A BLOCKED FORCE-BASED APPROACH FOR RAILWAY-INDUCED VIBRATION SIMULATION CONSIDERING STRONGLY COUPLED TRACK-SOIL-BUILDING SYSTEMS

Robert Arcos[1], Arnau Clot[1], Yazdan Shafieyoon[1], Jordi Romeu[1]

[1] *Acoustical and Mechanical Engineering Laboratory (LEAM), Universitat Politècnica de Catalunya - BarcelonaTech (UPC), Carrer Colom, 11, 08222 Terrassa (Barcelona), Spain.*

Abstract

Ground-borne vibration induced by railway traffic is a growing concern in densely populated urban environments. Railway-induced ground-borne noise and vibration prediction tools are valuable assets when implementing or upgrading railway systems, as well as when constructing new civil structures near existing operational lines. Railway-induced vibration simulations are typically computationally expensive due to several factors, including the unbounded and heterogeneous nature of the soil, the fact that dynamic loads generated by wheel-rail interaction are moving forces, and the strong dynamic coupling between the different subsystems involved. To reduce computational effort, it is common to assume that no significant dynamic coupling exists between the track (or track–tunnel) system and the building of interest. However, in situations where the proximity between the tracks and buildings is high, this assumption may no longer be valid. To address this issue, the present paper proposes an efficient methodology to simulate the response of strongly coupled track-soil-building or track-tunnel-soil-building systems based on the blocked force concept. The proposed approach consists of first determining the blocked forces at the building-soil interface using a model of the track-soil or track-tunnel-soil system excited by the moving train-track dynamic loads. These forces are then applied to the corresponding track-soil-building or track-tunnel-soil-building system to compute the building vibration response. By avoiding the explicit modelling of moving loads in this second stage of the methodology, the computational procedure is significantly simplified.

Corresponding author: *robert.arcos@upc.edu.*

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1. Introduction

Ground-borne noise and vibration arising from railway traffic is a growing concern in urban environments, especially in densely populated areas. The assessment of expected vibration exposure using numerical simulation tools is particularly useful when implementing a new railway line, applying changes on the operation characteristics of an existing railway system (on the circulation speed, on the frequency of train pass-bys or the type of train vehicles employed, among others), designing vibration mitigation measures or when predicting the levels of vibration on new buildings planned in the vicinity of operational railway lines. Railway-induced vibration simulations are typically computationally expensive due to several factors, including: the unbounded and heterogeneous nature of the soil that poses complications to numerical methods that does not naturally fulfil the Sommerfeld condition; the moving nature of the dynamic loads generated by the wheel-rail interaction, which require special modelling schemes; and the strong dynamic coupling between the different subsystems involved, that make the substructuring processes more computationally demanding, especially when coupling an longitudinally infinite domain as track-soil or track-tunnel-soil systems are, with finite system such as a building. Regarding the latter, a common assumption when assessing the response of a particular building to railway traffic is to consider a weak coupling between the source, i.e. the track system, for at-grade railways, or the track-tunnel-soil system, for underground railways, and the receiver, typically a targeted residential building structure [1], [2].

However, in situations where the proximity between the track and the targeted building is high, the assumption of considering a weak coupling dynamic relationship between the source and the receiver may no longer be valid according to Coulier et al. [3]. In this cases, the simulation should account for the source-receiver strong coupling. An interesting approach based on an iterative method to perform such simulations is presented Edirisinghe and Talbot [4]. In that work, a track-tunnel system is considered to be the source while a single pile foundation is set be the receiver structure. The models of the two sub-systems are coupled through an iterative wave-scattering scheme: the far-field wave-field radiated by each sub-system is used to excite the other, and this exchange is repeated over successive iterations until the solution converges, yielding the response of the fully dynamically coupled tunnel-pile system. Another approach to conduct railway-induced vibration simulations accounting for the source-receiver strong coupling is presented by Bucinskas et al. [5]. This approach is based on a mixed frame of reference environment, in which the moving frame of reference employed to determine the wheel/rail interaction forces and the train-induced response coexists with a fixed frame of reference, which is very useful when finite structures need to be coupled to the track-(tunnel)-soil system. This work can be seen as an extension of the methodology presented by Noori et al. [6] to the present problem; in that case, the methodology was applied to dynamic vibration absorbers coupled to the interior floor of a double-deck tunnel system for simulating railway-induced vibrations.

