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A numerical procedure to evaluate vibrations and re-radiated noise in buildings generated by railway traffic

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Abstract

The high number of railway projects in urban environment requires 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 environment). The system track-ground-building 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 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, an application example is presented, where the vibrations and re-radiated noise levels inside the building due to railway traffic are assessed.

Keywords: Railway traffic; FEM-PML model; MFS acoustic model; vibrations; re-radiated noise

1 Introduction

Ground-borne noise and vibrations have become a major environmental concern in urban areas. The vibrations can arise from different kinds or sources and are the reason of several complaints due to the annoyance of inhabitants on buildings surrounding metro lines [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 enclosed in a trench, the inhabitants' annoyance is revealed in terms of vibrations and re-radiated noise, since direct noise is prevented from reaching the buildings or significantly attenuated. The complexity of the problem is high, when the dynamic interaction between different subdomains is engaged, namely, the vehicle-track interaction, the track-soil-structure interaction, and the structure–acoustic medium interaction. This complexity 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 [2].

The aim of this paper is to present an integrated methodology that allows simulating the entire 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 [3-5] and it is based on the Method of Fundamental Solutions (MFS). This model, established as an uncoupled methodology, is firstly validated in relation to a fully coupled methodology, being then applied to a case study where the re-radiated noise levels inside a building due to railway traffic is assessed. Finally, a summary of the main conclusions is presented.

2. Mathematical formulation

2.1. Generalities

The problem to be solved here consists of a mixed elastodynamic-acoustic problem, in which the sound pressure level generated within a dwelling by a train passage is to be estimated. For this case, a track-ground-structure coupled problem is firstly solved, followed by the analysis of the acoustic part of the problem.

Figure 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.

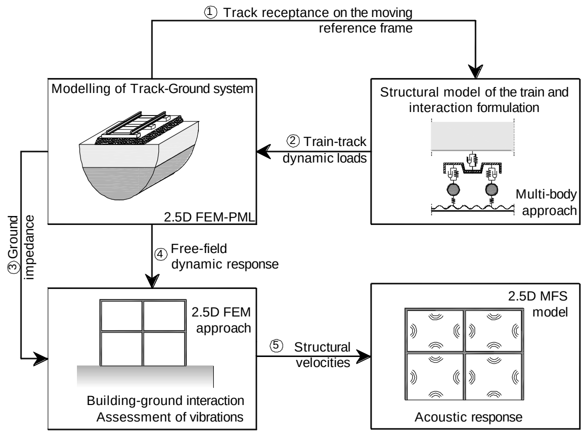

Figure 1 – Scheme of the numerical modelling approach.

Regarding the modelling strategy of the train and train-track interaction, two components of the load are considered: i) the static load, resulting from the weight of the train; and ii) the dynamic load, due to the dynamic interaction between the train and the track. For the latter component, which requires simulation of the dynamic train-track interactions, a compliance procedure is adopted respecting the requirements of equilibrium and compatibility between the train and the track [6-8]. To simulate the track-ground-building system, a 2.5D FEM-PML model is adopted. This 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 [3, 9, 10]. 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 reflexion of waves, a 2.5D PML approach is adopted. Additional information about the modelling strategy can be found in [4, 10]. From this 2.5D FEM-PML model, it is possible to compute structural vibration velocities along the structure-acoustic medium interface. As described in the following section, the dynamic response of the structure-acoustic medium interface will be used as input for the acoustic model.

2.2. Acoustic analysis

The results computed in terms of structural vibration velocities along the structure boundary, which limits the acoustic space, are then imposed as boundary conditions for the assessment of the sound pressure levels generated within the closed room (an acoustic compartment). For this case, the relevant governing equation is the well-known Helmholtz equation, which can be written 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 MFS is used, following the scheme presented in Figure 2.

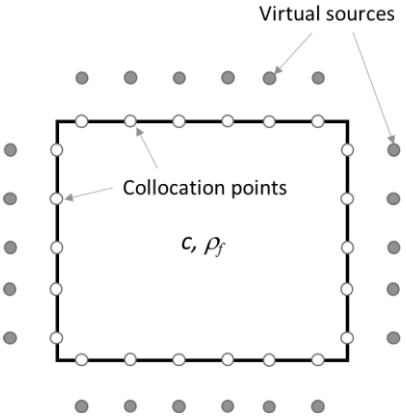

Figure 2 – Schematic representation of the acoustic problem.

