Prediction of structure-born sound and secondary airborne sound by three dimensional finite element models

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Introduction

Nowadays sensitive utilisations as residential, cultural or office buildings often are located near traffic infrastructure. This situation leads to a rising noise and vibration exposure in urban environment. Typical vibration sources in urban environments are road and railway traffic, industrial sources or construction work. The prediction of structure-borne sound and secondary airborne sound in buildings can be difficult and uncertain due to the numerous characteristics of the source, transmission paths and receiving structures. The two and three-dimensional finite element method (FEM) is a prediction procedure which is able to simulate high complex transfer paths and receiving structures. Models and methods based on the FEM will be introduced to predict structure-borne and secondary airborne sound in complex buildings.

As an experience as consulting engineers the railway traffic is one of the most important sources of annoyance by vibrations, structure-borne sound and secondary air borne sound. So this paper will focus on railway traffic as a source.

Basics of ground borne sound

To predict ground borne sound as a basis of the structure-borne and secondary air borne sound a rough classification into three parts of a prediction model can be made. The first part is the excitation which in our case is the railway traffic at the track. The second part is the transmission of vibration through the ground. The third part is the reception at a structure for example a house.

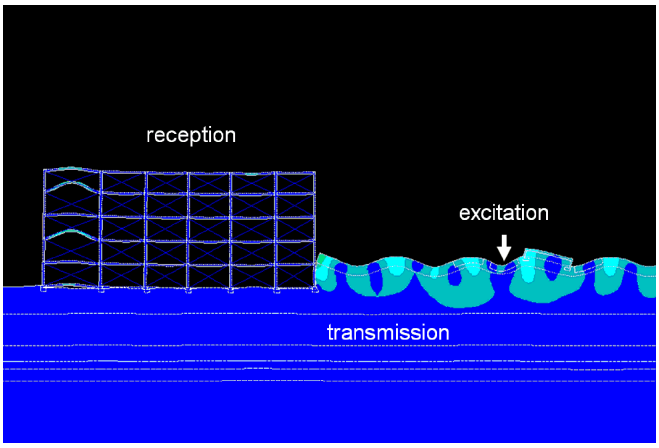

Figure 1: Scheme of vibration propagation

Figure 1 shows a two dimensional finite element model with an excitation force at a modelled track. The force is calculated on basis of vibration measurements in the ground at selected distances of the track.

The excitation at the track bed is calculated on basis of the results of vibration measurements in the ground. If the excitation is measured directly at the track, the track itself, the track bed and the dynamic processes of the train has to be modelled too, to calculate the vibrations which will be radiated into the ground. To predict the vibrations at a distant building of an existing track this is not necessary at all. The excitation at the track bed can be calculated with a ground model using the results of the vibration measurements and the dynamic properties of the single soil layers.

The vibrations are propagating in three different wave forms shown in figure 2.

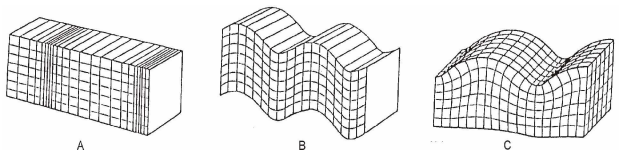

Figure 1: wave forms of ground born sound, A) pressure wave, B) shear wave C) Rayleigh wave [1]

Rayleigh waves are surfaces wave. They are a result of the interaction between P-waves (pressure or compression waves) and S-waves (shear waves).

$$c_p = \sqrt{\frac{G}{\rho}\frac{2(1-\nu)}{(1-2\nu)}} \quad (1)$$

$$c_s = \sqrt{\frac{E}{2\rho(1+\nu)}} \quad (2)$$

c_p – pressure wave velocity [m/s]

G – shear modulus [N/m²]

ν – Poisson's ratio

ρ – density [kg/m³]

c_s – shear wave velocity [m/s]

E – Young's modulus [N/m²]

Beside the mentioned material properties in the formula (1) and (2) the damping of the soil layers also has a sustainable impact on the vibration that will be transferred to a building.

