Design of Railway-Induced Ground-Borne Vibration Abatement Solutions to be Applied in Railway Tunnels by Means of a Hybrid Modelling Approach

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Abstract. This paper presents a methodology for the design of vibration abatement solutions to be applied in railway tunnels in the context of problems where an already operative underground railway infrastructure is inducing excessive vibration levels to particular nearby buildings. In such cases, where some parts of the global system are already constructed, the inclusion of experimental data measured at the specific site to be studied increases significantly the accuracy and reduces the uncertainty of the predictive model. This paper proposes to use experimentally measured vibration transmissibility functions between the tunnel wall and the particular buildings to be studied as a model of the tunnel/soil/building system. This model, combined with a numerical model of the tunnel/track system, forms the global hybrid approach presented in this paper. Vibration abatement solutions can be included in the tunnel/track model in order to assess their efficiency. This methodology can be used for the study of any vibration abatement solution to be applied in the tunnel structure. In this paper, two types of these solutions are specifically studied: rail fastening system retrofitting in order to modify the rail fastener stiffness and the application of dynamic vibration absorbers.

Keywords: Railway-induced ground-borne vibration · Vibration mitigation measures · Experimental/numerical hybrid modelling · Optimisation

1 Introduction

Railway-induced ground-borne vibration is a major environmental concern in urban areas. When a new railway infrastructure becomes operational, it is common to have neighbourhood complaints about noise and vibration annoyance.

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Although a predictive study of railway-induced ground-borne noise and vibration levels of the new infrastructure was conducted and required vibration mitigation measures were designed and finally implemented, the noise and vibration levels could not accomplish the required law (or more restrictive vibration levels required) in some particular nearby buildings or facilities. These situations are normally due to particular conditions not accounted for in the general prediction study. Therefore, at least for particular sites where the legislation is not accomplished, vibration abatement measures should be applied in these cases.

In the present investigation, a methodology for the prediction of the efficiency of vibration mitigation measures applied in operational railway tunnels is presented. In such cases, vibration measurements on the rail, track, tunnel and surrounding buildings can be used to enhance the accuracy of the efficiency predictions for new vibration mitigation measures to be installed in the tunnel. This type of hybrid modelling has been found as an interesting option to enhance the accuracy of railway-induced vibration predictions in previous investigations. In [1], Verbraken et al. proposed to combine numerical and empirical predictions, aiming to construct a hybrid model that combines the advantages of both approaches: on one hand, numerical models allow for a great flexibility in dealing with different train/track models; on the other hand, empirical models based on experimental measurements of the particular site to be studied allow for an accurate assessment of the vibration propagation between the measuring points. They presented analytical expressions for the force density and the line source transfer mobility functions defined in the procedure stated by the Federal Railway Administration (FRA) of the U.S. Department of Transportation [2] for detailed vibration assessment [3]. These analytical expressions can be used instead of experimentally obtained ones in order to transform the empirical model into a hybrid approach. Degrande et al. [4] presented two hybrid models where the applicability of these analytical expressions is shown. Kuo et al. [5] presented a more detailed application example of these two hybrid models. More recently, Lopez-Mendoza et al. [6] have proposed a hybrid model to predict railway-induced vibrations in buildings in which they combine the building response, obtained from a FEM model of the isolated structure, and the ground surface response due to rail traffic, obtained from experimental measurements in the specific site. In [7], a hybrid model is stated in order to accurately deal with track singularities, such as switches and crossings, by combining experimental measurements of the vibration transfer functions between the rail and nearby structures with a theoretical model of the vehicle/track system that is able to account for track singularities. Recently, Mouzakis et al. [8] have proposed to use measured transmissibility functions between the vibration in nearby buildings and the vibration at the tunnel wall or invert induced by a muck track operator for the assessment of ground-borne noise and vibration of new underground railway lines.

The methodology presented in this paper combines transmissibility functions between the vibration of the floors of the studied building and the vibration in the tunnel wall, as a model of the tunnel/soil/building system with a numerical model for modelling the system consisting of the track, the tunnel and the locally surrounding soil. The term *transmissibility function* is used in this paper instead of *transfer function* in order to clearly specify that it is a transfer function between the vibration response at two points. Two applications of this methodology for assessing the efficiency of ground-borne vibration mitigation measures are presented in this paper: rail fastening system retrofitting (RFSR) and dynamic vibration absorbers (DVAs).

