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A hybrid methodology for the assessment of railway-induced ground-borne noise and vibration in buildings based on experimental measurement in the ground surface

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In this paper, a hybrid experimental/numerical methodology for the assessment of railway-induced ground-borne noise and vibration in buildings based on experimental measurement in the ground surface is presented. This methodology is specifically designed for the prediction of railway-induced vibration in buildings to be constructed close to operative railway infrastructures. A set of virtual forces applied in the ground, as a model of the incident wave field induced by the railway infrastructure, are obtained from vibration experimental measurements in the surface of the ground close to the future building foundation. These virtual forces can be subsequently applied on a model of the building/soil system to obtain a prediction of the vibration that will be induced by the existing railway track to the studied building. In the present work, this methodology is presented and validated numerically by a two-dimensional example and a two-and-a-half-dimensional one. The proposed hybrid model simplifies the usual numerical procedure for these problems, since a model of the railway infrastructure is not longer required. Moreover, it reduces the uncertainty of the prediction due to the use of experimental measurements of the particular site to be studied. In addition, it provides a higher accuracy and flexibility than empirical models based on experimental transmissibility functions between the ground surface and the building.

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1 INTRODUCTION

Nowadays, railway-induced noise and vibration is a public concern. Many countries all around the world have established regulations for the maximum noise and vibration levels that can be reached in buildings nearby of a railway infrastructure. This regulations are set mainly to control the annoyance to the building inhabitants, but also to ensure the correct operation of sensitive machinery and equipment and, eventually, to avoid any building damage (usually non-structural). In particular, since several urban railway lines are underground, railway-induced ground-borne noise and vibration is the most important railway-based source of environmental pollution in urban environments.

One of the most common situations in where a railway-induced noise and vibration assessment is required is the construction of a new building nearby to an existing and operational urban railway line. In such cases, the railway line administration or the city council usually demands a study that certify that the railway-induced ground-borne noise and vibration levels that will be registered when the building will be constructed will comply with the applicable noise and vibration law. Thus, prediction models of the building response to noise and vibration are required in those situations. Various theoretical models that account for the comprehensive system, i.e. the railway infrastructure, the soil and the building to be studied, have been developed during last three decades. One on the first proposals in this regard was presented by Chua et al.[1], in where they proposed a two-dimensional (2D) finite element method (FEM) model of the comprehensive track/tunnel/soil/building system. Obviously, three-dimensional (3D) modelling approaches are more accurate to obtain the building response in the context of railway-induced ground-borne vibration. Fiala et al.[2] used a decoupled approach to assess the vibration response of the building. This approach considers a weak coupling between the tunnel/soil and the building/soil systems. For the tunnel/soil system, a two-and-a-half-dimensional (2.5D) FEM model for the tunnel and a 2.5D boundary element method (BEM) model for the soil are used. In contrast, for the building/soil model, a 3D FEM-BEM model is considered. A similar approach was presented by Lopes et al.[3], where, in this case, the soil is modelled by using a 2.5D FEM with perfect matched layers (PML) as a sub-model of a comprehensive track/tunnel/soil model. Hussein et al.[4] proposes a 3D model of the comprehensive system by using semi-analytical approaches for the building and the tunnel/soil systems. The building structure, considered to be coupled with soil by piled foundations, is modelled as a 2D frame based on axial and bending beam elements. More recently, Clot et al.[5] presented a 3D building based on axial beams, as a model of the piles and the columns, and bending rectangular plates, as a model of the floors.

The uncertainty on the railway-induced ground-borne predictions in buildings due to the imperfect knowledge of the local subsoil conditions is found to be significant in various scientific works. As explained by Lopes et al.[3] and Papadopoulos et al.[6], the soil condition significantly influences the response of the building by affecting the incident wave field and the dynamic behaviour of the building. Therefore, comprehensive models of the track/tunnel/soil/building system implicitly contain uncertainty in this two aspects. In order to reduce the uncertainty of computational models, hybrid modelling based on the combination between in situ experimental data and a theoretical model is an interesting alternative. In framework of hybrid modelling for soil/building dynamic interaction problems, Auersch[7] presented a semi-empirical model that combines precalculated results obtained from detailed numerical models, a database of experimental data build from many experimental measurements and several specific analytical models. Sanayei et al.[8] proposed a hybrid approach where building is modelled by finite axial columns with added floor impedances obtained from infinite thin plate models, and where the incident wave field is represented by previously known column base forces or measured vibrations at the loading dock floor.

