A Numerical Model for Re-radiated Noise in Buildings from Underground Railways

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Summary

A numerical prediction model is developed to quantify vibrations and re-radiated noise due to underground railways. A coupled FE-BE model is used to compute the incident ground vibrations due to the passage of a train in the tunnel. This source model accounts for three-dimensional dynamic interaction between the track, tunnel and soil. The incident wave field is used to solve the dynamic soil-structure interaction problem on the receiver side and to determine the vibration levels along the essential structural elements 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 Bakerloo line tunnel of London Underground has been modelled using the coupled periodic FE-BE approach. The free-field response and the re-radiated noise in a portal frame office building is predicted.

1 Introduction

Ground-borne vibrations induced by underground railways are a major environmental concern in urban areas. These vibrations propagate through the tunnel and the surrounding soil into nearby buildings, causing annoyance to people. Residents in buildings are affected both by vibrations of the structure (5-80 Hz) and through the re-radiated noise (20-200 Hz) from the walls and ceilings of the rooms.

For the prediction of ground-borne vibrations and re-radiated noise in buildings, a modular architecture is adopted, which consists of the following subproblems: the dynamic vehicle-track-tunnel-soil interaction problem, the dynamic soil-structure interaction problem, and the prediction of re-radiated noise in the structures.

In the first subproblem, discussed in details in reference [4], the free field vibrations are predicted, by computing the contact force generated by the wheel/track interaction and then solving the dynamic track-tunnel-soil interaction problem. The dynamic track-tunnel-soil interaction problem is tackled using the coupled periodic FE-BE model developed within the framework of CONVURT [1]. A finite element method is used to model a periodic unit of the tunnel, while a boundary element method is used to model the soil as a horizontally layered elastic half space [1].

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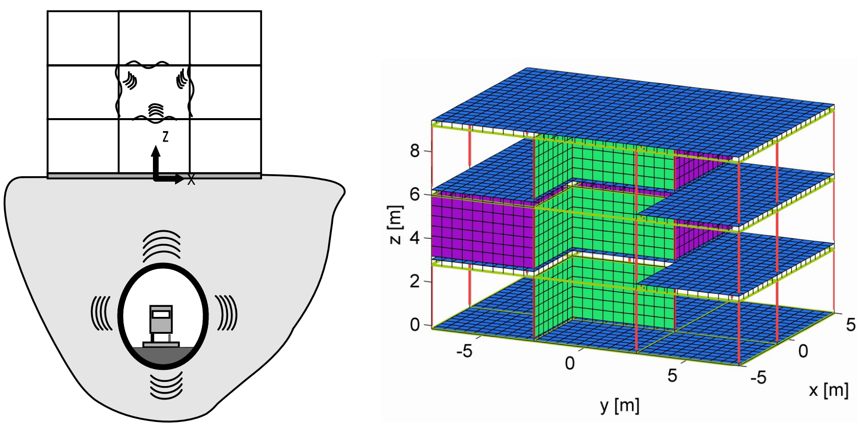
Once the incident wave field in the soil has been determined, the dynamic response of a three-dimensional building due to this incident wave field is computed. Similarly to the tunnel-soil interaction, a subdomain formulation is employed where a finite element method is used for the structure and a boundary element formulation is used for the soil. This approach allows investigation of influence of dynamic soil-structure interaction on the structural response [2].

In the third subproblem, the computed structural displacements are used as a vibration input for the computation of ground-borne noise in the building's enclosures. A spectral finite element method is applied to the acoustic problem, which, for the case of low wall absorption, can lead to a direct integral representation of the internal sound pressure.

To demonstrate the efficiency of the approach, the tunnel on the Bakerloo line of London Underground is modelled. The free field response is predicted in the frequency range 1-150 Hz, and subsequently the re-radiated noise in a hypothetic nearby multi-story portal frame office building is estimated.



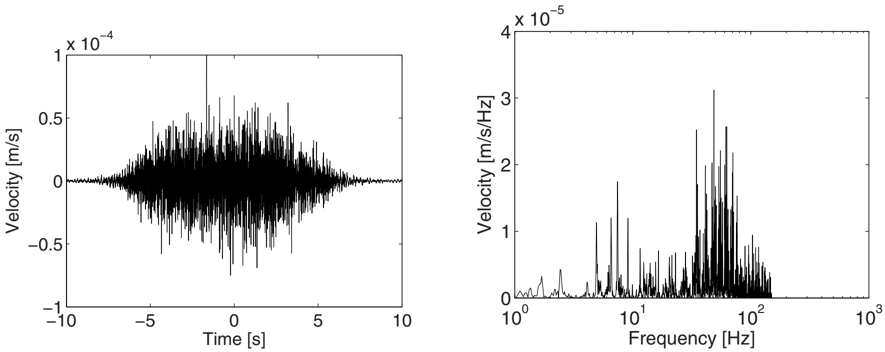
(a) (b)

Fig. 1. (a) Scheme of the numerical example. (b) Finite element model of the three-story portal frame office building.