2 Methodology

2.1 Modelling Approach

Since the present model is created for optimization purposes, it has been developed to be highly computationally efficient in a particular task: obtaining the building responses associated to a large set of parameters of the vibration abatement solutions studied. The global hybrid modelling approach used to dynamically represent track/tunnel/ground/building systems consists of the following parts:

- Modelling of the tunnel and the locally surrounding ground: It is proposed to use a two-and-a-half-dimensional finite element method and boundary element method (2.5D FEM-BEM) coupled approach, where a FEM mesh is used to model the tunnel and a BEM mesh is used to account for the locally surrounding soil. This 2.5D FEM-BEM approach used in this investigation is outlined in [9].
- Railway track modelling: The track model consists of two Euler-Bernoulli beams, as a model of the rails, connected to the tunnel invert through continuously distributed springs, as a model of the rail fastening systems.
- Vibration abatement solutions: In order to design a modelling strategy able to efficiently deal with parametric studies of the vibration abatement solutions, a model of these solutions should be included in the track/tunnel system by dynamic substructuring techniques, always avoiding its inclusion as a part of the 2.5D FEM-BEM model. As already mentioned, two type of abatement solutions are studied in this paper. On one hand, for the RFSR, the semi-analytical model of the track allows for the calculation of the response of the system for various rail fastening system stiffnesses avoiding the recalculation of the 2.5D FEM-BEM model of the tunnel/soil system. On the other hand, for the application of DVAs, the methodology for coupling a distribution of DVAs over a model of a railway system presented in [10] is used. In the present study, only one longitudinal distribution of DVAs is considered. Moreover, all the DVAs of the distribution are assumed to be exactly equal to each other.
- Tunnel/soil/building model: This model consists on the transmissibility functions between the acceleration of vibration at the tunnel wall and at the specific buildings to be studied. These transmissibility functions should be obtained by simultaneous experimental measurements in the tunnel wall and the particular buildings due to normal operation train pass-bys. The influence of abatement solution on the measured transmissibility functions is discussed in Sects. 2.2 and 3.

- Train pass-by response: In this paper, the response due to the train passages is computed by means of the methodology presented in [11].

2.2 Tunnel/Soil/Building Model

To model the wave propagation from the tunnel to the building, the present approach takes advantage of the physical existence of the full transmission path between these two systems to use a fully experimental model. This model is based on the transmissibility functions that relates the acceleration of vibration in the tunnel wall of the tunnel with the acceleration of vibration at a particular point (or a set of points) in the studied building. To generate these transmissibility functions, the response of the tunnel wall and the building floor due to the train pass-by needs to be measured simultaneously using triaxial accelerometers. Then, a single input spectrum in the frequency domain $\ddot{U}_t(\omega)$ can be approximately obtained using triaxial information at the tunnel wall as

$$\ddot{U}_t = \sqrt{|\ddot{U}_{t_x}|^2 + |\ddot{U}_{t_y}|^2 + |\ddot{U}_{t_z}|^2}, \tag{1}$$

where $\ddot{U}_{t_x}$, $\ddot{U}_{t_y}$ and $\ddot{U}_{t_z}$ are the spectra of the vibration acceleration measured at the tunnel wall in x, y and z directions, respectively, in the frequency domain. A single output signal in the frequency domain $\ddot{U}_b(\omega)$ can also be approximately obtained using triaxial information measured at the building floor as

$$\ddot{U}_b = \sqrt{|\ddot{U}_{b_x}|^2 + |\ddot{U}_{b_y}|^2 + |\ddot{U}_{b_z}|^2}, \tag{2}$$

where $\ddot{U}_{b_x}$, $\ddot{U}_{b_y}$ and $\ddot{U}_{b_z}$ are the spectra of the vibration acceleration measured at the building floor in x, y and z directions, respectively, in the frequency domain. As both input and output signals are transient signals, the transfer function between the tunnel wall and the building can be obtained by

$$T_{tb}(\omega) = \frac{E_{tb}(\omega)}{E_{tt}(\omega)} \tag{3}$$

where $E_{tb}(\omega)$ is the cross-energy spectrum between $\ddot{U}_t$ and $\ddot{U}_b$, and E_{tt} is the energy spectrum of $\ddot{U}_t$. Thus, this T_{tb} can be used in the context of the global model as a zero-phase filter to be applied to the simulated time signal of the vibration acceleration at the tunnel wall to obtain the predicted response in the target building. Although this filter is simplified by avoiding the phase information of the exact transmissibility between the vibration at the tunnel wall and the target building floor, this assumption seems to be reasonable taking into account the stochastic nature of the rail unevenness profiles used as the input of the simulation process presented.

Noteworthy, it is assumed here that the application of DVAs would not affect the transfer function between tunnel wall and the building. So, the transfer function, obtained in the absence of DVAs, could be also used after the application of DVAs. This assumption is considered based on the work of Arcos et al. [12], in which a similar hybrid model approach was used to compute the optimal rail fastening system stiffness. The conclusions of that work arise that the transfer functions between tunnel wall and the building are not significantly affected by changing the stiffness of the rail fastening system.

3 Results

As already mentioned, the methodology proposed in this paper can be used for the optimization of vibration mitigation measures to be applied in railway tunnels. Application examples for RFSR and DVA mitigation measures are presented in this section.

3.1 Application for Rail Fastening System Retrofitting

For the example of application of this methodology for RFSR, a simple tunnel of 6 m of radius is considered. The evaluation point in the tunnel is placed at the tunnel wall, at 2 m from the tunnel invert. An evaluation point in the soil is also considered and it is placed at a distance of 10 m from the centre of the tunnel and at $\pi/4$ rad from the vertical. The vehicle model used in the simulation is the one presented in [13]. Experimental transmissibility functions between the tunnel wall and the targeted building floor are obtained from vibration measurements on the studied site. Left plot on Fig. 1 shows a prediction of the insertion loss (IL) associated to the maximum transient vibration value (MTVV) in the building floor as a function of the rail fastening system stiffness. Right plot on this figure shows the simulated transmissibility functions between the tunnel wall and the evaluation point in the soil for discrete values of the stiffness of the rail fastening system ranging between 5 kN/mm and 75 kN/mm. Maximum deviations with respect to the mean value of 2 dB are found, showing the validity of the hybrid methodology presented.