More recently, López-Mendoza et al.[9] have presented a computationally efficient model to predict the ground-borne railway-induced vibration levels in buildings considering soil-structure interaction. The methodology is designed, specifically, for cases where the incident wave field is known, because it is previously computed numerically or because it is measured in the ground surface. This model account for the soil-structure interaction by adding spring and damper elements to the foundation of the building model.

In this paper, a new methodology for the prediction of the ground-borne vibration induced by operational urban railway lines in buildings to be constructed in the surroundings of the infrastructure is presented. This method uses railway-induced vibrations measured in the ground where the the new building will be constructed to compute a set of virtual forces that represent the incident wave field induced by the nearby operational railway line. These virtual forces are then used on a model of the particular building/soil system to be studied in order to predict the vibration levels at any point of the structure. Thus, this method considers a weak coupling between the railway infrastructure and the building structure. The methodology is numerically validated in 2D and 2.5D domains for an example of a two-storey building with shallow foundations in the surrounding of a underground railway infrastructure.

2 METHODOLOGY

In this section, the new hybrid methodology for the prediction of the railway-induced ground-borne vibration in buildings to be constructed nearby to railway urban lines is presented. This is a hybrid method, since it combines experimental measurements on the soil surface and a numerical model of the building/soil system. The method is based an approach similar to the method of fundamental solution (MFS). This method uses a set of virtual forces that satify a previously known boundary conditions, evaluated in set of points called collocation points, to obtain the response of the system. Here, the MFS approach presented by Arcos et al.[10] is applied. In that methodology, the known condition in the collocation points is the acceleration of vibration from experimental measurements, or alternatively the displacement of vibration directly integrated from the acceleration measurements. The MFS usually considers an amount of virtual forces smaller than the amount of collocation points, since the number of collocation points is normally considered to be large to properly account for the boundary conditions, but they can be represented accurately with a small set of virtual forces. This implies the use of a minimization algorithm but, in contrast, the method becomes more computationally efficient. However, the number of collocation points in the present method should be always small, which enables to consider the same number of virtual forces than collocation points without compromising significantly the computational efficiency. Thus, the minimization algorithm is no longer required.

The first step on this methodology is to perform an experimental measurement of railway-induced vibrations in the ground surface in where the particular building to be studied will be constructed with a setup of accelerometers. The measured time-domain accelerations $\ddot{\mathbf{u}}_c$ at the collocation points can be transformed to frequency-domain displacements $\mathbf{U}_c$. From that displacements, the virtual forces can be computed as

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

where $\mathbf{F}_v$ is a column vector that contains the virtual forces and $\mathbf{H}_{cf}$ 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. Then, the response of building/soil system can be obtained by

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

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 model specifically developed for the case study.

3 NUMERICAL VALIDATION OF THE METHODOLOGY

In this section, the previously explained hybrid method is validated numerically. In order to achieve this validation, four 2.5D FEM-PML models has been created, all of them based on the approach presented by Lopes et al.[11]. For this validation, Eqs. (1) and (2) are assumed to be formulated in the wavenumber-frequency domain. These four models are described in this section. The properties of the materials of the different sub-systems appearing in the four models are defined in the Table 1.

Instead of using experimental measurements, $\mathbf{U}_c$ is obtained numerically by using a 2.5D model of a tunnel/soil system. In this system, the railway underground infrastructure considered consists of a tunnel of 8.5 m of inner diameter with a tunnel wall thickness of 0.35 m. The center of the tunnel is located at 19.2 m from the ground surface. The mesh created for the tunnel/soil system is presented in Fig. 1, where 20 collocation points are uniformly distributed from 14.325 m to 28.325 m, horizontally from the tunnel center. The excitation assumed in this model consists on a vertical unitary force applied on the tunnel invert. Then, a model of the soil, presented in Fig. 2, is used to obtain $\mathbf{H}_{cf}$ the virtual forces by using Eq. (1). There are 20 virtual forces uniformly distributed in a semicircumference of 7 m of radius. A building/soil model has been also constructed and it is presented in Fig. 3. The building is made up of 2 floors with 3 m of height and a span between walls of 4 m. The thickness of the walls and the floors is considered to be 0.3 m. The depth of the shallow foundations is 1.4 m from the ground surface. From this model, the Green's functions matrix $\mathbf{H}_{bf}$ that relates the response on the evaluation points P1, P2 and P3 with the virtual forces can be obtained. Then, the response on the evaluation points can be obtained by using Eq. (2).

