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TRANSMISSION OF SOUND THROUGH DOUBLE-PLATE PANEL STRUCTURES – A NUMERICAL STUDY OF COUPLING PARAMETERS IN LIGHTWEIGHT PANEL STRUCTURES

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Abstract. *In the present paper, a finite-element model of a double-plate panel is implemented to investigate the transmission of sound through a simple lightweight structure. A numerical study is performed of the following three coupling configurations: 1) Structure-borne sound via plate-stud-plate structures without air inclusions; 2) transmission via the plate-stud-plate structure including the internal acoustic medium; 3) transmission via plate-air-plate connections in a double-leaf panel with no structural coupling between the two plates. A fully coupled analysis is performed in which solid finite elements are adopted for the structure, whereas the acoustic medium is discretized into fluid continuum elements. The computations are carried out in frequency domain in the low frequency range and the load acts as a diffuse sound field on one side of the panel.*

1 INTRODUCTION

Lightweight building techniques are currently progressing faster than the development of prediction tools for the acoustic behavior of such structures. In order to ensure that the increasing demands to sound insulation between dwellings are being accommodated, reliable prediction tools are needed at an early stage of the building design. For a variety of simple structures, analytical solutions have been established [9], and for heavy structures, statistical energy analysis (SEA) [15, 7, 6, 13] 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.

Fahy and Gardonio [13] 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) [2] 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) [3, 17, 4, 18] are well established methods. Another energy based method is the European standard EN 12354 [1], 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 [16].

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 [5, 12, 10]. 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. Ongoing research is concerned with the loss factors in the different types of couplings that occur in lightweight structures including both different types of beams [8, 14] as well as line coupling versus point coupling [13, 8, 14]. The goal of the present paper is to obtain a greater knowledge on the coupling between fluid and structure using FEM tools for the prediction of sound transmission in lightweight building structures. The method of investigations will primarily be based on a numerical investigation using available elements in the commercial FEM software package ABAQUS [11]. The following Section 2 presents the double panel lightweight wall element and different modeling scenarios and finally results are given and discussed in Section 3 and 4.

Flanking noise in a similar panel structure is analysed in a companion paper by Gandalal, Dickow, Andersen and Sorokin.

2 PROBLEM DESCRIPTION

Lightweight wall and floor constructions are often made from panel structures with plates on stud (or joist) frames. In such a panel, the frames may be either single or double-stud frames with or without different porous and elastic layers included to reduce the transmission of sound and vibration through the panel. In the case of single-stud frames there is direct structural coupling from one side of the panel to the other. In the present study the subject of investigation is a single-stud double-plate panel without porous or elastic layers, see Figure 1. The goal of this preliminary study is to investigate the effect of the air inclusions in the model while at the same time gaining experience regarding how to model such structures for future investigations.

2.1 Numerical model

The panel consists of two plates mounted on a frame structure with a total of six cavities, see Figure 1. The stud dimensions are 50 mm by 60 mm and the plate thickness is 20 mm. The total wall dimension is 3350 mm (w) by 2600 mm (h) by 100 mm (d). The studs are placed 550 mm part (center-to-center). Homogeneous and isotropic materials are assumed. The material properties are:

- Timber (plate and studs): Young's modulus 14 GPa, Poisson Ratio 0.35, density 500 kg/m^3. Damping is set to 1% of the stiffness.
- Air: Bulk modulus 141360 Pa, density 1.2 kg/m^3.

The damping is applied as structural damping, i.e. the damping forces are assumed proportional to the forces caused by stressing of the structure. This simulates the effects of friction in the timber.

