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A parametric study on the isolation of ground-borne noise and vibrations in a building using a coupled numerical model

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Underground traffic induced vibrations and noise in buildings are a major environmental concern in urban areas. To quantify these vibrations a numerical prediction model has been developed and validated.
A coupled FE-BE model is used to compute the incident ground vibrations due to the passage of a train in the tunnel. A dynamic soil-structure interaction model is used to determine the vibration levels of the building. The soil-structure interaction problem is solved by means of a 3D boundary element method for the soil coupled to a 3D finite element method for the structural part. An acoustic 3D spectral finite element method is used to predict the acoustic response.
The coupled numerical model is used to quantify the efficieny of vibration and noise mitigation measures at different stages of the vibration propagation chain. Vibration isolation with a floating slab track is modeled on the source side, base isolation is incorporated in the structure model, and a box-within-box arrangement is considered for the isolation of re-radiated noise in the buildings rooms. The insertion gain of the three methods is compared using the model of a multi-story portal frame office building subjected to ground-borne vibrations from an underground railway line.

1 Introduction

Significant noise and vibrations in buildings near railway tracks and subway tunnels are attributed to trains moving on an uneven track. Vibrations are transmitted through the surrounding soil to nearby buildings, and induce structural vibrations that are dominant in the frequency range between 1 Hz and 80 Hz. Structural vibrations cause re-radiated noise in the building's enclosures, which is dominant in the frequency range between 30 Hz and 200 Hz. In order to be able to design vibration isolation countermeasures, prediction tools are needed that can model the vibration propagation from the railway to the structure.

This paper presents a numerical model for the prediction of ground-borne vibrations and re-radiated noise in buildings. The numerical model is capable of handling the complex vibration propagation problem from the moving vehicle to the structure's room, which can practically be divided into three weakly coupled subproblems.

The first subproblem deals with the vibration generation into the soil by moving vehicles on a surface or underground railway track. The second subproblem is the dynamic soil-structure interaction problem, where the incident wave field is applied as an excitation to a coupled soil-structure model and the structural vibrations are determined. In the third subproblem, the radiation problem is solved, where the sound pressure radiated into the closed rooms of the structure by vibrating walls is determined.

The source model consists of a distributed parameter track model coupled to a periodic finite element model of the tunnel. The surrounding soil is modelled by a periodic boundary element method using the Green's functions of a layered half space [1, 2]. The structural vibrations due to the incident wave field are computed by means of a three-dimensional coupled finite element-boundary element model, based on the subdomain formulation proposed by Aubry and Clouteau [3]. Finally, for the sound radiation problem, an acoustic spectral finite element method is applied. A similar model has been recently presented for the case of structural vibrations and re-radiated noise due to high-speed surface railways [4].

The methodology is used to classify different measures to mitigate structural vibrations and re-radiated noise, at different levels in the vibration propagation chain. Firstly, a floating slab track is investigated by modifying the track model in the first subproblem. This countermeasure has the advantage that it reduces the ground vibrations and yields a global vibration isolation in all surrounding buildings. The second countermeasure is base isolation of the structure, which is modelled by modifying the structure model in the second subproblem. The last investigated method is a local noise and vibration isolation of a single room in the building by means of a box-within-box arrangement.

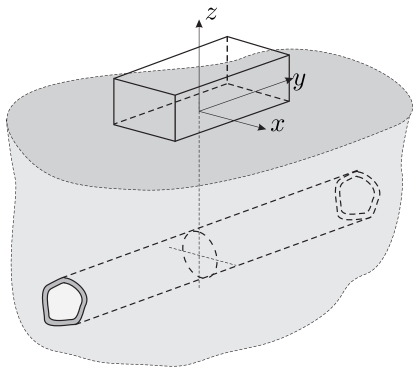

Figure 1: The problem geometry.

2 The numerical model

The geometry of the problem investigated is shown in Fig 1. A straight underground railway tunnel is placed under a building resting on a layered half space.

2.1 The incident wave field

An invariant concrete tunnel embedded in a layered half space at a depth of 13.5 m is considered. The tunnel has an internal radius $r_i = 2.7\,\mathrm{m}$ and a wall thickness $t = 0.3\,\mathrm{m}$. A conventional non-ballasted concrete slab track is considered in the tunnel with UIC 60 rails and soft rail pads with a stiffness $k_{\mathrm{rp}} = 50\,\mathrm{MN/m}$ discretely supporting the rails at an interval $d = 0.6$ m on the concrete sleepers. The track is modelled as an infinite beam on continuous support. The surrounding layered half space consists of two layers with a thickness of 2 m and 18.5 m respectively, on top of a half space. The top layer has a shear wave velocity $C_s = 180$ m/s, while the second layer is stiffer and has a shear wave velocity $C_s = 220$ m/s. The underlying half space has a shear wave velocity $C_s = 320$ m/s. A Poisson's ratio $\nu_s = 0.33$ and a density $\rho_s = 2000$ kg/m^3 is assumed in all layers.