With the aim of checking the presented methodology, a model of the corresponding comprehensive tunnel/soil/building system has been created. The mesh of this model is presented in Fig. 4, where the collocation are only highlighted to show the correspondence with the hybrid model. In order to be in accordance with the models used for the hybrid methodology, the center of the building is located at 21.35 m horizontally from the center of the tunnel. In this model, the excitation considered is also a vertical unitary force applied on the tunnel invert. The response obtained by this reference model in any evaluation point of the building and the surrounding ground should match the response in the same points obtained by the hybrid methodology. The comparison between the responses of both models for several case are presented in the following sub-sections.

3.1 2D Problem

In this section, a comparison of the response obtained by the reference and hybrid models for the 2D problem is shown. The results for a 2D case are obtained from a 2.5D modelling by considering the wavenumber equal to zero. Figs. 5 and 6 show this comparison for the evaluation points P1 and P2, respectively, for the horizontal and vertical displacement in time and frequency domains. As shown, both responses are in good agreement up to 200 Hz. For higher frequencies, both models should not behave properly since the elements size of FEM are not small enough.

3.2 2.5D Problem

In this section, a comparison of the response obtained by the reference and hybrid models for the 2.5D problem is shown. The results for this case are obtained at the specific frequencies of 31.5 Hz and 63 Hz for a set wavenumbers uniformly distributed between -1 rad/m and 1 rad/m. The amplitude of the displacement in longitudinal, horizontal and vertical directions are compared at the evaluation points P1 and P3. Figs. 7, 8, 9 and 10 are showing the described comparison. It can be observed that the hybrid approach results are in a good agreement with the reference model.

4 CONCLUSIONS

In this paper, a new methodology for the prediction of railway-induced vibration in buildings to be build close to an operational railway infrastructure is proposed. This is a hybrid approach, based on weak coupling between the railway infrastructure and the building, that uses experimental measurements of the railway-induced vibration in the ground surface to obtain the wave incident field, combined with a theoretical building/soil model to obtain the response of the system. This hybrid model simplifies the usual numerical procedure for these problems, since a model of the railway infrastructure is not longer required. Moreover, it reduces the uncertainty of the prediction due to the use of experimental measurements of the particular site to be studied. In addition, it provides a higher accuracy and flexibility than empirical models based on experimental transmissibility functions between the ground surface and the building. The results obtained show that the proposed hybrid model is working accurately for the all the cases studied. This methodology could be also been used for the prediction of re-radiated noise inside buildings if a noise radiation model in cavities is considered[12,13].

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Table 1 – Properties used on the different materials.

Material	E (GPa)	ρ (kg/m^3)	ν	ξ
Soil	0.39	2000	0.3	0.04
Tunnel	30	2500	0.2	0.01
Building	30	2500	0.2	0.01

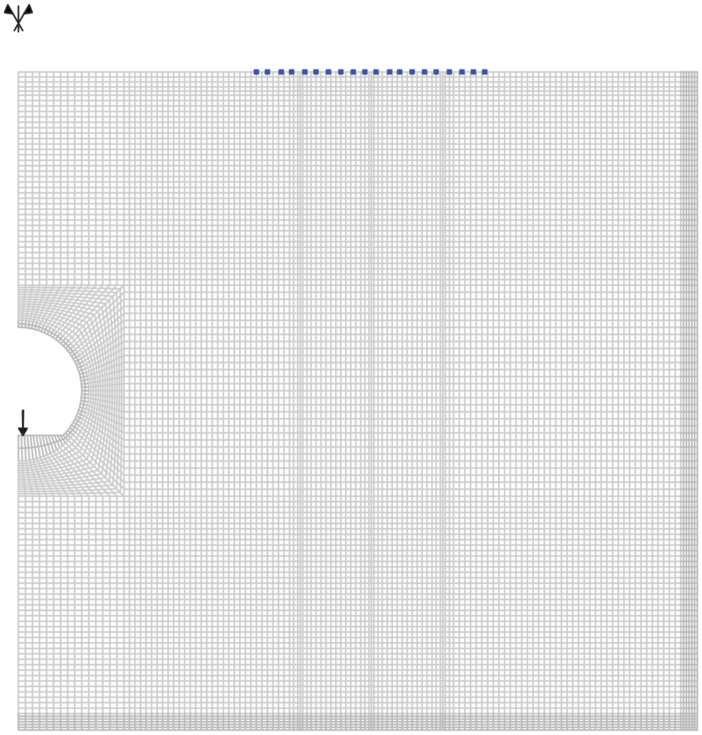

Fig. 1 – Mesh of the tunnel/soil system, location of the applied force and position of the collocation points (in blue).