The panel is modeled in the commercial FEM package ABAQUS using solid continuum finite elements for the structure and fluid continuum elements for the air inclusions in the fi-

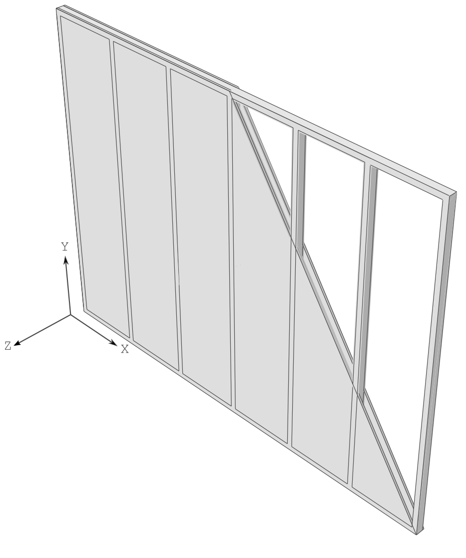


Figure 1: Overall geometry of the double-plate wall panel. The structure consists of two plates tied to a stud frame. A specification of the panel is given in Section 2.1

nite cavities. 20-node brick elements with quadratic spatial interpolation of the displacement are adopted with a mesh size of 5 cm. The mesh is designed such that the nodes constituting the plate mesh align with the nodes on the frame structure. All structural contact points are connected using tie constraints in x, y, and z-directions. As three-dimensional solid continuum elements have no rotational degrees of freedom, only displacements are considered. The coupling between the structure and the acoustic medium in the cavities is handled by tie constraints as well. The boundaries are clamped, i.e. all nodes on the top, bottom and side surfaces of the structure are rigid. Three different scenarios are investigated:

1. Structure-borne sound via plate-stud-plate structures without air inclusions,
2. transmission via the plate-stud-plate structure including the internal acoustic medium,
3. plate-air-plate transmission when there is no structural connection between the two plates.

In the latter case, half of the studs are tied to one plate, while the other half are tied to the other. Thus, the total mass of the panel is unchanged while the stiffness is of course reduced significantly. Furthermore the size of the cavities is unchanged compared with cases 1 and 2. When calculating the eigenfrequencies of the panel, a fourth case is investigated; similar to case 3 but without the structural-acoustical coupling. This is done to see how the coupling affects the modes related to the finite air-filled cavities inside the panel.

2.2 Excitation

If a concentrated load (point force) is applied directly to the panel, the position of the excitation is likely to be located in a nodal line of one or more of the structural modes of the panel. Therefore, as the present paper is dealing with transmission of sound through the entire panel, a diffuse field excitation model has been utilized. In ABAQUS, a diffuse field loading condition may be approximated by a number of deterministic incident plane waves coming from angles distributed over a hemisphere encapsulating the loaded surface. The number of incident plane waves used for the approximation is given by N^2, where N is called the number of seeds.

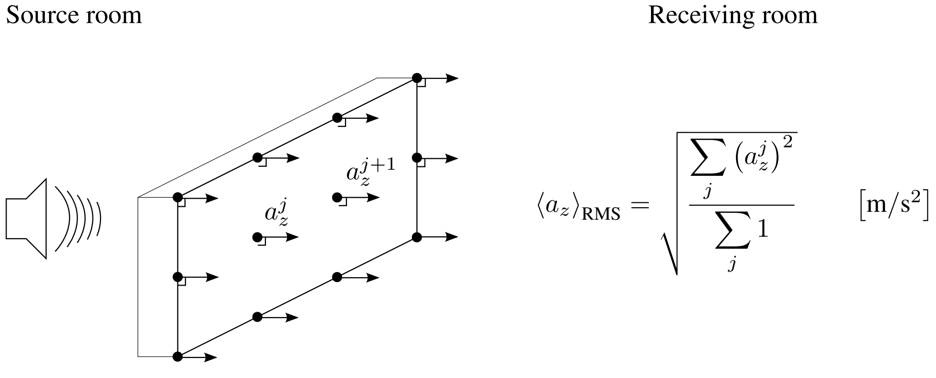


Figure 2: The structure is excited by a diffuse field in the source room. The investigated output quantity in the receiving room is the translational surface acceleration, normal to the plane of the plate, expressed as the root-mean-square (spatial average) acceleration. Here a_z^j is the magnitude of the acceleration (z-direction) of the jth node on the plate surface.