The periodicity or invariance of the tunnel and the soil in the longitudinal direction is exploited using the Floquet transform, limiting the discretization effort to a single bounded reference cell and formulating the problem in the frequency-wavenumber domain [1, 2]. A general analytical formulation is used to compute the response of three-dimensional invariant or periodic media that are excited by moving loads [5].

The dynamic interaction between the wheel and the rail is responsible for generating vibrations from moving trains. A metro train travelling with a speed of 50 km/h on an uneven rail is modelled. The train consist of seven cars each of length 16 m. The bogie and axle distance on all cars are 10.34 m and 1.91 m, respectively. The mass of the coach with passengers is 43000 kg, while the mass of the bogie and axle are 3600 kg and 1700 kg, respectively. In this paper, two excitation mechanisms are considered: the quasi-static excitation and the unevenness excitation. For the quasi-static excitation, the axle loads are constant and equal to the total weight of the train per axle. For the unevenness excitation, the contact forces are computed from the rail unevenness expressed as a stochastic process characterized by a single-sided power spectral density (PSD) in the wavenumber domain [6].

Figure 2 shows the time history, and one-third octave band spectrum of the vertical component of the free field velocity at the origin of the coordinate system. The dominant part of the frequency content is between 10 and 80 Hz, which gives rise to low-frequency vibrations and re-radiated noise in the buildings. The higher frequency components up to 150 Hz are also present but are considerably attenuated due to the material damping in the soil. The peak in the frequency content corresponds to the wheel-track resonance frequency. The passage of the individual axles of the train is not apparent in the time history, as the contribution of the quasi-static forces is negligible in the free field and the dynamic forces due to the rail unevenness dominate.

2.2 Countermeasure 1

The isolation of the source is considered to mitigate the vibrations induced by moving trains. This has an advantage with respect to the isolation at the receiver side that it affects several structures in the surrounding. Ballast mats, soft rail pads and floating-slab tracks are widely used as vibration countermeasures for underground railway tracks. Floating slabs are considered to be very effective in mitigation of vibrations in the wide frequency range of interest. Rubber bearings or steel springs are accommodated between the slab and the tunnel bed.

In this paper, the vibration isolation efficiency of a floating slab track with an isolation frequency of 10 Hz is investigated. The isolation frequency of the floating slab track is defined as the resonance frequency of a

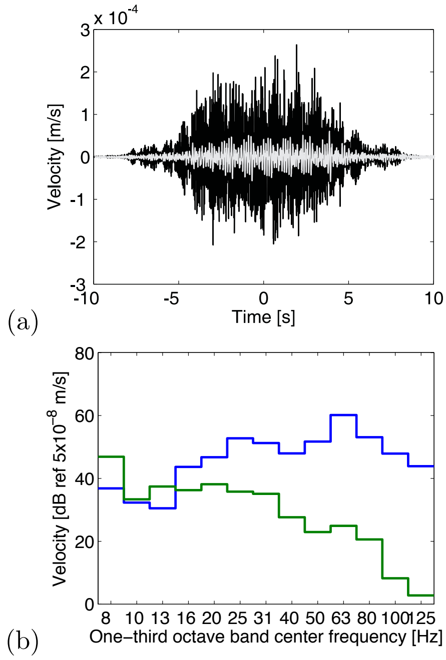

Figure 2: (a) Time history and (b) one-third octave band spectrum of the vertical component of the free field velocity at the center of the surface foundation due to the passage of the train.

single-degree-of-freedom system with a mass equal to the track's mass per unit length and stiffness equal to the vertical stiffness of the slab bearings. Discontinuous concrete slabs of dimensions 31 m × 2.5 m × 0.3 m are supported by two rows of 17 springs with a spring stiffness of 10 MN/m each. The slab is modelled as a continuous beam coupled to the tunnel via a uniform support, that has a low stiffness corresponding to the isolation frequency of 10 Hz.

Fig 2 shows that the vibration levels have significantly reduced above 15 Hz. This can be explained by the fact that, above the isolation frequency, energy remains confined to the slab and is not transmitted to the tunnel and the soil. At frequencies below 15 Hz, however, no benefit is achieved and vibration levels have increased instead. These low frequency vibrations are not important from the perspective of the re-radiated noise.