The transferred vibration energy from the source to a receiving point at a structure e.g. a house leads to a transfer

function. The transfer functions will be calculated by the simulation model. The FE model is solving the differential equation of motion (3) at all nodes of each element within the model [2].

$$M \cdot \ddot{x}(t) + C \cdot \dot{x}(t) + K \cdot x(t) = F(t) \qquad (3)$$

M – mass matrix

C – damping matrix

K – stiffness matrix

F(t) – time dependent force vector

x(t) – vector of nodal displacement

As a result of the FE model the structure-borne sound can be calculated as a vibration velocity or a velocity level. With the knowledge of the sound radiation properties of a room in the receiving structure and the calculated velocity levels the secondary air borne sound can be calculated with the help of a building acoustics model or for a first assessment estimated by the following formula (4) [3]:

$$L_p = L_v + 10 \cdot \log(\sigma) - 10 \cdot \log\left(\frac{A}{4 \cdot S}\right) \qquad (4)$$

L_p – sound pressure level [dB] (secondary airborne sound)

L_v – vibration velocity level [dB] (calculated with FE model) (ref. $v_0 = 5*10^{-8}$ m/s)

σ – radiation loss factor

A – equivalent absorption area [m²]

S – sound radiating surface [m²]

Range of application

In practice the prediction of structure-born sound and the resulting secondary airborne sound is based on established reference transfer functions. This is an adequate type of prediction if the transfer paths are not that complex (standardized receiving structure, common residential buildings) or the existing situation enables one to carry out sufficient measurements at the excitatory, transmitting and receiving media.

To predict complex transfer paths in most cases no reference transfer function will be available. Therefore an appropriate prediction method has to be found. The finite element method (FEM) is a method which is able to calculate even high complex transfer paths.

Because of the unique characteristics of projects respectively the cases the FEM prediction is used it is reasonable to use case studies to explain the vantages of this method.

Case study I

The first case study will show the requirement of the FE modeling with respect to a highly complex vibration transfer due to the construction and the applied materials.

Figure 2: View of the reviewed building (design: Soeters Van Eldonk architecten b.v., Amsterdam)

Figure 2 shows a view of the building which is located next to a train station. The façade is part of the frame and is important to model in an adequate way. Inside the building between the cores an additional complex staircase is planned. This causes lead to unique floor construction at every level. More than 40 different beam elements were used within this model to simulate the steel beam supporting.

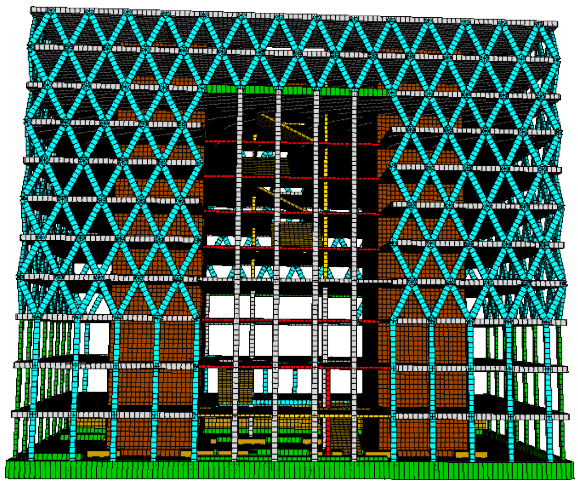

Figure 3: Finite element model of the building

The excitation of the building is very low frequent because of the particularities of the ground. Figure 4 shows the result of the measurement which were carried out at the building site.