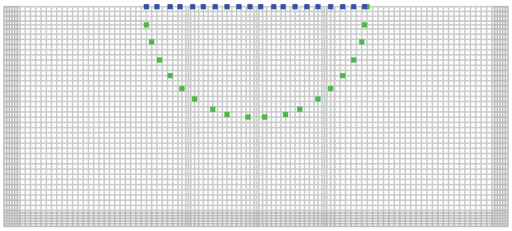

Fig. 2 – Mesh of the soil, where the position of the collocation points and the virtual forces is highlighted in blued and green, respectively.

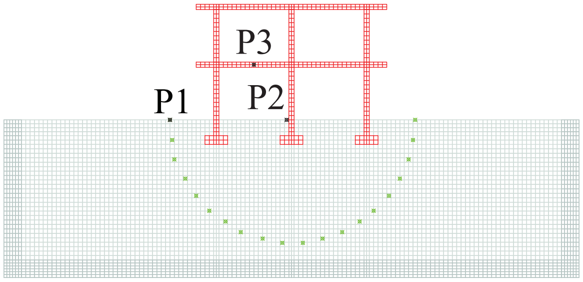

Fig. 3 – Mesh of the building/soil system, where the position of the evaluation points P1, P2 and P3 is represented by black points and the position of the virtual forces is highlighted in green.

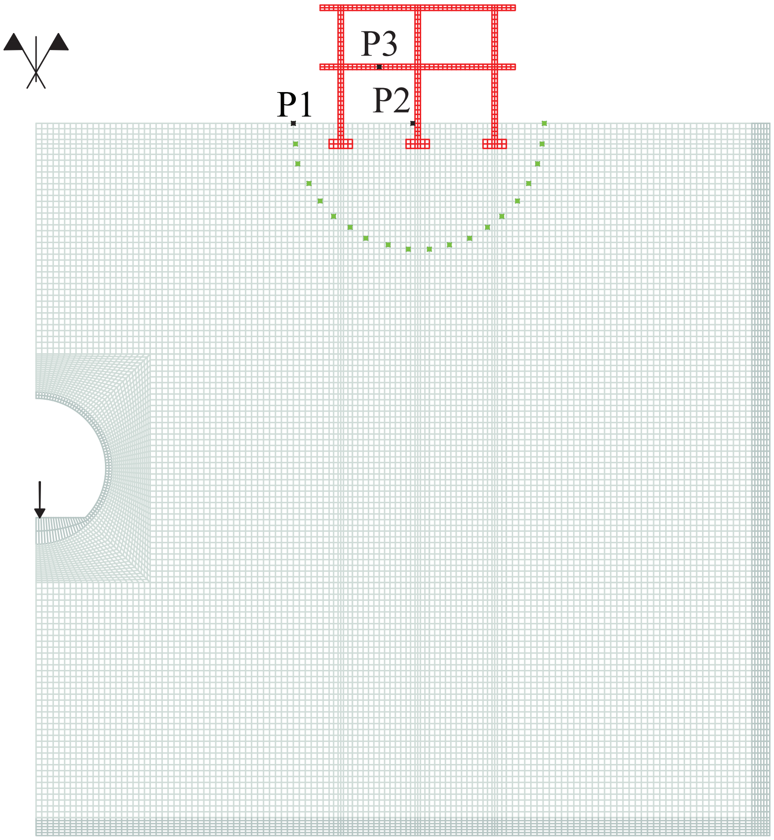

Fig. 4 – Mesh of comprehensive tunnel/soil/building system, where the position of the evaluation points P1, P2 and P3 is represented by black points and the position of the collocation points used in the hybrid method is highlighted in blue.