2 The Incident Wave Field

The thory of computing the incident wave field is described in reference [4]. Here, only a brief introduction is presented. The model of a moving vehicle on a track periodic or invariant in the longitudinal direction is used to compute the incident wave field. The periodicity 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 formulate the problem in the frequency-wavenumber domain [3][1]. The vehicle is modelled as a set of concentrated masses representing the train's unsprung masses. The reference cell of the track and the tunnel is modelled by means of a finite element method. The tunnel is embedded in a horizontally layered soil. The geometrical and material characteristics of the soil, the tunnel and the track, as well as methodology for the determination of the incident wave field are decribed in [4] and [5].

Fig. 2 shows the vertical component of the free-field incident velocity computed in the corner point of the building at coordinates {-5 m, -7.5 m, 0 m}. The vibration source is the rail roughness expressed as a stochastic process with a power spectral density decreasing with the longitudinal wave number. The train speed is 50 km/h. The dominating part of the frequency content is between 20 Hz and 80 Hz with a peak at 50 Hz, which corresponds to the wheel-track resonance frequency. The bogie passages are not clearly visible in the time history as the tunnel is situated at a considerable depth, however, due to the specific train composition, the observed velocity spectrum is quasi-discrete. The computed incident wave field has been validated by means of the experiments performed on the Bakerloo line [4] [6].



(a) (b)

Fig. 2. (a) Time history and (b) frequency content of the vertical component of the incident wave field in the soil at coordinates {-5 m, -7.5 m, 0 m}

3 Dynamic Soil-Structure Interaction

A weak coupling between the incident wave field and the structure is assumed, meaning that the presence of the building has no effect on the vibration generation mechanism and the free field displacements are applied as an excitation on the coupled structure-soil model.

The decomposition method proposed by Aubry et al. and Clouteau [7] is used to formulate the dynamic soil-structure interaction problem. The structure is modelled in the frequency domain by a 3D structural finite element method. The equation of motion of the building is:

$$\left(\mathbf{K} - \omega^2\mathbf{M} + \hat{\mathbf{K}}^g\right)\hat{\mathbf{u}} = \hat{\mathbf{f}} \tag{1}$$

where the structural displacements are denoted by $\hat{\mathbf{u}}$, $\mathbf{M}$ and $\mathbf{K}$ denote the finite element mass and stiffness matrices, and $\hat{\mathbf{K}}^g$ stands for the frequency dependent stiffness matrix of the soil. The force $\hat{\mathbf{f}}$ and the stiffness of the soil are computed with a 3D boundary element model in the frequency domain, using the Green's functions of a layered half-space.

The portal frame office building, shown in Fig. 1b, has the dimensions 15x10x9.6m and is symmetrically placed on the free surface above the tunnel. The three story 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 0.3x0.3 m and horizontal beams of dimensions 0.3x0.2 m. This frame structure supports 0.3 m thick horizontal slabs. The structure has a reinforced concrete central core which surrounds the stair-case. The thickness 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 5x6x3 m, and is located on the first floor, behind the core wall; room 2, which has the dimensions, is located on the second floor; a smaller room 3 with dimensions 5x4x3 m is located on the first floor, besides the core. The masonry in-fill walls are 0.06 m thick. The finite element size is chosen as 0.5 m, which is fine enough for computations up to 150 Hz.