The present paper proposes an efficient methodology to simulate the mentioned problems involving strongly coupled track-soil-building or track-tunnel-soil-building systems. The proposed approach consists of first determining the blocked forces at the building-soil interface using a model of the track-soil or track-tunnel-soil system excited by the moving train-track dynamic loads. These forces are then applied to the corresponding track-soil-building or track-tunnel-soil-building system to compute the building vibration response. By avoiding the explicit modelling of moving loads in this second stage of the methodology, the computational procedure is significantly simplified.

2. Strong coupling formulation

The response of a track-(tunnel)-soil system when modelled on the basis of 2.5D domain framework can be defined by [7]

$$u_i(x,\omega) = \frac{1}{2\pi v} \sum_{n=1}^{N_a} \int_{-\infty}^{+\infty} \bar{H}_i \left(\frac{\omega - \tilde{\omega}}{v}, \omega \right) f_n^{w/r} \exp\left[-\mathrm{i} \left(\frac{\omega - \tilde{\omega}}{v} \right) (x - x_{0,n}) \right] \mathrm{d}\tilde{\omega}, \tag{1}$$

where $u_i(x,\omega)$ is the frequency-domain response at an arbitrary $y-z$ position of the track-(tunnel)-soil system in the ith direction, $H_i(k_x,\omega)$ is the 2.5D transfer function of the response of the system at the mentioned arbitrary point due to a moving vertical force applied to the track, $f_n^{w/r}$ is the dynamic wheel/rail interaction force of the nth train axle, N_a is the number of axles of the train, $x_{0,n}$ is the longitudinal position of the nth train axle at time equal to zero, v is the train speed, $\tilde{\omega}$ is the angular frequency associated with the dynamic wheel/interaction forces in the moving frame of reference and ω is the angular frequency of the response seen from a fixed frame of reference.

On the other side, considering a finite element model of the building, its response due to an excitation coming from its foundation can be obtained from the following expression [1]

$$\begin{bmatrix} \mathbf{D}_{ii} & \mathbf{D}_{ib} \\ \mathbf{D}_{bi} & \mathbf{D}_{bb} + \mathbf{D}_{bb}^{s} \end{bmatrix} \begin{Bmatrix} \mathbf{u}_i \\ \mathbf{u}_b \end{Bmatrix} = \begin{Bmatrix} 0 \\ \mathbf{D}_{bb}^{s} \mathbf{u}_{\text{inc}}, \end{Bmatrix} \tag{2}$$

where $\mathbf{u}_i$ and $\mathbf{u}_b$ are vectors that collect the frequency-domain displacements corresponding to the degrees of freedom of the interior and boundary (at the foundation/soil interface) nodes, respectively, $\mathbf{D}$ is the dynamic stiffness matrix of the building subsystem, $\mathbf{D}_{bb}^{s}$ represents the inverse of the direct receptance matrix of the soil subsystem accounting for the corresponding cavities associated with the building foundations (obtained using, for example, the boundary element method [1]), and $\mathbf{u}_{\text{inc}}$ are frequency-domain displacements of the degrees of freedom at the soil-building interface due to railway traffic excitation.

In weak coupling approaches, the matrix $\mathbf{D}_{bb}^{s}$ is typically obtained considering just the soil subsystem, while $\mathbf{u}_{\text{inc}}$ are computed as free-field displacements, not accounting the effect of the building in the calculation. In contrast, the response of the building considering a strong coupling can be obtained if the receptance matrix $\mathbf{D}_{bb}^{s}$ is obtained using the full track-(tunnel)-soil system and $\mathbf{u}_{\text{inc}}$ is obtained using Eq. (1) in the presence of the building structure. The first requirement can be achieved by Fourier anti-transforming along the longitudinal wavenumber k_x the 2.5D transfer functions of the track-(tunnel)-soil system at the $y-z$ positions of the building-soil interface degrees of freedom due to forces at those same locations. The second requirement can be complied modifying the transfer function on Eq. (1) to account for the building structure following a similar procedure as the one presented in [6]. In a nutshell, this strategy starts with the transfer functions of the track-(tunnel)-soil system in the wavenumber-frequency domain, transforms them to the space-frequency domain to obtain the response at the positions of the interface between the 2.5D system and the 3D one to be coupled, couples that two systems in that domain, and comes back to the wavenumber-frequency obtaining a modified version of the transfer function in Eq. (1) that considers the building structure. As observed, the overall procedure to be conducted is highly intricate in formulation terms and involves three stages of numerical Fourier transforms to finally find the response at the building structure considering a strong coupling strategy.