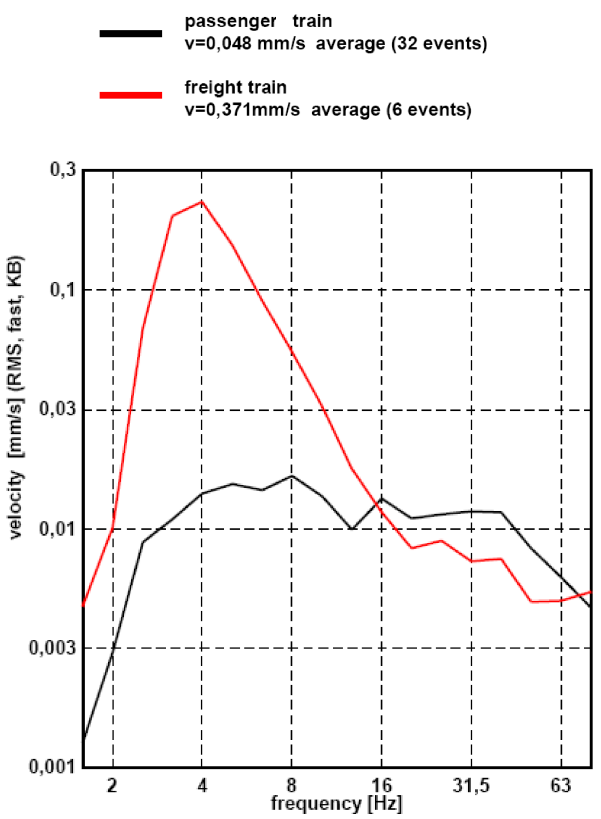

Figure 4: results of the vibration measurements at a metal rod in the ground

After the measurement was carried out one of the first global advices was that no resonance frequency of the components of the building may be between 2,5 and 12,5 Hz. By a modal analysis of the FE model different resonance frequencies were located within this range. The main problem was the staircase between the cores and the stair construction. One of these calculated resonance frequencies is shown in figure 5.

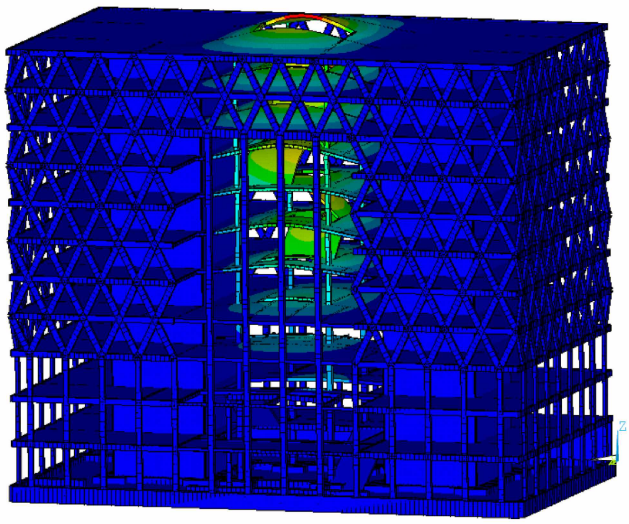

Figure 5: Calculated resonance frequency at 5.2 Hz (raised scale factor for illustration)

Because of the accuracy of the FE model an optimization of the staircases is possible in order to design a staircase by means of resonances.

Case study II

The building that is described in the second case study is located near eight parallel rails. The rails are highly frequented by freight trains. Under the rails a road tunnel is located which is also used as the bearing of the building. The figures 6 and 7 gives an insight into the location and the foundation structure of the building.