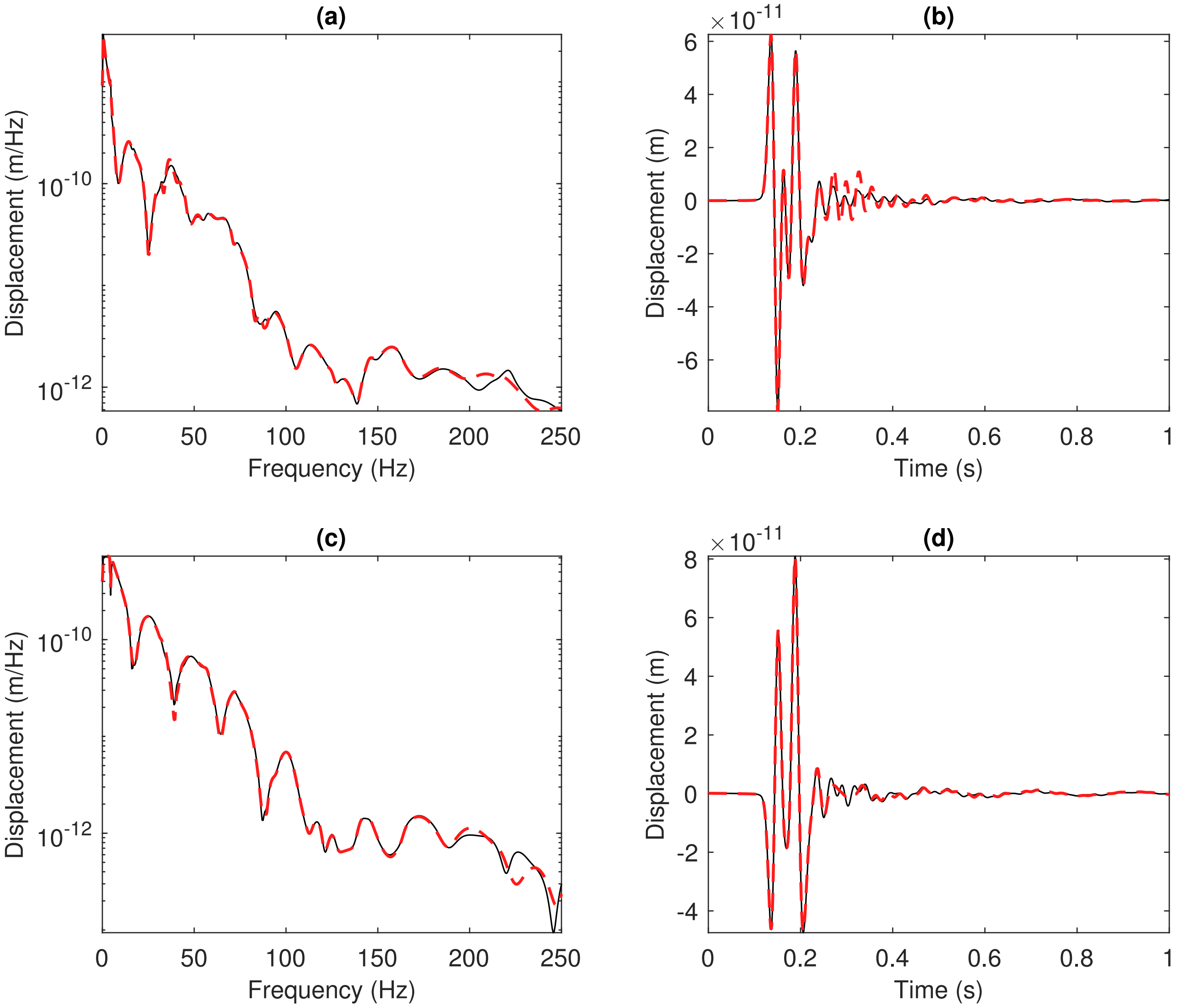

Fig. 5 – Results for the displacement of vibration at the collocation point P1 for the 2D study case. The plots a) and b) correspond to the vertical displacement, on the frequency and time domains, respectively, and the plots c) and d) correspond to the horizontal displacement, also on frequency and time domains. Continuous black lines represent the results of the reference model and the dashed red lines the results of the hybrid method. Frequency domain plots are showing the amplitude of the response.