3. Novel blocked forces approach

In this section, a novel methodology to compute the response of buildings close to railway system adopting a strong coupling strategy is presented. This methodology involves the application of blocked forces in the soil-building interface towards a more simplified approach for this type of simulations. This blocked-force-based approach is deployed considering that the track-(tunnel)-soil system is the source while the building is the receiver. Specifically the interface between the two domains lies on the soil-foundation interface. In this basis, the blocked forces on the degrees of freedom across the foundations-soil interface $\mathbf{f}_{bc}$ can obtained by solving the following system of equations

$$\mathbf{f}_{bc} = \mathbf{D}^{s}_{bb}\mathbf{u}^{f}_{\mathrm{inc}}, \tag{3}$$

where the f subscript on the $\mathbf{u}^{f}_{\mathrm{inc}}$ denotes that those are free-field displacements, which can be computed directly using Eq. (1) considering the 2.5D transfer functions of just the track-(tunnel)-soil, without involving the building. Also, the matrix $\mathbf{D}^{s}_{bb}$ should be obtained considering the full track-(tunnel)-soil system, as it should be done in the "traditional" strong coupling approach. Subsequently, that blocked forces are applied to the global track-tunnel-soil-building system. Since those forces are not moving in the longitudinal direction, the construction of this global model is simpler. In fact, Eq. (2) can be easily reformulated for this case, having

$$\begin{bmatrix} \mathbf{D}_{ii} & \mathbf{D}_{ib} \\ \mathbf{D}_{bi} & \mathbf{D}_{bb} + \mathbf{D}^{s}_{bb} \end{bmatrix} \begin{Bmatrix} \mathbf{u}_{i} \\ \mathbf{u}_{b} \end{Bmatrix} = \begin{Bmatrix} 0 \\ \mathbf{f}_{bc}, \end{Bmatrix} \tag{4}$$

where $\mathbf{D}^{s}_{bb}$ is the same matrix employed when obtaining the blocked forces by Eq. (3). Thus, it can be seen that this method allows for computing the strong coupling response to railway traffic excitation of track-(tunnel)-soil-building systems with a procedure of similar complexity as the classical weak coupling approaches. Specifically, the only additional numerical operations to be conducted are to determine $\mathbf{D}^{s}_{bb}$ from the 2.5D transfer functions of the track-(tunnel)-soil system, a procedure similar to the one developed when determining the track receptance matrix required to compute the wheel/rail interaction forces.

4. Conclusions

This paper has presented a novel blocked force-based methodology for efficiently simulating railway-induced vibrations in strongly coupled track-soil-building and track-tunnel-soil-building systems. The approach deploys a blocked force-based substructuring, where the train-track-(tunnel)-soil system is considered be the source, while the building is assumed to be receiver, being the interface between them the foundation-soil interface. The method first determines the blocked forces at that interface and then applies that forces to the global coupled system to compute the building response, accounting for the dynamic interaction between the railway infrastructure and the building. By replacing the moving loads with stationary blocked forces in the final coupled model, the proposed methodology substantially simplifies the formulation and over numerical complexity of the strong coupling problem. The main advantage of the proposed approach is that strong source-receiver coupling can be considered with a computational procedure of complexity comparable to that of conventional weak coupling approaches. The additional numerical effort is mainly associated with determining the dynamic stiffness matrix at the soil-building interface from the 2.5D transfer functions of the track-(tunnel)-soil system. The proposed methodology therefore provides an efficient framework for extending railway-induced vibration simulations to situations where the proximity between railway infrastructure and buildings makes the weak coupling assumption inappropriate.

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