2.3 Structural response

The modeled structure is a three-story portal frame office building located directly above the tunnel. The dimensions of the building are 10 m × 15 m × 9.3 m in the x, y and z directions, respectively. The structure is modeled by means of a three-dimensional structural finite element method. The finite element mesh is shown in Fig 3.

The superstructure is supported by a 0.3 m thick reinforced concrete raft foundation. The basic structure consists of a reinforced concrete portal frame structure containing vertical columns of cross sectional dimensions 0.3 × 0.3 m and horizontal beams of dimensions 0.3 × 0.2 m. This frame structure supports three 0.3 m thick slabs. The structure has a reinforced concrete central core which surrounds the stair-case. The thickness

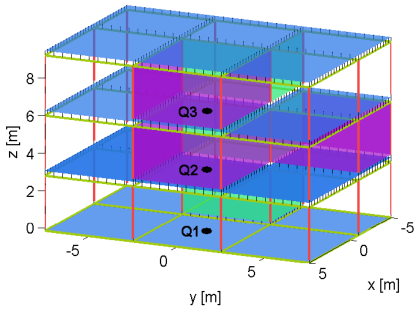

Figure 3: Finite element mesh of the office building and location of the observation points Q1, Q2 and Q3 in the building.

of the core walls is 0.15 m. The structural model is extended with the in-fill walls of three rooms besides the core. Room 1 has dimensions $6 \times 5 \times 3$ m and is located on the first floor, behind the core wall; room 2, which has the same dimensions, is located on the second floor; a smaller room 3 with dimensions $4 \times 5 \times 3$ m is located on the first floor, besides the core. The masonry in-fill walls are 0.06 m thick. Figure 3 also shows the position of the observation points Q1, Q2 and Q3 in the building, located on the ground floor, first floor and second floor, respectively, at the horizontal coordinates $x = 2$ m, $y = 0$ m.

The subdomain method proposed by Aubry et al. [3] and Clouteau is used to formulate the dynamic soil-structure interaction problem. Figures 4 and 5 display the vertical component of the structural velocity computed at points Q1 and Q2 in the office building. Comparing the incident wave field at the foundation (Fig 2) with the vibration velocity of the foundation (Fig 4), the effect of dynamic soil-structure interaction can be investigated. This effect is a slight attenuation of the ground vibrations due to the presence of the office building. Around a frequency of 25 Hz, a slight amplification can be observed, as vibrations propagate from the foundation to the upper level. This is due to the local bending modes of the slabs. In the higher frequency range (above 70 Hz), the structural vibrations are attenuated due to the structural damping.

2.4 Countermeasure 2

The second investigated countermeasure is base isolation of the office building. This is performed by isolating the superstructure from the foundation by placing springs between the foundation and the columns of the superstructure. The isolation frequency is defined as the resonance frequency of the SDOF system consisting of the total mass m of the superstructure and the total stiffness k of the springs. Since the superstructure does not behave as a rigid body at high frequencies, the efficiency of the base isolated building is overestimated by this SDOF model. However, this simple SDOF model is widely used to denote the base isolation frequency.

In the present example, 9 springs of vertical stiffness k_z are placed under the columns that are not connected to

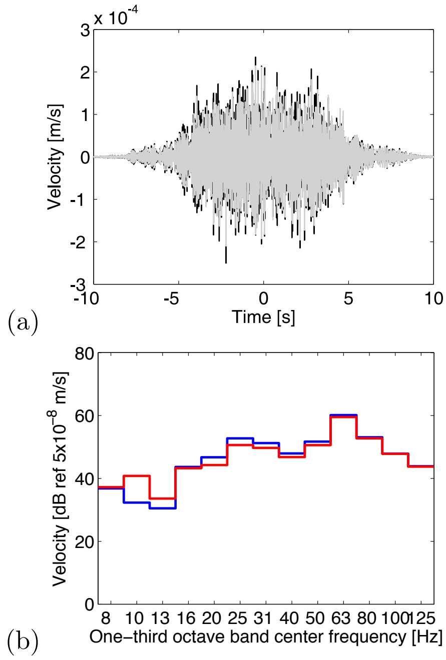

Figure 4: (a) Time history and (b) one-third octave band spectrum of the vertical component of the structural velocity at point Q1 in the office building due to the passage of the train.