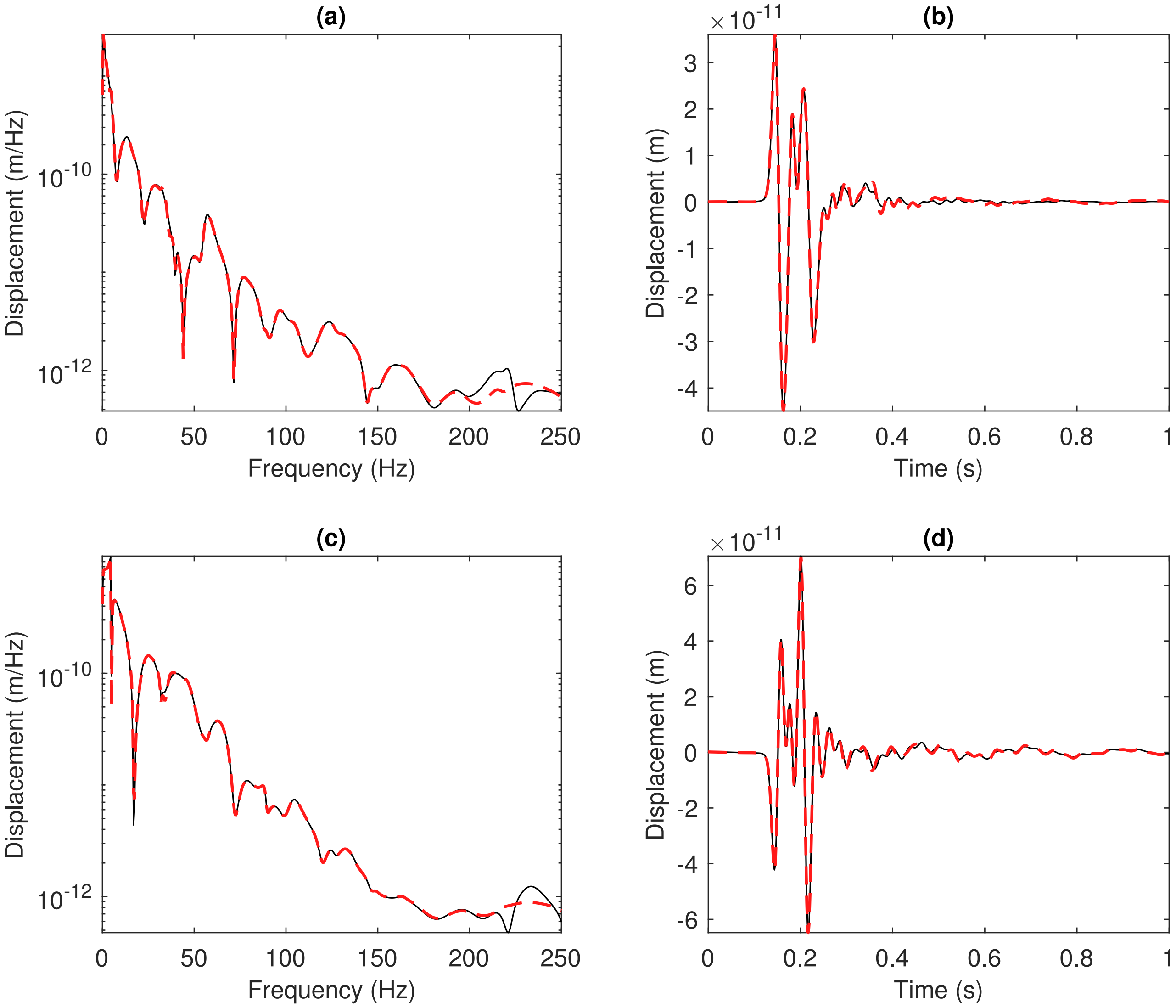

Fig. 6 – Results for the displacement of vibration at the collocation point P2 for the 2D study case. The plots a) and b) correspond to the vertical displacement, on the frequency and time domains, respectively, and the plots c) and d) correspond to the horizontal displacement, also on frequency and time domains. Continuous black lines represent the results of the reference model and the dashed red lines the results of the hybrid method. Frequency domain plots are showing the amplitude of the response.