The Method of Fundamental Solutions 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)) [11]. The acoustic response at a generic point x is thus reproduced considering the effects of virtual sources located outside this domain, as expressed in the equation (2).

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

In this equation, $G^{2.5D}\left(x, x_0^{(m)}, k_a\right)$ corresponds to the Green's function of the sound pressure, which can be written as a Hankel function of the second kind and order zero:

$$G^{2.5D}(x, x_0, k_a) = -\frac{\mathrm{i}}{4} H_0^{(2)}(k_a r) \tag{3}$$

where $x_0^{(m)}$ represents the coordinates of the virtual source *m* (with *m*=1,2,…,*NS*); r corresponds to the distance between the source point and the domain point; and k_a is the acoustic wavenumber, given by:

$$k_a = \sqrt{\frac{\omega^2}{c^2} - k_z^2} \tag{4}$$

To complete this process, it is necessary to impose boundary conditions at the set of collocation points, giving rise to a linear system of equations that allows determining the amplitudes of the virtual sources A_m. So, and in the case of prescription of velocities at the boundary, the unknowns A_m can be obtained by the following relation:

$$\sum_{i=1}^{NP} \sum_{m=1}^{NS} \left[A_m H^{2.5D}\left(x_P^{(i)}, x_0^{(m)}, k_a, \vec{n}\right)\right] = v_{N,i} \tag{5}$$

In this expression, the Green's function for particle velocities, $H^{2.5D}\left(x_i, x_0^{(m)}, k_a, \vec{n}\right)$, is defined in the eq. (6) by the Hankel function $H_1^{(2)}(k_a r)$ of the second kind and order one.

$$H^{2.5D}\left(x_P^{(i)}, x_0^{(m)}, k_a, \vec{n}\right) = \frac{1}{4\rho c} H_1^{(2)}(k_a r) \frac{\partial \mathrm{r}}{\partial \vec{n}} \tag{6}$$

In this equation, $x_P^{(i)}$ corresponds to the coordinates of the collocation point *i* (with *i*=1,2,…,*NP*); $\vec{n}$ represents the direction along which the particle velocity is calculated; and ρ and c are the medium density and sound propagation velocity, respectively. The prescribed velocities in each collocation point located at the boundary follow the condition:

$$v_{n,i} = -\frac{1}{\mathrm{i}\rho\omega} \frac{\partial \mathrm{p}}{\partial \vec{n}}(x_i) \tag{7}$$

3. Uncoupled methodology validation

Before presenting a practical application of the previously presented methodology, this section focus on the evaluation of the reasonability of the simplifications introduced, namely the weak coupling between structural and acoustic vibrations. In an engineering perspective, this assumption looks to be realistic, since it is not credible that the acoustic pressure inside the room has significant effect on the vibration of the walls.

Thus, a fully coupled methodology based in the FEM is used in order to assess the acoustic response in the building's enclosures. The choice of this method is based on its ease of application, since the elastic domain is also simulated using the FEM. However, the MFS can also be used in a fully coupled methodology together with FEM. This solution is much more competitive for problems with large computational domains, such as 3D problems. In the present case, where a 2D structure is analyzed, the FEM proves to be an efficient methodology and for this approach two different models need to be defined: i) the Acoustic model; and ii) the Structural model. After that, these independent models are compatibilized by connection matrices, establishing the equilibrium and compatibility dynamic conditions between the elastic structure and the acoustic space. The adopted mathematical formulation can also be found in Desmet and Vandepitte [12], and therefore it is not presented herein.

To compare the uncoupled and the coupled methodologies referred previously, a practical example with the mechanical and geometrical properties exhibited in Figure 3 is considered.