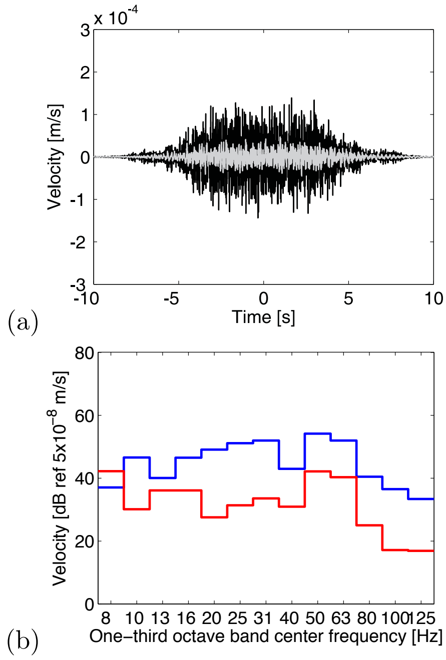

Figure 5: (a) Time history and (b) one-third octave band spectrum of the vertical component of the structural velocity at point Q2 in the office building due to the passage of the train.

the core, and a distributed spring of total stiffness $3k_z$ is placed under the core elements. The total stiffness and the total mass of the superstructure results in an isolation frequency $f_z = 10$ Hz. It should be mentioned that the 10 Hz base isolation frequency is relatively high and a lower isolation frequency is often pursued in practice for a more efficient performance.

Figures 4 and 5 display the vertical structural velocity in the base isolated building at points Q1 and Q2. Unlike the case of the track isolation, the incoming wave field does not change and the vibration levels at the foundation of the building remain approximately the same as in the unisolated case. The effect of base isolation can be observed by comparing the vibration levels at the foundation (point Q1) and the first floor (point Q2) of the building. The reduction in the vibration levels on the first floor is about 10-15 dB around the wheel-track resonance frequency, and increases to 20 dB in the higher frequency range.

2.5 Acoustic response

After determining the structural vibrations, the acoustic response of the closed rooms can be computed. This computation involves the solution of the Helmholtz equation in closed acoustic domains.

As the impedance of the radiating walls is much larger than that of the internal acoustic space, a weak coupling between structural and acoustic vibrations is assumed. The acoustic pressure inside the room has no effect on the vibration of the walls and the computed structural vibration velocity is applied as a boundary condition in an acoustic boundary value problem.

The internal acoustic space of the closed rooms is characterized by the speed of sound $C_a = 343$ m/s and the density of the air $\rho_a = 1.225$ kg/m^3. The absorbing surfaces of the rooms are characterized by an acoustic impedance relating the acoustic pressure to the difference of normal structural and acoustic velocities of the acoustic boundary. At relative low frequencies, the acoustic impedance can be computed from the walls' acoustic absorption coefficient α, which gives the ratio of the absorbed and the incident acoustic energy when a normal incident acoustic plane wave is reflected from the surface. In the present paper, an absorption coefficient $\alpha = 0.15$ is assumed. This value is typical for absorbing rooms with furniture and carpeted floors.

The internal sound pressure is computed by means of an acoustic spectral finite element method, in which the internal pressure is expressed in terms of the acoustic room modes of the rectangular rooms with rigid walls [4].

The time history and one-third octave band spectrum of the acoustic response due to the passage of a train in the tunnel is displayed in Fig 6. The dominant one-third octave bands are determined by the acoustic modes of the room. The sharp peak in the 63 Hz one-third octave band is due to the coincidence of the wheel-track resonance frequency and the first vertical acoustic room mode.

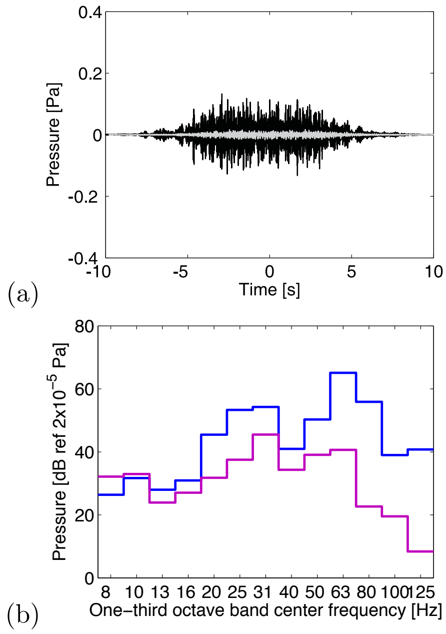

Figure 6: One-third octave band spectrum (magenta line) of the sound pressure in room 1 with the box-within-box arrangement due to the passage of the train.