3.2 Application for Dynamic Vibration Absorbers

For the example of application of this methodology in the case of DVAs, a particular stretch of the double-deck tunnel of the Line 9 of Metro Barcelona and a nearby building with excessive vibration levels are considered in the study. Specific parameters of that case study are accounted for in the model. Experimental vibration measurements from hammer testing at the track and the tunnel and from train circulations are performed and used for tuning the vehicle/track/tunnel model and to obtain the transmissibility functions between the tunnel wall and the building floor. Figure 2 shows the response of the building floor with or without DVAs. The DVAs parameters used in this case are obtained applying a optimisation process based in genetic algorithm, applicable in this case due to the substructured nature of the present methodology.

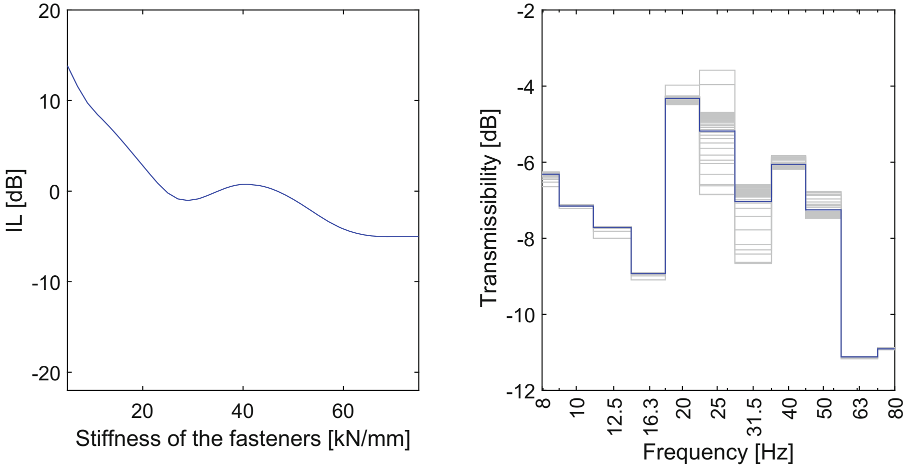

Fig. 1. Results of the application example for RFSR: Predicted IL in terms of MTVV of the building floor (left) and variability of the transmissibility functions in one-third octave bands between the tunnel wall and the evaluation point in the soil.

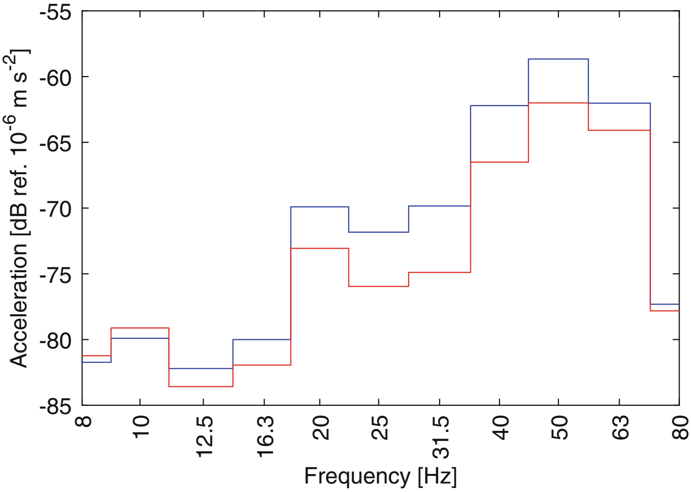

Fig. 2. Acceleration of building floor vibration in one-third octave bands with (red plot) and without DVAs (blue plot).

4 Conclusions

The methodology outlined in this paper allows for the designing of vibration abatement solutions to be applied in operational railway tunnels that are inducing excessive vibration levels to particular nearby buildings. In such cases, since most of the global system associated to the ground-borne vibration problem to be studied is already existing, the inclusion of experimental data measured at the specific site increases significantly the accuracy and reduces the uncertainty of the predictive model. Experimentally measured vibration transmissibility functions between the tunnel wall and the particular buildings and a numerical model of the vehicle/track/tunnel/system are the foundations of the present methodology. The most important benefits of the presented hybrid approach are the enhancement of the accuracy because of the inclusion of experimental data in the model and the suitability of the methodology for parametric studies of the vibration abatement solutions to be applied in the tunnel.

The applicability of the present methodology has been discussed for two kinds of vibration mitigation measures, showing its potential for the design of vibration countermeasures to be applied in the tunnel or the track. This methodology can be used for other kinds of vibration mitigation measures to be applied in the tunnel or the track as long as the inclusion of the vibration mitigation measure model on the global model is performed by using dynamic substructuring techniques.

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