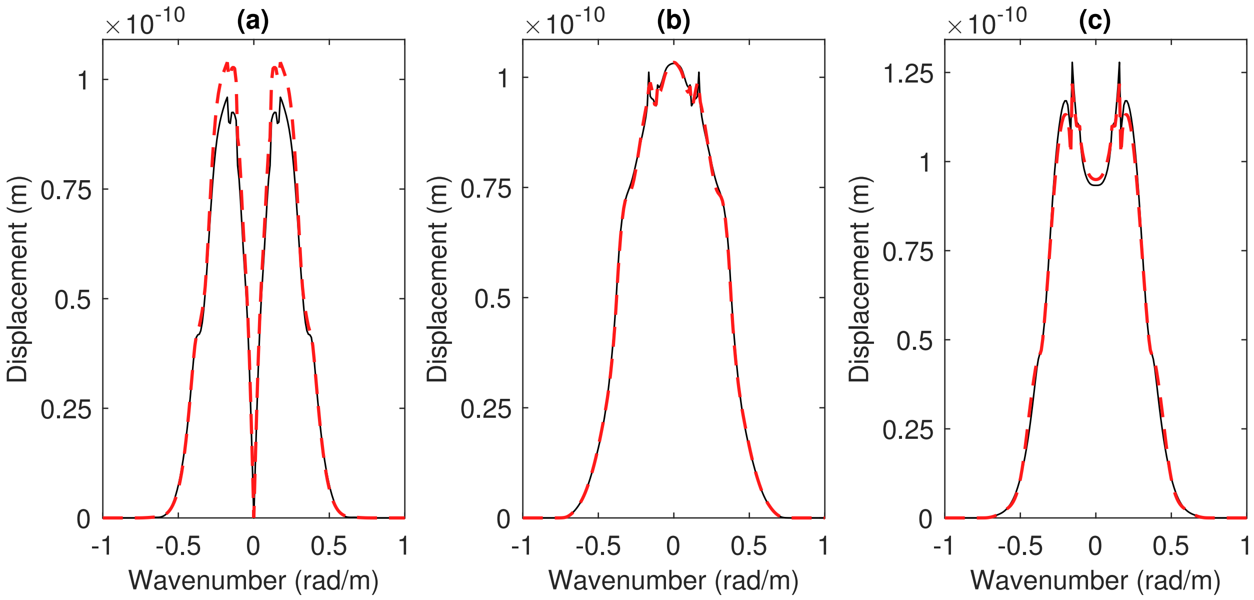

Fig. 7 – Amplitude of the displacement of vibration at the collocation point P1 for the 2.5D study case at a frequency of 31.5 Hz. a), b) and c) plot represent the longitudinal, horizontal and vertical displacement, respectively. Continuous black lines represent the results of the reference model and the dashed red lines the results of the hybrid method.

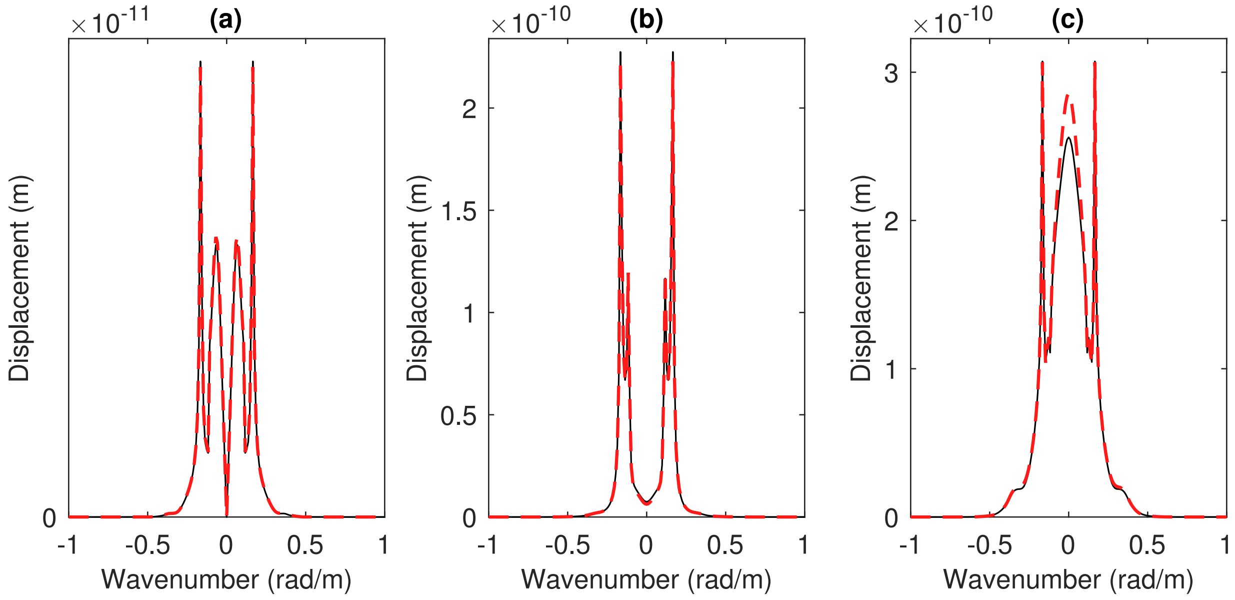

Fig. 8 – Amplitude of the displacement of vibration at the collocation point P3 for the 2.5D study case at a frequency of 31.5 Hz. a), b) and c) plot represent the longitudinal, horizontal and vertical displacement, respectively. Continuous black lines represent the results of the reference model and the dashed red lines the results of the hybrid method.