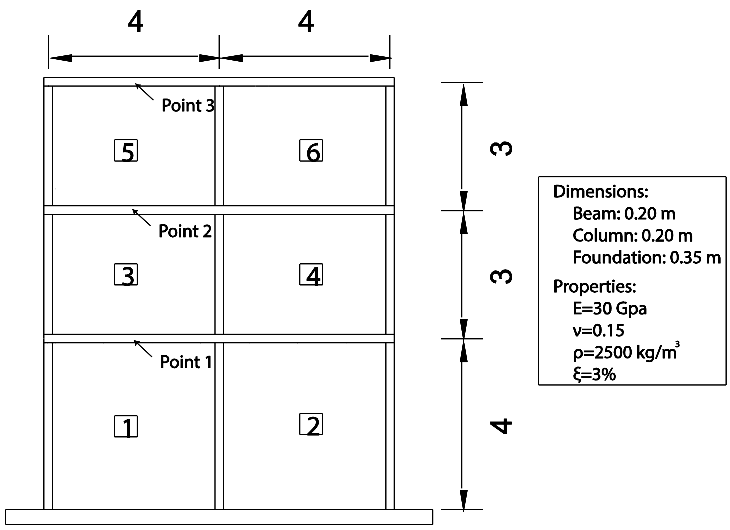

Figure 3 – Geometrical and geomechanical properties of practical example (dimensions in m).

For this particular structure, a dynamic uniform vertical displacement applied in all the points of its foundation was considered, which can be written as:

$$u(t) = Ae^{i\omega t} \tag{8}$$

Where the displacement amplitude *A* is considered to be unitary.

For this study, two different excitation frequencies are analysed in a first step, namely, 50 Hz and 150 Hz. For each one of them, the acoustic pressure response inside the building is evaluated and shown in the colormaps of the Figure 4. Acoustic pressure levels (SPL) are defined by:

$$SPL = 10\log_{10}\frac{p^2}{{p_{ref}}^2} \quad [\text{dB}] \tag{9}$$

where p_{ref} takes the value of $2\text{x}10^{-5}$ Pa, as exposed by FRA [13].

