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Experimental Research of Vibration Transmission in Wooden Junctions with a View Towards Statistics

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The measurements of sound propagation in lightweight buildings often show a variation between nominally identical constructed structures. These variations can be due to variations in structural properties, measurement uncertainties or workmanship related factors. Better knowledge about the sources for these variations can lead to lowered production costs. Ongoing research is concerned with the transmission of vibration through wooden junctions found in lightweight building structures. In the literature numerous results of different experiments performed on simple junctions can be found. However, these results are often based on series of measurements performed on a single test subject only, which in the case of wooden structures may not provide results representable for similar junctions in general. The present paper discusses considerations of designing a series of repeated vibration measurements on wooden plate/beam T-junctions.

1 Introduction

Multi-family dwellings and offices build from lightweight materials are becoming a cost efficient and environmentally friendly alternative to traditional heavy structures. According to a recently published Swedish state-of-the-art report concerning acoustics in wooden buildings [1], a great variance in the sound insulation of lightweight wood constructions is observed. Such variations necessitate higher safety margins to the legal requirements. As a consequence, most of the apartments have to be over dimensioned so that the lowest performing apartments can meet the requirements, which inevitably leads to increased costs. Meanwhile, the trend is going towards increasing demands to the acoustic performance of building elements both from the people living or working in the buildings as well as in the various building codes of European countries. The trend is adding focus to the low frequency range, where traditional lightweight structures are not performing well due to the low mass of the constructions and rather low transmission losses occurring through junctions. These variations and performance issues leave the building industry reluctant to abandon traditional (heavy) construction materials like concrete. To lower the costs associated with expensive test houses and over dimensioning of structures, a better knowledge of the sources of the observed variations is needed.

Inspired by Negreira Montera et. al. [2, 3]—who has performed measurements of eigenfrequencies and modeshapes on a number of different types of wooden T-junctions—the present paper discusses future work including a series of repeated measurements. The work is part of a PhD project on prediction of sound transmission in lightweight building structures. The main goal is to extend the work of Galbrun [4] by investigating typical junctions in lightweight plate/beam structures utilizing experimental modal analysis in conjunction with numerical analyses using a finite element method (FEM). The work will contain several aspects including; what information can be extracted from the modal parameters; how does the extracted information relate to the transmission of vibration across junctions; how can structural properties be extracted and used for modeling larger and more complex structures by numerical methods. The frequency range of interest is up to low-mid frequencies, i.e. the range below 500 Hz. In order to be able to draw general conclusions from the measured data, focus on statistics will be maintained throughout the process.

1.1 State-of-the-art

The international state-of-the-art on acoustics in wooden multi-story buildings is summarized in [1]. For a variety of simple structures, analytical solutions have been established [5], and for heavy structures, statistical energy analysis (SEA) [6–9] has in general been found to provide a reliable prediction of noise transmission. However, SEA has limited validity for lightweight structures such as wooden floor and wall panels. An SEA based investigation focusing on flanking transmission through double leaf gypsum walls is provided by [10], whereas [11] investigates Flanking transmission caused by continuous structural elements passing under partitioning walls in lightweight dwelling constructions with SEA methods. Rib-stiffened plates such as typical lightweight wall and floor constructions are considered in [12].

Fahy and Gardonio [9] describe the transmission of sound through bounded partitions from a wave point-of-view, but when it comes to bounded double-leaf partitions the transmission behavior becomes too complicated for analytical approaches. Therefore, the wave propagation problems have to be numerically analyzed using a method depending of the frequency region considered. The conventional finite element method (FEM) [13] can be used, especially for low-frequency problems where the considered elements can be considered short compared with the wavelength. However, the frequency range of interest for wave propagation problems is often such that FEM analysis seems to be quite difficult due to the requirement of small element sizes to match the wavelength which implies huge unmanageable data sets. Therefore, instead of FEM for high-frequency analysis, where the elements are long compared to a wavelength, the so-called energy methods such as SEA and energy finite element method (EFEM) [14–17] are well established methods. Another energy based method is the European standard EN 12354 [18], which is widely used to predict sound transmission in buildings. However, as with SEA, EN 12354 is based on assumptions which are typically not fulfilled by lightweight building structures. Therefore, predictions of sound transmission in such structures using EN 12354 may be imprecise [19]. Furthermore, EN 12354 assumes reciprocity in the prediction of the sound reduction index. Mahn and Pearse [20] reveals that this is not always the case for lightweight constructions. In [21], the vibration reduction index is being investigated by comparison of measurements and predictions (both full SEA and EN 12354).