2.3 Response

Preferably, the model should include an acoustic medium inside the receiving room such that the sound pressure could be used to find the transmission loss of the structure. However, due to the computational complexity associated with such a model, this is not included yet. Instead, the investigated output quantity in the receiving room, $\langle a_z \rangle_{\mathrm{RMS}}$, is the translational surface acceleration, normal to the plane of the plate, expressed as the spatial root-mean-square acceleration. This is depicted in Figure 2.

3 RESULTS

3.1 Modal analysis

Eigenfrequencies of the four different configurations, i.e. 1) without air inclusions, 2) with air inclusions, 3) without structural coupling and 4) without any coupling, have been found using the Lanczos algorithm implemented in ABAQUS. In the cases without structural coupling between sending and receiving room, half of the ribs are connected to one plate, while the other half are connected to the other plate. The results are shown in Figure 3. A comparison of calculated eigenfrequencies in the case of using shell elements for the plates instead of solid continuum elements is shown in Figure 4.

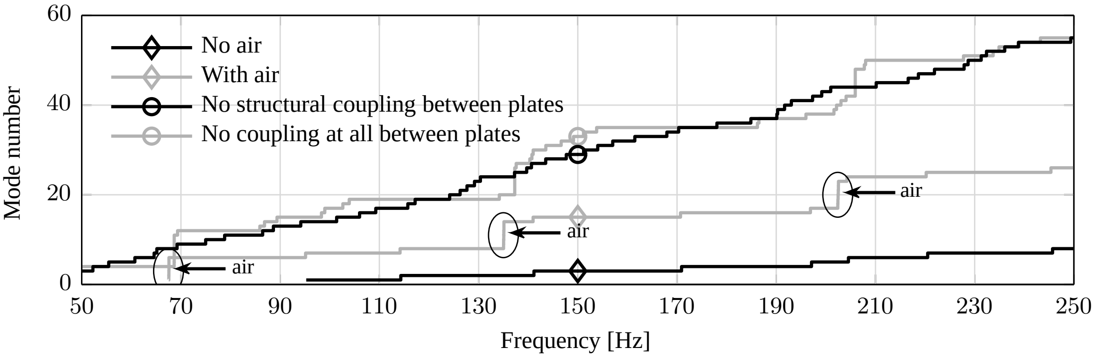


Figure 3: Eigenfrequencies of the four different configurations: 1) without air inclusions, 2) with air inclusions, 3) without structural coupling and 4) without any coupling between the two plates. Groups of air-modes in the fully coupled case are indicated by arrows.

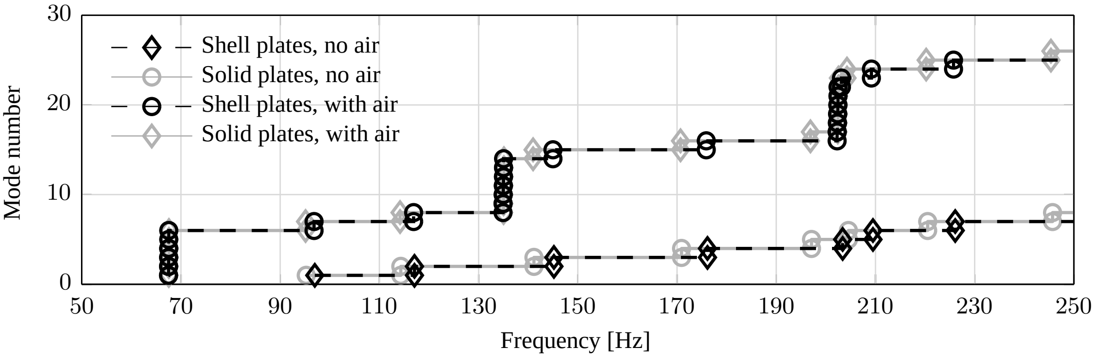
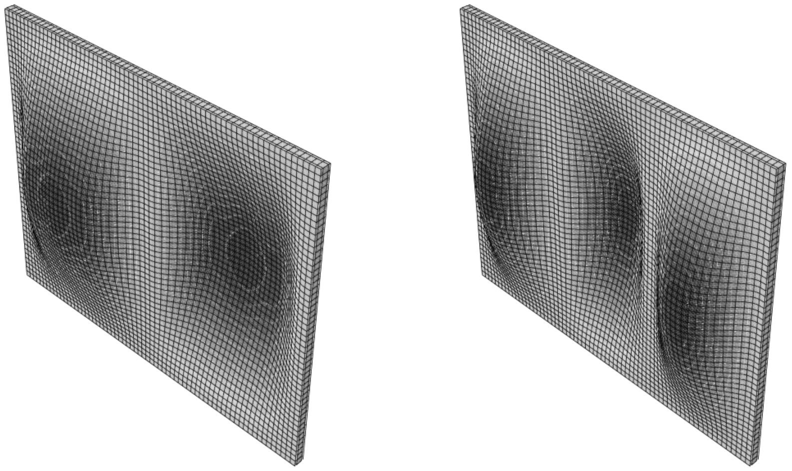