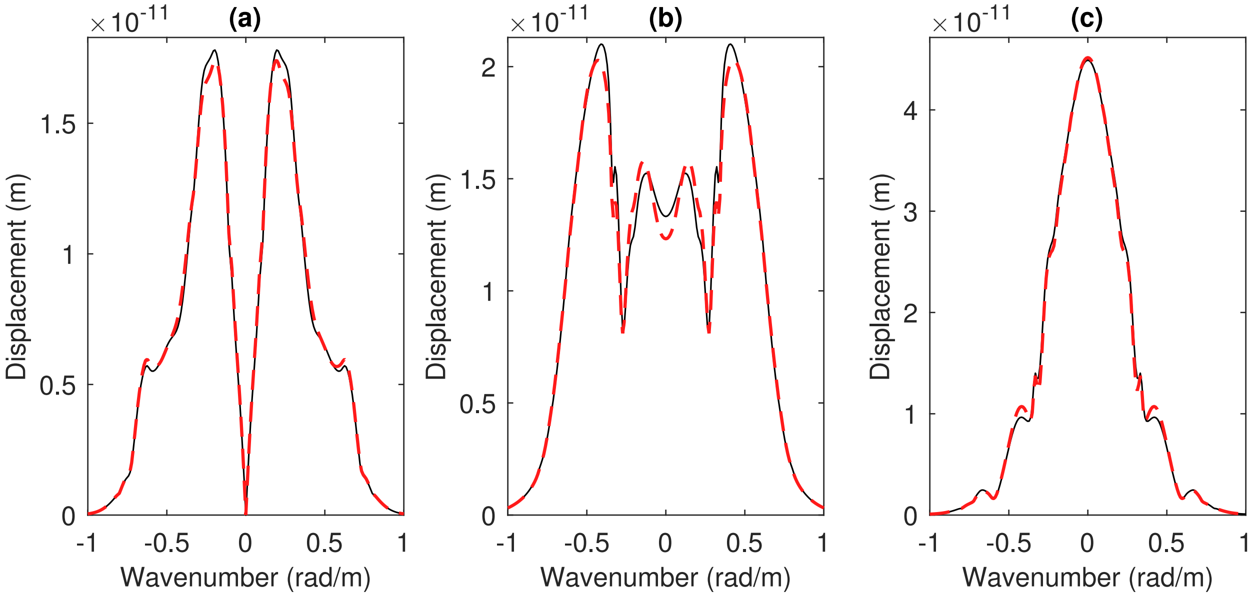

Fig. 9 – Amplitude of the displacement of vibration at the collocation point P1 for the 2.5D study case at a frequency of 63 Hz. a), b) and c) plot represent the longitudinal, horizontal and vertical displacement, respectively. Continuous black lines represent the results of the reference model and the dashed red lines the results of the hybrid method.

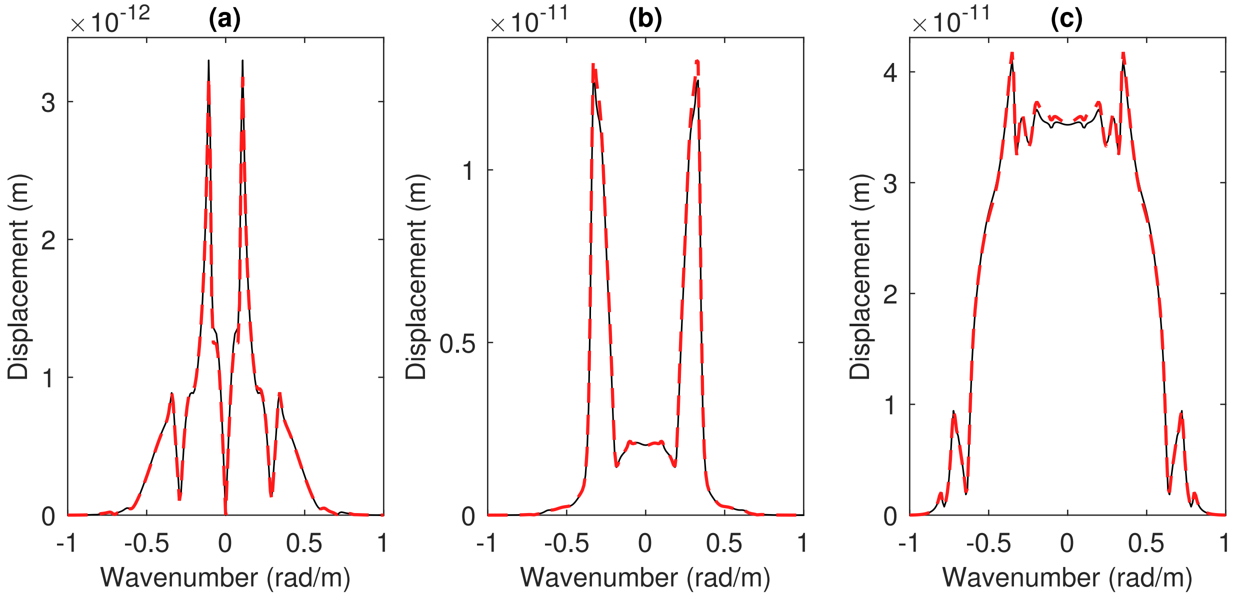

Fig. 10 – Amplitude of the displacement of vibration at the collocation point P3 for the 2.5D study case at a frequency of 63 Hz. a), b) and c) plot represent the longitudinal, horizontal and vertical displacement, respectively. Continuous black lines represent the results of the reference model and the dashed red lines the results of the hybrid method.