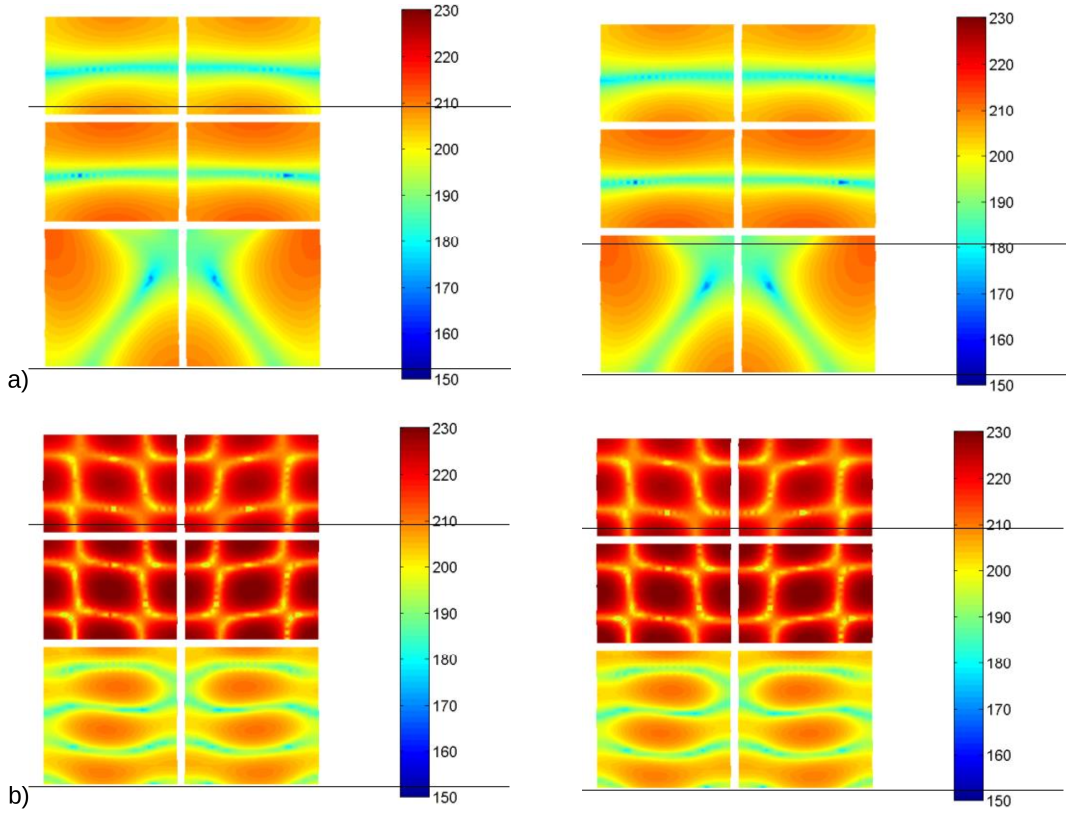

Figure 4 – Acoustic pressure levels (SPL in dB: p_{ref}=20μPa): a) *f*=50 Hz; b) *f*=150 Hz (on the left side: FEM coupled approach; on the right side: MFS uncoupled approach).

As can be seen from Figure 4, there is a notable correspondence between the both approaches. In fact, regarding the acoustic response, there is no significant differences in the results provided by the strong coupling and the weak coupling. Despite this agreement, a more thorough analysis of the problem was made, considering a wider range of frequencies. Thus, the acoustic response for a point in the middle of the acoustic space 1, represented in Figure 3, is evaluated. The result is shown in the form of a transfer function that relates the response obtained (acoustic pressure) and the applied excitation (displacement), as shown in Figure 5.

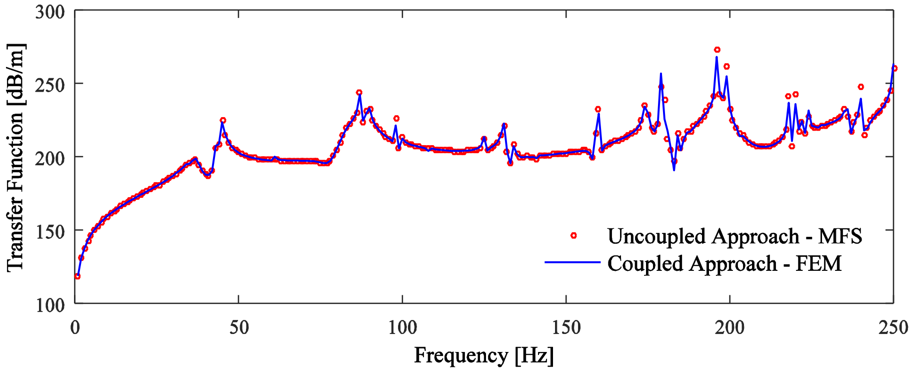

Figure 5 – Acoustic transfer function for a point in the middle of the acoustic space 1.

Once again, an excellent agreement between the results obtained from the two distinct approaches was found. However, Figure 5 also shows that, for some specific frequencies, slight differences of the results occur. This aspect is related to resonant phenomena of the acoustic field, which deserve a more detailed analysis that is out of the scope of the present paper.

4. Case study

4.1. General description

The selected case study corresponds to a railway line situated in a trench of an urbanized region. 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. Figure 6 gives an overview of the problem geometry and configuration.