Currently there is an increasing focus on the transmission of low frequency noise, as sources like road and air traffic or even home theater subwoofers become part of everyday life for many people. Recently, research has been presented where sound transmission in the low frequency range through lightweight structures has been predicted with numerical methods [22–24]. The results from these papers indicates that FEM tools can give reliable results for prediction of sound transmission loss, however more investigations have to be performed in this field where the influence of different modeling strategies will be considered. The construction of a lightweight structure is fairly complex and many variables belonging to material models, junction types and coupling phenomenons between structure and acoustic medium have to be modeled in a proper way. Although basic theories are well established, modeling transmission through simple structural elements is not straightforward as numerous of the mentioned variables need to be considered. Some of the modeling difficulties are well known, but only a limited number of applications have been evaluated. Recent work based on FEM includes Clasen and Langer [25] in which a 2D model of airborne transmission between rooms using Timoshenko beams corrected for transversal shear locking is incorporated. In this model damping mechanisms are included. Wooden panels often show orthotropic behavior. In Bard et al. [24] such an orthotropic model is presented.

Approaches using the boundary element method are seen too. In Santos [26] the fluid/structure coupling is taken into account using BEM.

Finally, modal methods are being applied for semi-analytical solutions to the problem of modeling a vibrating rib-stiffened plate. In [27–29] a simplified model using Fourier sine series expansions assuming pure bending waves is utilized to investigate the effects of periodicity in rib-stiffened plates.

On-going research is concerned with the loss factors in the different types of couplings that occur in lightweight structures. This includes different types of beams [4, 30] as well as line coupling versus point coupling [4, 9, 30] and rigid versus pinned couplings [31], the main concern being the adaptation of statistical methods to lightweight structures. Galbrun [32] investigates the importance of including higher-order flanking paths, where the standard EN12354:2000 only includes first-order flanking transmission. In [33, 34] graph theory is applied to address the issue of determining how energy is distributed over different paths.

It is generally accepted, that the variation of craftsmanship needs to be considered when assessing either measured or modeled results of transmission of sound and vibration in wooden structures [35–38].

2 Objectives

Inspired by the work of Galbrun [4], an in-depth investigation of wave propagation across different configurations of simple wooden junctions is planned. The goal is to obtain a greater knowledge of how waves propagate through different types of junctions, and how these may be modeled using FEM. This knowledge will be helpful in the design and analysis of lightweight building structures. Furthermore, the results may be used to improve SEA predictions of such structures, since these predictions rely on how energy is distributed between different subsystems [28, 29].

The approach in the present PhD project is using the commercial finite element software Abaqus® to investigate wave propagation occurring in junctions of lightweight structures, while continuously verifying the model experimentally. The experimental part of the project involves a series of measurements on different simple junctions. The suggested approach will reveal possible weaknesses of the model at an early stage of the design.

Besides accurately modeling a certain physical object—namely the test subject—by FEM, the investigations aim to extract material parameters from experimental vibration testing and determine if—and how— these may be used in modeling a larger structure.

The work presented here is part of a European Interreg project, ”Silent Spaces”. Within Silent Spaces a parameterized modular finite-element model for analysis of vibration transmission in multistory lightweight buildings is in the phase of development. One of the major challenges in such work is to simplify the model without losing information that may impact the results significantly. The findings of the previously mentioned investigations may possibly contribute to this work in terms of important knowledge about the behavior at junctions.

3 Method

As the computing power available rapidly increases, extremely detailed finite-element models of various types of wood have been made by different research groups in the past years, and thus it becomes relevant to consider the repeatability of measurements in detail when comparing results of a model to measurements. In the following, considerations of designing a series of repeated vibration measurements on wooden plate/beam T-junctions will be given. The underlying idea is to evaluate how well measurements can be expected to match a detailed finite-element model.

