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Using spectral finite elements for parametric analysis of the vibration reduction index of heavy junctions oriented to flanking transmissions and EN-12354 prediction method

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ABSTRACT

The vibration reduction index of heavy junctions is predicted by means of a model based on spectral finite elements. This is equivalent to a finite element method but faster and with smaller computational costs. This advantage is used in order to perform a parametric analysis of the vibration reduction index for several junction types: T-shaped, L-shaped and +-shaped. The influence of several parameters such as: damping, junction dimensions or the mass ratio on the vibration reduction index is observed. The study is focussed to provide data and guidelines oriented to the EN-12354 design method for flanking transmission in buildings.

1. Introduction

Indirect sound transmissions can be a cause of poor sound insulation. Sometimes the sound insulation provided by single elements is lower than expected due to the flanking transmission paths. Its control is also very important in laboratory set ups in order to make a fair characterisation of the direct airborne insulation of walls [1]. This phenomenon takes place in many situations like vehicles, ships or buildings.

Several models have been developed in order to predict flanking transmissions. Statistical energy analysis (SEA) was used in [2] for the study of long transmission paths in buildings. A global approach based on a modal description of the structures but supposing weak coupling with fluid zones is proposed in [3]. A more versatile two-dimensional vibroacoustic finite element (FEM) model was implemented in [4]. It is able to deal with strongly coupled situations. The vibration transmission through junctions has also been studied with FEM in [5,6]. All these methods are complementary in order to cover the whole frequency range considered in building acoustics. Using the FEM is computationally expensive and often limits the frequency range (to low and mid frequencies) or the dimensions of the structures that can be studied. Mainly when dealing with vibroacoustic problems or parametric analyses with large number of situations to be considered. On the contrary SEA is, in general more adequate at high frequencies with no limitation on computation costs.

A model oriented to building acoustics is developed in [7,8]. Its goal is to predict the flanking transmissions in buildings by means of the properties of the isolated components (i.e. walls) and a simple description of their connection. The parameters characterising the individual building components are: the sound reduction index (R), the radiation efficiency (σ) and the surface of the partitions (S). The sound reduction index of an indirect path is calculated as

$$R_{ij} := 10\log_{10}\left(\frac{1}{\tau_{ij}}\right) = R_i + D_{ij} + 10\log_{10}\left(\frac{\sigma_i}{\sigma_j}\right) + 10\log_{10}\left(\frac{S_0}{S_j}\right) \quad (1)$$

where S_0 is a reference area. D_{ij} is the vibration level difference. It contains the information of the relationship between the components of the building that are in contact (transmission of vibrations between floors, adjacent walls, floors and walls) and is defined as

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$$D_{ij} = -10\log_{10}(d_{ij}) \text{ with } d_{ij} = \frac{\langle v_{rms,j}^2 \rangle}{\langle v_{rms,i}^2 \rangle} \quad (2)$$

where $v_{rms,j}$ is the root mean square velocity, $\langle \bullet \rangle$ means spatial average on the receiving structure (j) or the excited one (i).

In heavy structures, very often it is considered that $\sigma_i = \sigma_j$ (reasonable for walls with plane faces) or $\sigma_i \approx 1$ (due to the low critical frequency) and paths R_{ij} and R_{ji} are averaged. The key parameter in order to evaluate indirect transmissions is the direction averaged vibration level difference $\overline{D_{v,ij}} = (D_{ij} + D_{ji})/2$.

This approach is adopted in the standard [9]. In the building, the transmission of vibrations through the junctions of the structure are very important in order to predict the indirect sound insulation. Final design quality highly depends on the uncertainty of input parameters such as $\overline{D_{v,ij}}$ [10]. But it depends on the specific situation (dimensions, boundary conditions, damping) or the laboratory conditions. For this reason in the EN-12354 [9] method, the vibration reduction index K_{ij} was defined

$$K_{ij} = \overline{D_{v,ij}} + 10\log_{10}\left(\frac{\ell_{ij}}{\sqrt{a_i a_j}}\right) \quad \text{with} \quad a_i = \frac{2.2\pi S_i}{cT_i}\sqrt{\frac{f_{ref}}{f}} \quad (3)$$

here ℓ_{ij} is the length of the junction, a_i is the equivalent absorption length of the wall i, S_i its surface, c the speed of sound in the air, $f_{ref} = 1000$ Hz is a reference frequency and T_i the reverberation time of the wall i that can be calculated as $T_i = 2.2/(\eta_{total} f)$ (being η_{total} the total loss factor).

