already low, so the indicated solution is not a very efficient one.

a) b)

Fig. 7 – Frequency content of the acoustic response at Point A1: a) one-third octave bands; b) Insertion loss curves (dB-ref 20µPa).

4. Conclusions

In this paper, the authors presented an integrated methodology to determine ground-borne vibration and re-radiated noise induced by railway traffic. For that task, a numerical model based in a sub-structuring approach was considered. In this specific case, a 2.5D FEM-PML model was used to compute the track-ground-building response. From the computed structural dynamic response, a 2.5D MFS model was used in order to assess the acoustic response inside the building's compartments. After the global model presentation, a case study was presented. In this conceptual example, it was possible to highlight the ability of the proposed approach to analyse the dynamic response of the system. In addition, a mitigation measure to reduce the vibration and re-radiated noise levels inside the building was studied. This measure consists in a continuous floating slab-track system, for which distinct values of the stiffness of the resilient mat beneath the slab were considered. In general, the efficiency of this measure comes from a positive combination of two essential factors: the frequency content of the response and the cut-off frequency assigned to each solution adopted. Thus, the efficiency will be higher when a solution with a small cut-off frequency is applied and the response has the most significant frequency content in the higher frequencies. This conclusion is valid for both structural and acoustic responses.

Acknowledgements

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