3.1 T-junction measurements

The test structure is a T-junction made from a particleboard plate connected to a spruce beam of rectangular cross section, see Figure 1. The size of the plate is 1.2 m by 0.6 m and represent a cut-out of an actual full size floor assembly [3]. The tests serves three main purposes:

- To test the repeatability the measurements
- To test the variation within presumably identical test subjects (same test conditions, same batch of wood, etc.)
- To investigate the accuracy of a finite-element model being developed in parallel with the measurements.

Estimated modal parameters from experimental modal analysis of each test subject are the quantities considered for comparison. Details of the modal testing and the numerical model will be given in the two succeeding subsections.

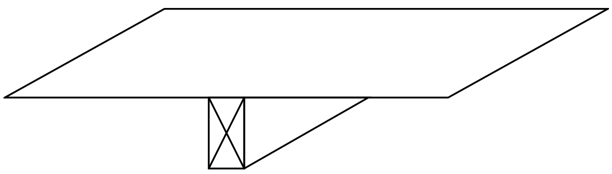

Figure 1: The test subject is a T-junction between a particleboard and a spruce beam. The size of the plate is 1.2 m by 0.6 m and represent a cut-out of an actual full size floor assembly.

In the planned series of repeated measurements on junctions, each series will be testing ten different—but supposedly identical—plate/beam junctions. The pieces are cut from the same batches of wood and are being stored under the same conditions. Since the material properties of wood are highly affected by environmental factors such as humidity and temperature, care must be taken to minimize the bias from these unwanted causes of variation. To do so, all junctions are tested consecutively on the same day and the measurements are repeated in a different order in the following days. This procedure allows for statistical significance of difference between days, time of day and individual test subjects to be examined.

3.2 Modal analysis

The tests are carried out as experimental modal analysis utilizing multiple accelerometers and an instrumented hammer. The accelerometers are B&K type 4507B mounted in special plastic sockets, which are glued to the test subject. This ensures a convenient and consistent mounting when testing multiple junctions consecutively. The test subject is suspended in elastic rubber cords to mimic free-free boundary conditions. A total of 28 accelerometers are mounted on the plate, and each measurement uses three excitations points with five hits in each point. The data acquisition software is Brüel & Kjær Pulse LabShop Modal Test Consultant, which facilitates a double hit detector and various other tools to improve and validate the quality of the measured data. The post-processing is performed with Brüel & Kjær Pulse Reflex Modal.

To ensure fair comparison with the results presented in [2] the measurement techniques have been discussed and planned in cooperation with our colleagues, Delphine Bard, Anders Sjöström and Juan Negreira Montero, at Lund University, Sweden.

3.3 Finite element modeling

In parallel with the experimental testing, a numerical model is build using the commercial FEM code Abaqus®. The numerical model is continuously compared to the experimental results. By doing so, potential errors and insufficiencies of the model may be caught at an early stage of the design. Furthermore, if unexpected or 'odd' discrepancies between the numerical and the experimental results occur, one model might help catch errors in the design of the other, and vice versa.

The performance of the numerical model will be tuned by trying to obtain material parameters using an inverse-FEM approach. This may be a rather computationally heavy task to perform since wood is not a simple material in terms of it being non-isotropic and non-homogeneous.

In addition to comparing numerical results with experimental ditto, a study of the robustness of the modal analysis post processing software will be conducted. The idea is to simulate (in the numerical model) frequency response functions corresponding to those measured in the experimental tests, i.e. 28 response points and three reference points. These frequency response functions will then be used as input to B&K Pulse Reflex Modal. The undamped natural frequencies may then be compared to those found by a numerical eigenvalue solver in the FEM software. Furthermore the sensitivity to noise may be tested by adding artificial noise to the otherwise clean frequency response functions before importing them in Pulse Reflex Modal.

4 Conclusion

In the present paper, future work in a PhD project on prediction of sound transmission in lightweight building structures has been discussed. The main goal is to extend the work of Galbrun [4] by investigating typical junctions in lightweight plate/beam structures utilizing experimental modal analysis in conjunction with numerical analyses using a finite element method (FEM). The work will contain several aspects including; what information can be extracted from the modal parameters; how does the extracted information relate to the transmission of vibration across junctions; how can structural properties be extracted and used for modeling larger and more complex structures by numerical methods. The frequency range of interest is the range below 500 Hz.

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