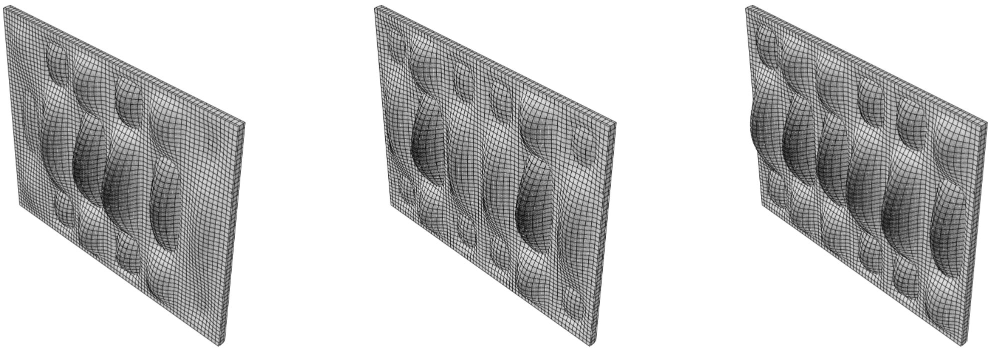
Figure 4: Eigenfrequencies with and without air when the plates are modeled using shell elements and solid continuum elements respectively.

By inspecting curves for cases 1) and 2) in Figure 3 it is clearly seen that the air inclusions provide a number of modes occurring in groups of six. Such a group is found between the 2nd and 3rd structural modes and the modeshapes of these are shown in Figure 6. Figure 5 shows the modeshape of the 2nd and 3rd structural modes.

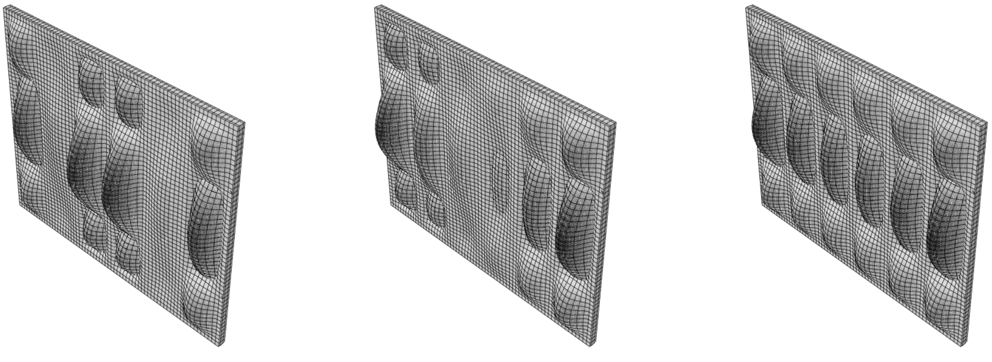


(a) Mode at 114 Hz (b) Mode at 141 Hz

Figure 5: Modeshapes showing the second and third structural modes.



(a) Mode at 135.04 Hz (b) Mode at 135.05 Hz (c) Mode at 135.07 Hz



(d) Mode at 135.09 Hz (e) Mode at 135.11 Hz (f) Mode at 135.11 Hz

Figure 6: A group of modes provided by the air inclusions.