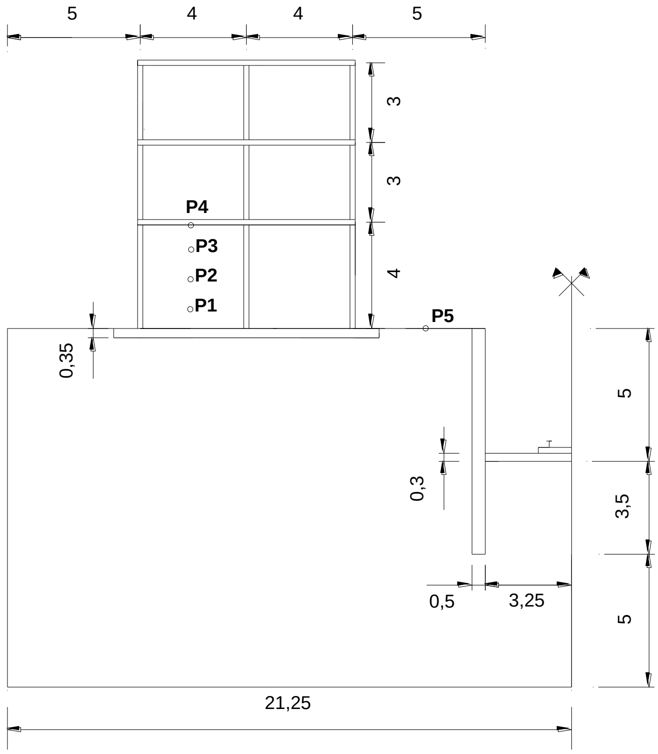

Figure 6 – Geometrical properties of the case study (dimensions in m).

The mechanical properties adopted for each material are depicted in Table 1. Properties adopted for the ground are compatible with an evolution over depth of S waves velocity from 200 m/s at the ground surface to 300 m/s at 13,5 m depth. The properties of the building are the same as those referred in Figure 3.

Table 1 – Geomechanical properties of the track-ground layers.

Element	Elasticity Module [GPa]	Poisson Coef. [-]	Density [kg/m^3]	Damping [-]
Ground	-	0.35	1950	0.04
Trench wall	30	0.15	2500	0.03
Concrete slab	30	0.15	2500	0.03

A STEDEF railway track was adopted, as depicted in Figure 7.

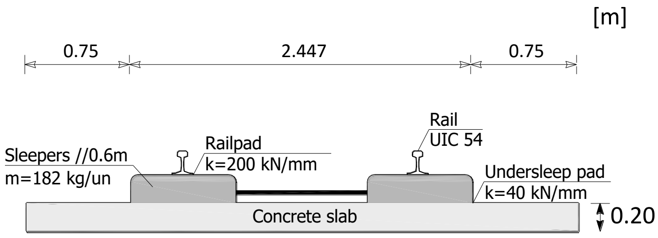

Figure 7 – STEDEF railway track.

Regarding to the rolling stock, the passage of the Alfa-Pendular train, at a running speed of 40 m/s, is considered. The main mechanical and geometrical properties of the Alfa-Pendular train can be found in Alves Costa [14].

As mentioned before, the train-track interaction is taken into account, being the dynamic interaction mechanism provided by the rail unevenness. A synthetic unevenness profile, with wavelengths ranging from 0.65 m to 31 m, was generated assuming the power spectral density (PSD) function expressed as:

$$S(k_1) = \frac{10^{-7} A k_3^2 (k_1^2 + k_2^2)}{k_1^4 (k_1^2 + k_3^2)} \tag{10}$$

where k_2 and k_3 are constants which take, respectively, the following values: 0.1464 rad/m and 0.8168 rad/m. Parameter A is related to the track quality and it is assumed as 208.841 m^3/rad, corresponding to Class 3 of the FRA approach. It must be noted that alternative studies, realized by Braun and Hellenbroich [15], suggest the use of a different analytical expression, that leads to values of spectral density function significantly lower.

Since the train speed is assumed to be 40 m/s, the adopted rail unevenness profile excites the train in the frequency range between 4 Hz and 200 Hz. This range of frequencies is particularly interesting for the study of vibrations and re-radiation noise induced by railway traffic inside buildings.

4.2. Ground-borne vibrations simulation

Figure 8 represents the time history and frequency content of the vertical vibration velocity in a point located in the ground free field. This point is referred in Figure 6 by number P5.