K_{ij} is supposed to be invariable or 'situation–independent' (see [11] for detailed explanations). For this reason EN-12354 [9] provides different K_{ij} formulas (Annex E) for different junction types that can be used in each design situation to calculate $\overline{D_{v,ij}}$ by means of Eq. (3).

This approach is relatively new [12] and even if it is implemented in the European standard [9], not many experimental data or related models have been reported. The results of laboratory measurements focused on cellular concrete junctions with and without elastic connections were published in [13,14] and in situ measurements on concrete and brick heavy junctions in [15]. Brick-concrete junctions were also tested in the laboratory [16]. The results showed that variation of K_{ij} can be important if there is low modal overlap.

The vibration reduction index K_{ij} has also been determined by means of the FEM in [17] for heavy concrete junctions with and without elastomer to attenuate vibrations. However, there it is commented that computational costs of a three-dimensional FEM model are very high (there is a large number of nodes and unknowns when the mesh is refined due to frequency increase). This limits quite a lot its applicability to low and mid frequencies or to the analysis of few situations. The FEM has also been used in [18] in order to obtain K_{ij} in lightweight junctions. They are more complicated from the geometrical point of view, the variation of materials and the relevance of some construction details like the connection between elements. In theses cases, it seems that formulating a simplified semi-analytical model is much more complicated.

A very related topic is the estimation of the transmission coefficient at junctions (ratio of transmitted and incident power $\gamma = W_{\text{out}}/W_{\text{in}}$). It is used in order to study how vibration energy flows in each junction type. Its main application is to derive coupling loss factors required in Statistical Energy Analysis (SEA).

The main difference with the vibration reduction index is the fact that transmission coefficients are usually obtained in a situation where the structures are infinite or semi-infinite and the excitation is an incoming vibration wave (i.e. bending or longitudinal). On the contrary, vibration reduction index K_{ij} is obtained with some excitation acting on the structure (i.e. point forces or acoustic pressure waves) which have finite dimensions. Moreover, transmission coefficients are more related with the energy flow (SEA coupling loss factors) while vibration reduction index is more related with velocity levels or kinetic energy (SEA subsystem energy).

A very well known model in order to estimate the transmission coefficients of junctions is the one presented in [19]. It is formulated for two-dimensional junctions and some hypotheses are required (i.e. equal material properties for all branches) in order to derive the analytical expressions. This is the basis of other improved models in some sense or another. For example [20] studied the asymmetry of junctions, [21] considered elastic elements or hinges used to attenuate the vibration transmission, [22] verified the importance of considering in-plane effects, or [23] analysed the effect of considering finite or semi-infinite branches in the determination of transmission coefficients. Sometimes the transmission coefficients are derived in terms of an average of the incident angle of the vibration wave [24]. Finally, some methodologies to relate the transmission coefficients and the vibration reduction indices have been proposed [25] and with the SEA coupling loss factors in [26,24,22].

The transmission coefficients and SEA coupling loss factors have also been predicted by means of models considering finite-dimension structures. Modal bases were used in [27] to formulate a methodology that was later verified with experiments in [28]. The FEM was used in [29] to calculate the coupling loss factors through the energies of every coupled element. And a SEA code was compared with three-dimensional FEM in [30].

The goals and contributions of the research presented here are:

- Use of a model based on spectral elements in order to predict the dynamic response of structures in the whole frequency range of interest (up to 5000 Hz). It is limited to structures with extrusion symmetry composed of shells (thin plate theory combined with plane stress elasticity, accounting for bending, shear and longitudinal waves). The model is compared with 3D finite elements and published laboratory measurements.
- Provide predictions for the vibration reduction index K_{ij} defined in the EN-12354 [9]. They are done with a deterministic model that accounts for the real dimensions of the structures (finite and with specific boundary conditions). Mechanical excitation (point forces) are considered.
- Study the vibration transmission behaviour of T, L and +-shaped junctions. The effect of local changes in the thickness is also considered.

The work here is limited to the case of heavy structures due to the range of masses and thicknesses used. Their typology will be uniform which is the case of usual concrete junctions. The prediction of flanking transmissions in lightweight structures is more complicated in the sense that some details play an important role. For example, vibration reduction index must be defined taking into account the wall types [18] (i.e. vibration transmission from a floor to each of the parts of a double wall can be different) or radiation efficiencies can be different depending on the shape in each side of a wall [31,32]. Other aspects that are important to adapt current techniques and regulations for lightweight constructions are discussed in [33,34,11,35].

The manuscript is organised as follows. The deterministic model is presented in Section 2, including a comparison with three-dimensional FEM in Section 2.2 and laboratory measurements already published in Section 2.3. The results are shown and analysed in Section 3 before the conclusions.