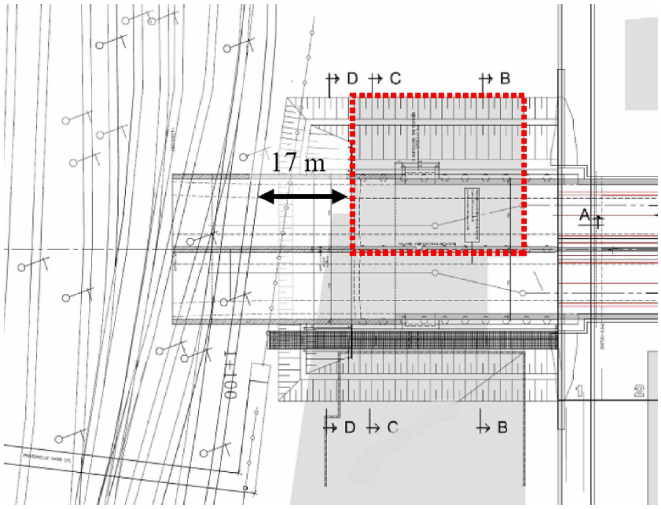

Figure 6: location of the building next to the rails an on a road tunnel

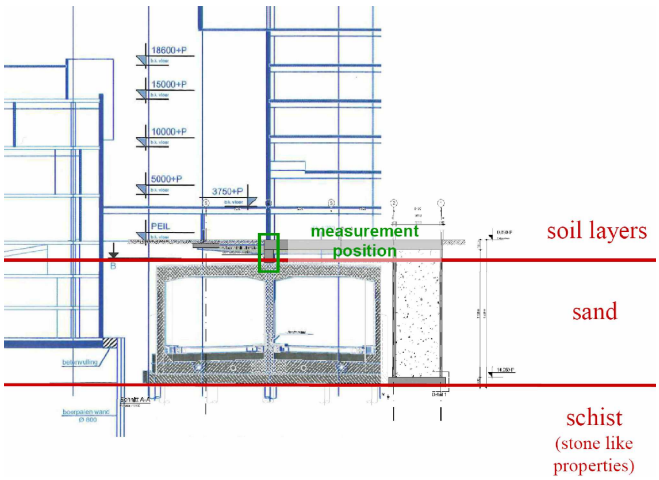

Figure 7: cross section of the foundation structure

The supporting structure on one side of the building consists of the middle tunnel wall. On the other side the building is based on a counterbalance for a overhang which is located at the 8th – 13th floor of the building at the side of the tunnel.

The only way to reduce the structure-borne sound at a stage of planning when Peutz was involved as a consultant, was to use steel spring elements at the bearing in the area of the tunnel wall. Under the influence of wind at the façade these relatively soft spring elements could cause a large deflection of the building. The large deflection would influence the statics of the building and could cause a feeling of queasiness for people working inside of the building. Therefore a detailed survey was started to investigate the need of vibration control measures.

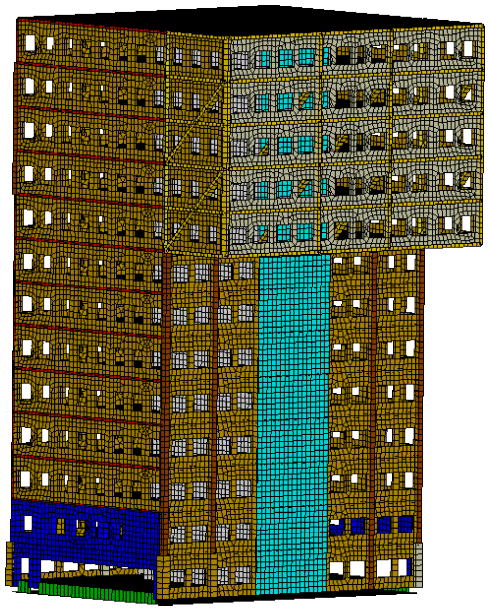

Figure 8: Finite element model of the building

Vibration measurements were carried out at the middle tunnel wall and in the ground. The ground structure with a fairly light upper soil layer consisting of sand and a lower schist layer causes an impedance mismatch. As a consequence the ground itself is not causing a relevant contribution to the vibration at the foundation. The main vibration excitation is caused by the tunnel wall. Because of the tunnel stiffness the excitation is fairly high frequent with peaks at 20 Hz and 50 Hz. Figure 9 shows the results of the measurement at the middle tunnel wall in terms of vibration velocity.