In the following, the structural response of the office building to the passage of the metro is presented. Fig. 3 displays the structural velocities at two points (Q1 and Q2) of the building. The point Q1 is located on the ground level, Q2 is located on the floor of room 1, both at horizontal coordinates x = -3 m, y = 0 m. The vibration levels at the point Q1 are very similar to the incident wave field, presented in Fig. 2. This indicates

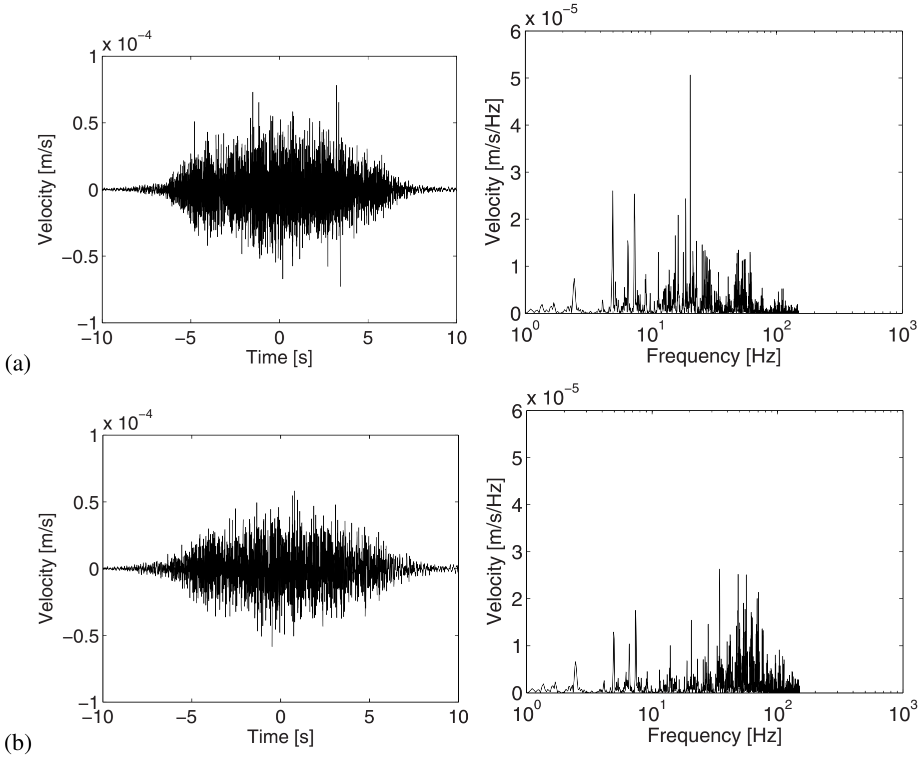


Fig. 3. Time history and frequency content of the vertical structural velocity in points (a) Q1 and (b) Q2

that, in the present case, dynamic soil-structure interaction plays a negligible role in the vibration transmission between the soil and the building. A significant vibration amplification can be observed between the foundation and the first floor due to the first local bending modes of the floor slab in the frequency range 20-30 Hz. The ground vibrations above 70 Hz are not transmitted up to the first floor, which is an effect of structural damping.

4 Re-radiated Noise in the Structure

After determining the structural response of the building, the acoustic radiation problem can be solved. 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 is characterized by the speed of sound $C_a = 343$ m/s and the density of the air $\rho_a = 1.2$ kg/m^3. The absorbing surfaces of the rooms are characterized by the acoustic impedance Z_a, relating the acoustic pressure $\hat{p}_a$ 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.

An acoustic spectral finite element method [8] is used to express the internal pressure $\hat{p}_a(\mathbf{x},\omega)$ in terms of the acoustic room modes:

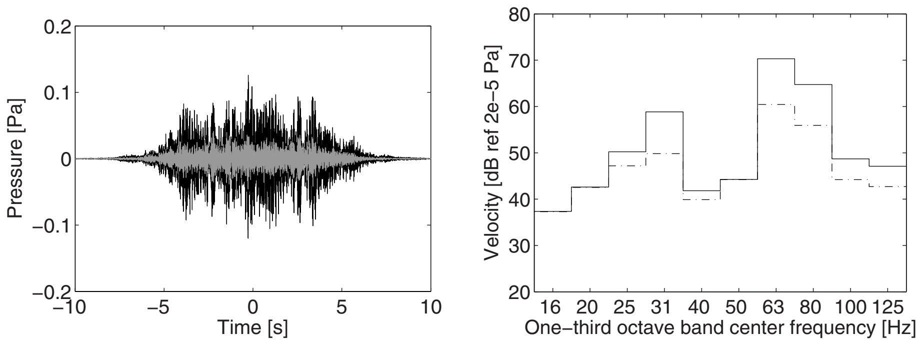
$$\hat{p}_a(\mathbf{x},\omega) = \sum_n \Psi_n(\mathbf{x})\hat{\beta}_n(\omega) \tag{2}$$

where $\Psi_n(\mathbf{x})$ denotes the n-th acoustic mode of the shoe-box shaped interior domain with rigid boundary conditions and $\hat{\beta}_n(\omega)$ is the corresponding modal coordinate. The application of the spectral finite element method results in a system of linear equations for the acoustic modal coordinates:

$$\left(\mathbf{\Lambda} + i\omega\mathbf{D} - \omega^2\mathbf{I}\right)\hat{\boldsymbol{\beta}} = i\omega\hat{\mathbf{F}} \tag{3}$$

where $\mathbf{\Lambda} = \mathrm{diag}\{\omega_n^2\}$ contains the eigenfrequencies of the acoustic domain, $\mathbf{I}$ is a unit matrix, $\mathbf{D}$ is the modal damping matrix related to the wall absorption, and $\mathbf{F}$ denotes the modal load vector [2].

Two different absorption coefficients are considered, assumed to be constant on the rooms' surface and over the whole frequency range: $\alpha = 0.03$ stands for a strongly reflecting room with uncovered concrete walls and an uncarpeted floor, while $\alpha = 0.15$ is typical for an unfurnished, carpeted room. A modal base including all the acoustic modes up to 200 Hz has been used in the spectral finite element method.



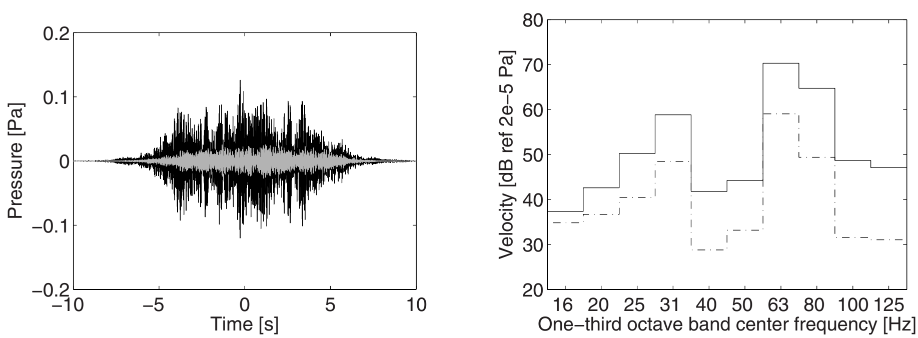
(a) (b)

Fig. 4. (a) Time history and (b) one-third octave band spectra of the sound pressure in room 1 during the passage of the train, with $\alpha = 0.03$ (solid black) and $\alpha = 0.15$ (gray dash-dotted)

Fig. 4 shows the pressure response in room 1 during the passage of the train for the two absorption coefficients. The dominant one-third octave bands are those containing the room's resonance frequencies at 28.6 Hz, 34.3 Hz, 57.2 Hz, 61.25Hz and 68.6Hz. Due to the frequency dependent sensitivity of the human ear, the apparent noise is determined by the 63 Hz peak. The one-third octave band spectra show a difference of 5 dB between the two wall absorptions above the first acoustic resonance of the room.

As an application, the effect of base isolation of the building on the re-radiated noise is investigated. The base isolation is performed by placing springs between the foundation and the columns of the first floor. 9 springs of equal stiffness k_z have been inserted below the structure's columns which are separated from the central core, and a distributed spring of total stiffness 3 k_z has been inserted under the core. In the example, the total mass of the superstructure and the stiffness of the springs result in an isolation frequency of 10 Hz.

Fig. 5 displays the re-radiated noise in Room 1 during the passage of the metro for the unisolated and the isolated buildings. The base isolation appears to be very



(a) (b)

Fig. 5. (a) Time history and (b) one-third octave band levels of the pressure in room 1 for the unisolated building (solid black) and the base isolated building (gray dash-dotted), for the case of $\alpha = 0.03$

effective, as the noise level in the room is reduced by 15-20 dB in the higher frequency range (above the 63 Hz band), where the human ear is more sensitive to the noise.

5 Conclusions

A 3D numerical model has been presented that is capable of predicting subway induced vibrations and re-radiated noise in buildings. The Bakerloo line tunnel of London Underground has been modelled using the coupled periodic FE-BE model and subsequently the structural and acoustic response in a hypothetic three-story portal frame office building has been predicted in the frequency range 1-150 Hz.

The dominant frequencies of the traffic induced acoustic response are basically determined by the first acoustic resonances of the room. The effect of wall absorption on the sound pressure has been investigated, and above the first acoustic resonance, a difference of 5 dB has been found between typical wall absorptions for concrete and carpeted walls. It has been shown how base isolation affects the re-radiated noise in the room.

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