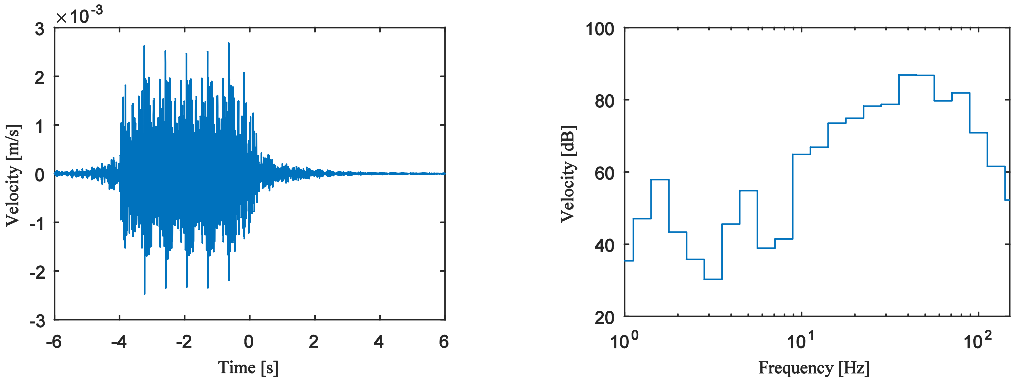

Figure 8 – Time history (left hand side) and one-third octave band (right hand side) of free field vertical ground velocity in point P5 (dB-ref. 10^{-8} m/s).

As can be seen, the dynamic response in the considered point of the free field is spread over a large range of frequencies. The higher frequency content is related to the dynamic interaction mechanism, i.e., with the train-track interaction loads induced by the track unevenness.

Figure 9 shows the time history and frequency content of the vertical velocity of point P4, located in the middle span of the 1st floor slab of the building (see Figure 6). It is interesting to see that the building structure filters/attenuates the higher frequency content. However, this effect is accompanied by the amplification of the response around the structure natural frequencies implying vertical motion of the building slabs.

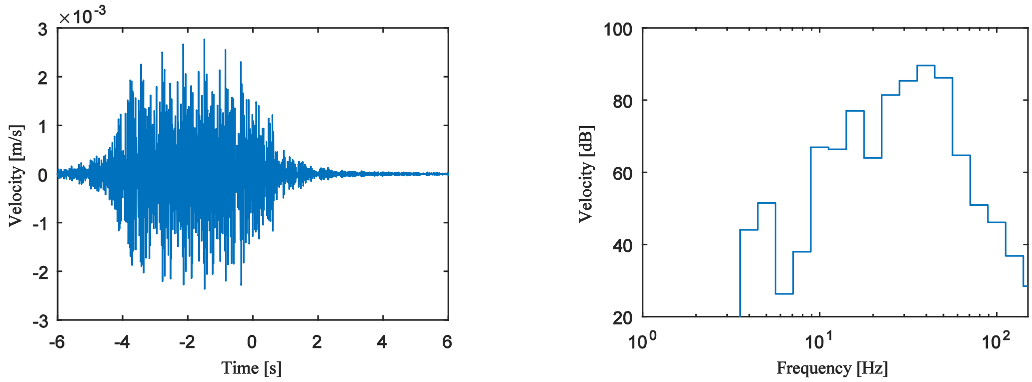

Figure 9 – Time history (left hand side) and one-third octave band (right hand side) of vertical structural velocity in point P4 (dB-ref. 10^{-8} m/s).

4.3. Acoustic response in the building's enclosures

The acoustic response inside the building's enclosures is computed from the structural velocities records developed along the structure-acoustic medium interface, as that represented in Figure 9. Figure 10 shows the time history and frequency content of the sound pressure for three different points located in the acoustic space 1 (Points 1, 2 and 3 in Figure 6).

Without going into great details, once the main goal of this work is just presenting the suitability of the numerical model to study these phenomenon, a few remarks can be pointed: i) in the time domain, the pressure levels have a significant variability; ii) around 50 Hz, the acoustic response has a higher content.

