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Scoping assessment of building vibration induced by railway traffic

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ABSTRACT

This work presents a scoping model to predict ground-borne railway vibration levels within buildings considering soil-structure interaction (SSI). It can predict the response of arbitrarily complex buildings in a fraction of the time typically required to analyse a complex SSI problem, and thus provides a practical tool to rapidly analyse the vibration response of numerous structures near railway lines. The tool is designed for use in cases where the ground-borne vibration is known, and thus can be used as model input. Therefore in practice, for the case of a new line, the ground motion can be computed numerically, or alternatively, for the case of new buildings to be constructed near an existing line, it can be recorded directly (e.g. using accelerometers) and used as model input. To achieve these large reductions in computational time, the model discretises the ground-borne vibration in the free field into a frequency range corresponding to the modes that characterize the dynamic building response. After the ground-borne response spectra that corresponds with the incident wave field is estimated, structural vibration levels are computed using modal superposition, thus avoiding intensive soil-structure interaction computations. The model is validated using a SSI problem and by comparing results against a more complex finite element-boundary element model. Finally, the new scoping model is then used to analyse the effect of soil properties, building height, train speed and distance between the building and the track on structural-borne vibration. The results show that the scoping model provides a powerful tool for use during the early design stages of a railway system when a large number of structures require analysis.

1. Introduction

The expansion of high speed rail (HSR) has been decisive for economic development across the world, however this growth has also led to an increase in those effected by ground-borne vibrations from railways [1]. The negative effects of this vibration are numerous and it is thus addressed in international standards. One of these standards is ISO2631 [2,3], where indoor, whole-body human exposure to vibration is evaluated in the frequency range, 1 Hz to 80 Hz. The vibration evaluation is based on the root-mean-square (RMS) value of the acceleration in the three orthogonal directions. Additionally, ISO14837 [4], a dedicated standard for the railway sector, is currently under development. This presents an overview of ground-borne vibration due to railway traffic, prediction techniques, experimental measurement, evaluation criteria and also mitigation.

It also discusses numerical modelling, including two-and-a-half-dimensional (2.5D) and three-dimensional (3D) models, which are referred to as detailed design models and can be used during the construction stage of new lines. 2.5D models are based on the assumption that the problem is homogeneous in the track direction, thus reducing the degrees of freedom. Several authors [5–13] have presented 2.5D methodologies to predict vibrations produced by railway traffic using boundary element (BEM)- finite element (FEM) coupled formulations. Three-dimensional models account for local soil discontinuities, underground constructions and structures that break the uniformity of the geometry along the track line [14–18], however, are more computationally expensive.

At the earlier stages of development for a new railway line, simpler and quicker methodologies are desirable. These models, called scoping models [4], allow engineers to asses long lengths of track in a reduced computational time, because typically, the train-track-soil interaction (source and propagation problem) is decoupled from soil-structure interaction (immission problem). Coulier et al. [19] studied the effect of assuming an uncoupled approach in a ballasted track and they concluded that it can be neglected for distances to the track longer than six times the Rayleigh wave length, thus validating this assumption.

Nelson and Sauernmann [20] presented a simple in-situ testing methodology based on impact-testing procedures to characterize soil vibrations and vehicle-track systems. Alternatively, Madshus et al. [21]

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developed a semi-empirical model from the statistical analysis of railway vibration measurements in Norway and Sweden. This model was used to study low frequency vibrations due to high speed trains (HST) on soft soils. Rossi and Nicolini [22] also presented an approach to predict train-induced vibration considering different train types, train speeds, track properties and distances to the track. The analytical expressions of the model were calibrated by experimental data. With et al. [23] proposed a scoping model to compute running RMS values of velocity based on the wheel force, the train speed and the distance to the track, while the Federal Railroad Administration (FRA) and the Federal Transit Administration (FTA) of the U.S. Department of Transportation have proposed empirical procedures to predict vibration levels due to railway traffic [24,25]. Verbraken et al. [26] verified by means of a numerical method the assumptions introduced in these approaches. Later, Kuo et al. [27] developed two models using a combination of field measurements and numerical methods based on the use of separate source and propagation mechanism, and implemented them using the definitions proposed in References [24,25]. Auersch [28] studied building induced vibrations using a simple soil-wall-floor model based on an empirical transfer function obtained from the characteristics of the structure. A soil modelled using a spring and a viscous damper was used to evaluate the effects of soil-structure interaction. François et al. [29] developed an analysis of building induced vibrations by employing simplified methods that discard SSI, but take into account the relative stiffness between the building and the soil. Recently, Conolly et al. [30,31] presented a scoping tool, called Scoperail, to predict in-door noise in buildings and structural vibrations values due to high speed trains. A 3D FEM model was used to generate vibration records for a wide range of train speeds and soil types, and these results were combined with empirical factors in order to compute vibrations due to train passages.

The present paper builds upon these previous approaches and proposes a scoping methodology to evaluate building induced vibrations at the early development stage of railway lines using modal superposition and considering SSI. Free-field response due to train passages is the required model input data, and can be obtained from numerical models and experimental records, including conventional, freight and high speed trains. Therefore the model can be used to predict structural vibrations in the cases of both new and existing lines. The proposed method allows to assess the building response with a very low computational effort, and can be used in a general purpose FEM program. This paper is organized as follows. First, the scoping model is presented. Next, the proposed model is numerically validated comparing with a more comprehensive methodology. Finally, the effect of the soil properties, the building height, the train speed and the distance from the track to the building on the results from the scoping model is analysed.