3.2 Frequency response

The frequency response of the panel has been investigated in the range 50-250 Hz with a 1 Hz resolution. The panel is excited by a diffuse field on one side and the response is considered on the opposite side. First, a comparison between responses of the structure (without air inclusions) when using respectively 10, 30 and 40 seeds is performed. The result is shown in Figure 7.

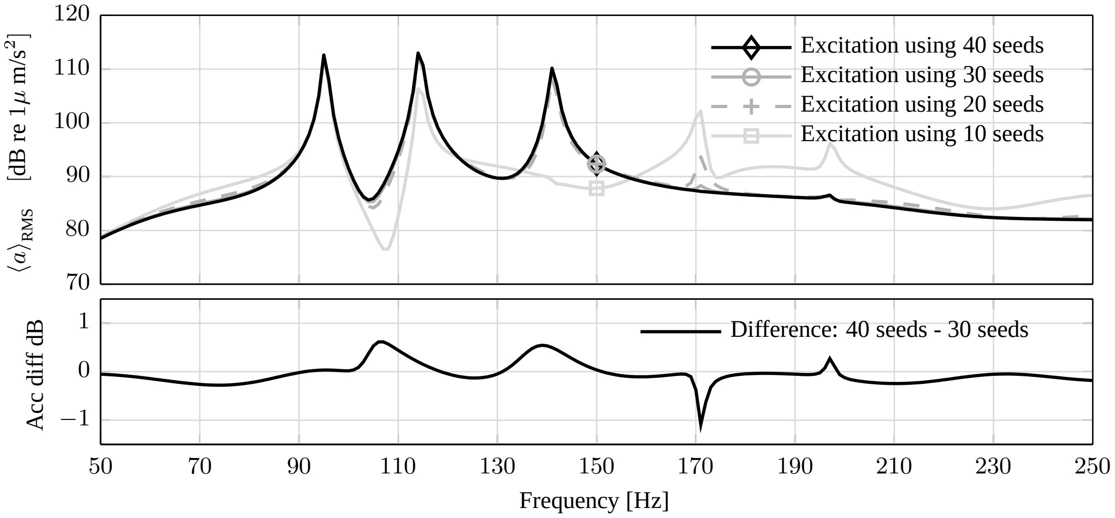


Figure 7: Spatial RMS acceleration of the receiving room plate surface as a function of frequency. The excitation of the sending room is a diffuse field simulated using 10, 30 and 40 seeds, i.e. using respectively 100, 900 and 1600 incident plane waves in ABAQUS. The calculations are performed without air inclusions in the model.

Next, using 30 seeds for diffuse field simulation in ABAQUS, the frequency responses with and without air inclusions are compared in Figure 8. The bottom part of the figure shows the difference between the two curves in the upper part. Finally, Figure 9 shows the response in the case of no structural coupling between the two plates in the panel structure.