2.6 Countermeasure 3

The third isolation method investigated, widely used in acoustic laboratories, smaller concert halls or theater rooms for both vibration and noise reduction purposes, is a box-within-box arrangement, where the whole interior boundary of a room is isolated from the vibrations of the building's walls and slabs. This method results in local vibration and noise isolation of the building's room.

In the model presented in this paper, the internal box consists of a 10 cm wide concrete floor slab and 6 cm wide concrete walls surrounded by a resilient material. For the sake of simplicity, this material has been modelled by a continuous spring-damper system, where the springs are connected to each node of the plate elements representing the floor and the walls. Similarly, the ceiling is modelled as a 6 cm thick wooden slab covered with a resilient material. The vertical isolation frequency of the room on springs has been chosen to 10 Hz and the horizontal resonance has been chosen to 8 Hz.

Fig 6 displays the acoustic response in room 1 to the passage of the metro train, for the case of the acoustic isolation with the box-within-box arrangement. The noise reduction is rather weak in the lower frequency range, but at the critical wheel-track resonance frequency, in the 63 Hz band, 25 dB reduction is achieved. In the higher frequency range, the reduction exceeds to 30 dB.

2.7 Comparison of the isolation methods

In the following, the vibration and noise isolation efficiency of the three reduction methods is compared. A useful way to evaluate the effectiveness of the isolation

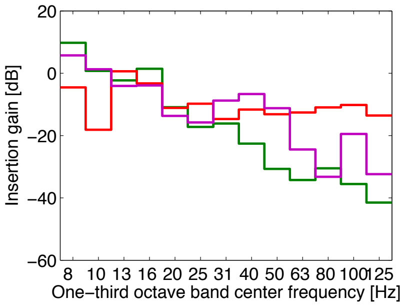

Figure 7: Insertion gain computed from the re-radiated noise in room 1 due to the passage of the metro train for the floating slab track (green line), the base isolation (red line) and the box-within-box arrangement (magenta line).

measure is to take the ratio of the response with and without isolation.

Figure 7 displays the insertion gain (the ratio of the response u^{iso} of the isolated and the response u^{uniso} of the unisolated system as $\mathrm{IG[dB]} = 20\log_{10}(u^{\mathrm{iso}}/u^{\mathrm{uniso}})$) computed from the re-radiated noise in room 1 for all noise isolation countermeasures. Considering that the noise reduction is more important above 40 Hz, the floating slab track is very efficient as it provides vibration isolation of the total building as well as the surrounding structures. However, one should not forget that the installation of a floating slab may result in larger vibrations and noise in the tunnel and the trains. The investigation of these effects is beyond the scope of the present paper. The isolation of the acoustic space with a box-within-box arrangement also provides effective noise isolation, exceeding 30 dB above 100 Hz. Base isolation of the building provides a reduction of about 15-20 dB at high frequencies. The amount of vibration reduction is much less than predicted by a single degree of freedom (SDOF) system. This difference is due to the fact that the complex superstructure does not behave as a rigid body on springs at higher frequencies. Due to the flexibility and internal vibrations of the building, the effective mass of the superstructure on the isolation springs is less and thus, the efficiency of the base isolation is reduced. For the case of the much simpler internal box structure at the box-within-box arrangement, this effect is less pronounced. The performance of the base isolated building can be enhanced by considering a lower isolation frequency of about 5 to 7 Hz, which is widely used in practice.

3 Conclusions

A numerical model has been presented that is used to compute structural vibrations and re-radiated noise in buildings generated by underground railway traffic. The model is a deterministic three-dimensional approach, accounting for vibration generation by a moving train on periodic media, dynamic soil-structure interaction and sound radiation into closed rooms.

The methodology has been used to demonstrate the efficiency of three vibration and noise reduction methods: a floating slab track, base isolation and a box-within-box arrangement. The countermeasures are assessed by calculating the insertion gain on the reradiated noise.

The floating slab track has been found to be a very effective vibration and noise reduction mechanism. This method provides the largest amount of vibration reduction in the investigated building, and it yields a vibration reduction at the source, which is advantageous to all the structures around the metro line. It has been found that base isolation of the structure can result in significant vibration isolation over all the building, but, for the case of complex structures, the isolation effect is less than predicted by SDOF models. This conclusion is significant, as mass-spring systems form the basis of the design of base isolation systems in many practical cases. It should also be mentioned that the base isolation frequency of 10 Hz considered in this paper is relatively high; in practice a lower isolation frequency is preferred for a better performance. The application of the box-within-box arrangement resulted in larger noise reduction than the base isolation. However, this method is relatively expensive, as it reduces the vibrations of a single room only.

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