2. Numerical model

This section describes the proposed scoping model. The dynamic analysis is carried out by modal superposition [32] of the structure subjected to support excitation, with the aim of computing the overall RMS value of the response due to an incident wavefield.

The dynamic equilibrium equation of a structure can be written as:

$$\mathbf{M}\ddot{\mathbf{u}}_t(t) + \mathbf{C}\dot{\mathbf{u}}_t(t) + \mathbf{K}\mathbf{u}_t(t) = \mathbf{F} \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices, respectively. $\mathbf{u}_t$, $\dot{\mathbf{u}}_t$, and $\ddot{\mathbf{u}}_t$ are the total displacements, velocities and accelerations, respectively, and $\mathbf{F}$ represents the external force. The total displacement can be decomposed as the sum of the ground motion $\mathbf{u}_g$ and that due to the structure deformation $\mathbf{u}$:

$$\mathbf{u}_t(t) = \mathbf{u}(t) + \mathbf{r}\mathbf{u}_g(t) \tag{2}$$

where the influence matrix $\mathbf{r}$ defines the wave incidence on the structure.

Substituting the Eq. (2) into the Eq. (1), and considering that the ground motion $\mathbf{u}_g$ does not produce either viscous force ($\mathbf{C}\mathbf{r}\dot{\mathbf{u}}_g = \mathbf{0}$) or elastic force ($\mathbf{K}\mathbf{r}\mathbf{u}_g = \mathbf{0}$), the following equation can be obtained:

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = -\mathbf{M}\mathbf{r}\ddot{\mathbf{u}}_g(t) \tag{3}$$

The displacement vector $\mathbf{u}$ is obtained by modal superposition as:

$$\mathbf{u}(t) = \sum_{i=1}^{N}\sum_{j=1}^{3} \boldsymbol{\phi}_i q_i^j \tag{4}$$

where $\boldsymbol{\phi}_i$ is the i-th mode shape, q_i^j the i-th modal amplitude due to a ground motion at direction j and N is the number of modes considered to describe the structural response.

Then, Eq. (3) can be rewritten for each direction j by the substitution of Eq. (4) and pre-multipliying by the mode shape transpose vector $\boldsymbol{\phi}_j^T$:

$$\sum_{i=1}^{N}\left[\boldsymbol{\phi}_j^T\mathbf{M}\boldsymbol{\phi}_i\ddot{q}_i^j(t) + \boldsymbol{\phi}_j^T\mathbf{C}\boldsymbol{\phi}_i\dot{q}_i^j(t) + \boldsymbol{\phi}_j^T\mathbf{K}\boldsymbol{\phi}_i q_i^j(t)\right] = -\boldsymbol{\phi}_j^T\mathbf{M}\mathbf{r}\ddot{\mathbf{u}}_g(t) \tag{5}$$

Eq. (5) can be decomposed into a system of N uncoupled equations taking into account the mode shape orthogonality condition with respect to the stiffness and mass matrices. Also, it can be assumed that this condition can be applied to the damping matrix. Eq. (5) then becomes:

$$\ddot{q}_i^j(t) + 4\pi\zeta_i f_i \dot{q}_i^j(t) + 4\pi^2 f_i^2 q_i^j(t) = -\Gamma_i^j \ddot{u}_g^j(t) \tag{6}$$

with

$$\Gamma_i^j = \frac{\boldsymbol{\phi}_i^T\mathbf{M}r^j}{\boldsymbol{\phi}_i^T\mathbf{M}\boldsymbol{\phi}_i} \tag{7}$$

where f_i is the natural frequency, ζ_i is the damping ratio, and Γ_i^j is the modal participation factor for the i-th mode at direction j.

The modal amplitude q_i^j can be written as:

$$q_i^j(t) = \Gamma_i^j \xi_i^j(t) \tag{8}$$

Introducing Eq. (8) in Eq. (6) yields:

$$\ddot{\xi}_i^j(t) + 4\pi\zeta_i f_i \dot{\xi}_i^j(t) + 4\pi^2 f_i^2 \xi_i^j(t) = -\ddot{u}_g^j(t) \tag{9}$$

The solution of Eq. (9) can be computed by means of the Duhamel's integral as [32]:

$$\xi_i^j(t) = \frac{1}{f_{di}}\int_0^t -\ddot{u}_g^j e^{-2\pi\zeta_i f_i(t-\tau)}\sin(f_{di}(t-\tau))d\tau \tag{10}$$

where $f_{di} = f_i\sqrt{1-\zeta_i^2}$ is the damped natural frequency. Eq. (10) is solved using the generalized single solved (GSSSS) integration algorithm U0-V0 developed by Zhou and Tamma [33]. This algorithm accurately calculates the low-frequency roots of Eq. (10).

Once the modal amplitude is obtained, the structural response can be computed from Eqs. (2) and (4). Different international standards evaluate structural vibration level, such as standard ISO 2631 [2] which defines the overall RMS value of the frequency-weighted acceleration, or alternatively, the velocity decibel (VdB) metric based on the running RMS value of the velocity [34]. Since the frequency weighting depends on the corresponding standard, it is not considered in the present work. Next, the procedure to asses the overall RMS value of the acceleration is developed. The VdB metric can also be estimated using a similar methodology.

The overall RMS value of the acceleration response is calculated as:

$$a_{RMS} = \sqrt{\frac{1}{T}\int_0^T \ddot{\mathbf{u}}_t^2(t)dt} \tag{11}$$

where T is the characteristic period defined by the DIN 45672-2 standard [35] where the structural response is assumed to be stationary. Then, the RMS value is obtained, accounting for the previously computed $\mathbf{u}_t(t)$ from Eqs. (2) and (4):