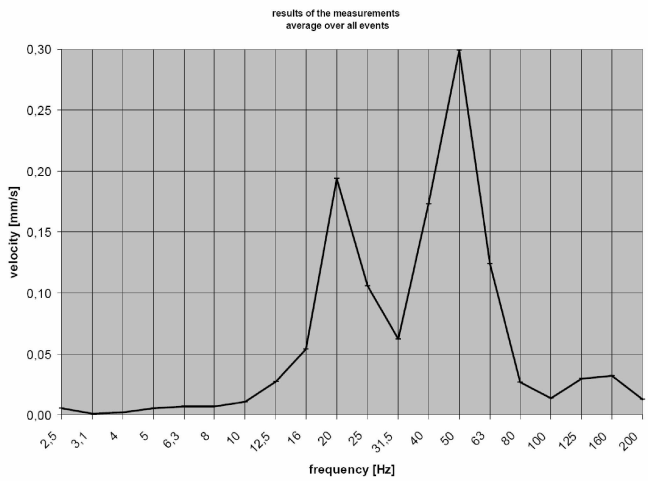

Figure 9: Results of vibration measurements at the middle tunnel wall

A FE model was set up to calculate the resonance frequencies by a modal analysis. By means of a harmonic response analysis the vibration velocities as a reaction of a modeled excitation at the foundation were calculated.

Figure 10 presents three transfer function as a difference of the structure-borne sound levels of the excitation and three selected floors of the building.

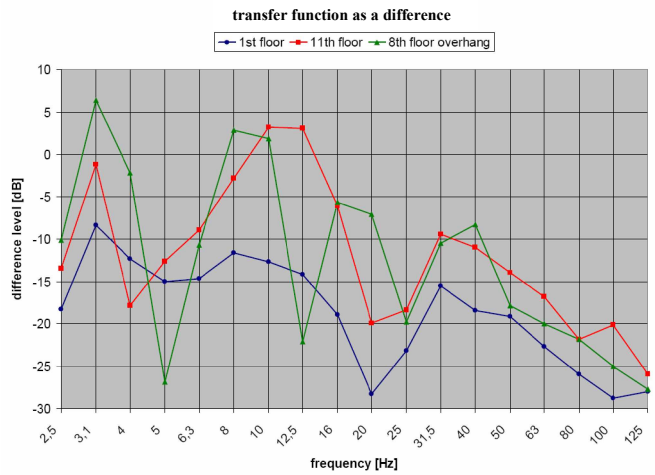

Figure 10: Calculated transfer function for three selected floors of the building

Figure 11 presents the corresponding linear secondary air borne sound level estimated with formula (4).

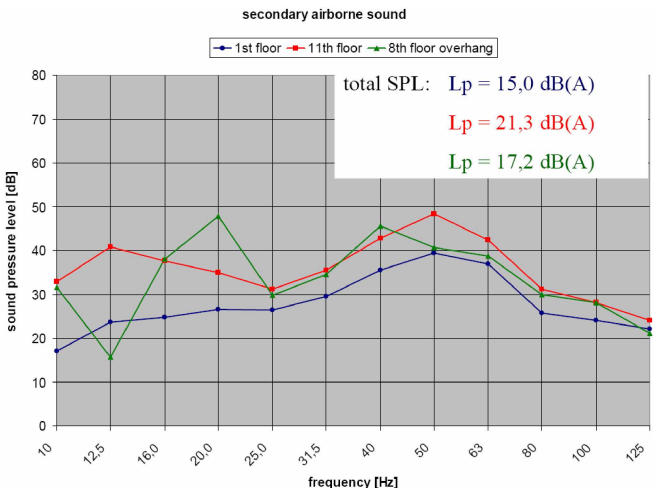

Figure 11: Estimated secondary air borne sound levels

The results of the calculation led to the advice that no global vibration control measures were necessary.

Summary

The FEM is a useful method to predict structure-borne sound and secondary air borne sound concerning complex transfer paths. Sometimes the FEM is criticized as a method of prediction because of its uncertain results. In our opinion the accuracy of prediction is depending on the choice of the material properties especially of the soil layer and the accuracy of the FE model. A detailed model and the right choice of the material properties in connection with suitable vibration measurements will lead to a reliable results.

References

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[2] Meirovitch, "Elements of vibration analysis" McGraw-Hill Book Co, 1986

[3] L. Cremer, M. Heckel, Körperschall, Springer-Verlag Berlin/Heidelberg/New York, 1967