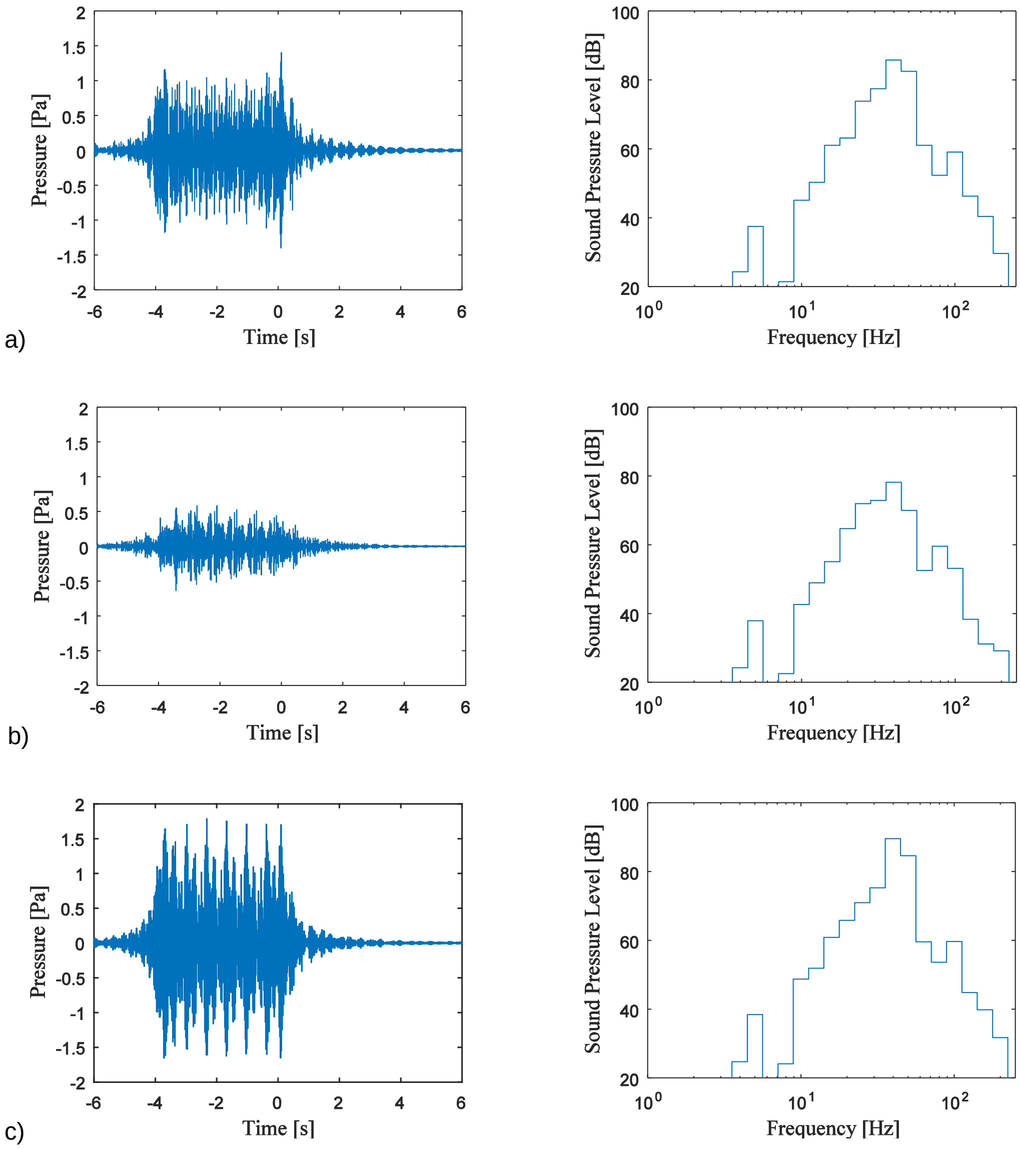

Figure 10 – Pressure time history (left hand side) and one-third octave band (right hand side) in three different points in acoustic space 1, during the passage of the Alfa-Pendular train: a) Point 1; b) Point 2; c) Point 3. (dB - ref. 20μPa).

5. Conclusions

This paper presents an integrated methodology to determine ground-borne vibration and re-radiated noise induced by railway traffic. For that, a numerical model based in a sub-structuring approach has been 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, the MFS was used in order to assess the acoustic response in the building's enclosures.

For this last step, the validity of the simplification assumed was discussed, i.e., the weak coupling between structural and acoustic vibrations. This analysis allowed concluding that the differences in the acoustic response computed through the coupled or the uncoupled approaches are negligible, allowing to use the sub-structuring model proposed.

After this introductory discussion, a case study was presented. In this application conceptual example, it was possible to highlight the ability of the proposed approach on dealing with practical engineering applications. In future works, out of scope of the present paper, this methodology will be used to study mitigation measures in order to reduce the vibration and re-radiated noise levels.

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