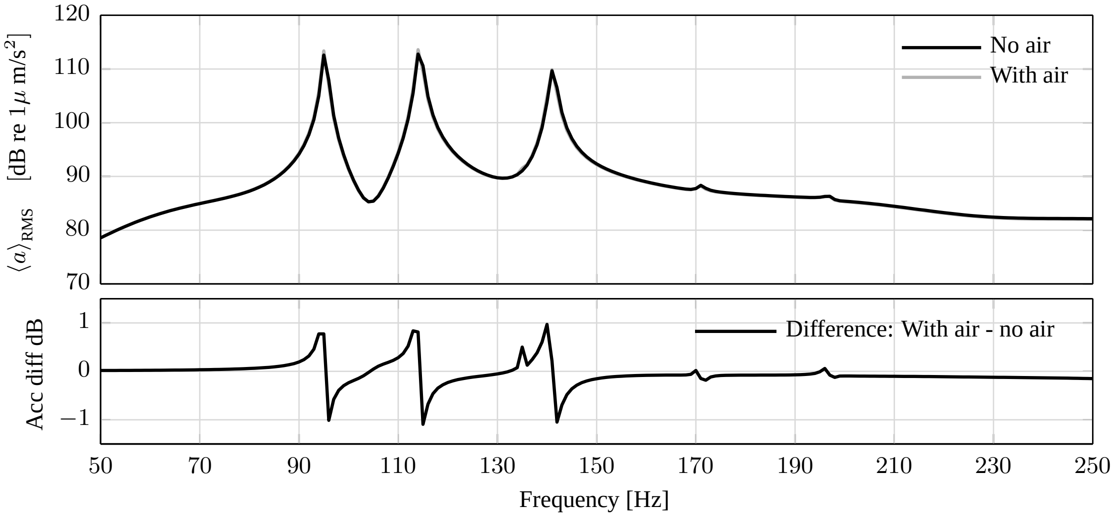


Figure 8: The effect of including the air inside the structure. The structure is excited by simulating a diffuse field using 30 seeds in ABAQUS. The bottom figure shows the difference between the two curves in the top figure.

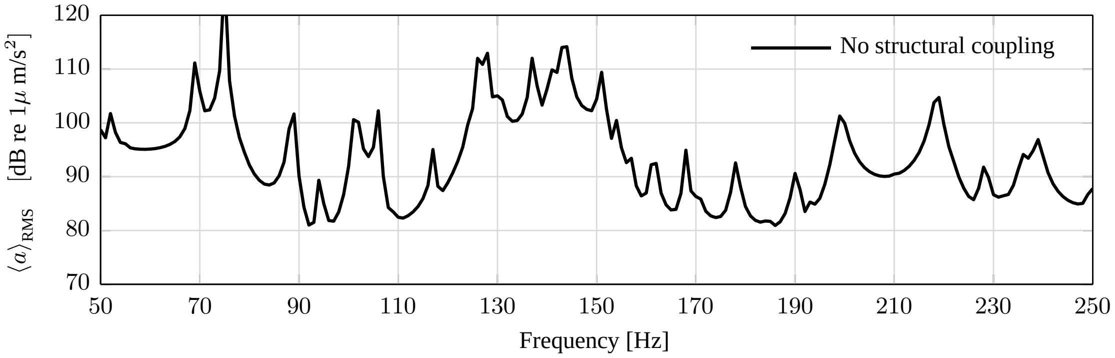


Figure 9: Spatial RMS acceleration of the receiving room plate surface as a function of frequency when there is no structural coupling in the model. The structure is excited by simulating a diffuse field using 30 seeds in ABAQUS.

4 DISCUSSION

As the presented results only represent the preliminary steps of a larger research project on sound transmission through lightweight building structures, focus has been on the basic details of how such structures are modeled for research purposes. Here, solid continuum elements have been adopted for the structure rather than elements based on simplified theory like that of shells and beams. For the considered frequency range, however, shell elements are expected to yield similar results as the wavelengths are large compared with the thickness of the panel. For the eigenfrequencies this is confirmed by looking at Figure 4, where it is seen that the difference is a slight frequency shift in the structural modes due to the shell elements having fewer degrees of freedom.

4.1 Modal analysis

By looking at Figure 3 and comparing the two curves with and without air inclusions in the cavities, it is seen that more modes appear within the considered frequency region when the air is included. Furthermore, the (structural) modes of the calculation without air appear in the calculation with air (the curves take a step up at the same frequencies). What is interesting, is the observation that the extra modes in the calculation with air inclusions are grouped together very closely in bunches of six. Based on this observation the actual modeshapes of such a group have been investigated. Figure 5 shows the second and third structural modes while Figure 6 shows the (air-related) modes in between the two. These modes (one for each cavity) differ slightly from each other in frequency due to the different positions of the air inclusions in the structure to which they are coupled.

Next, the eigenfrequencies in the case of no structural coupling between the two sides of the panel are considered. The curve (Figure 3) does not show the same groups of air related modes, which is rather unexpected as the air inclusions are identical to the other cases. This result may be explained by the fact that the coupling between the structure and the air becomes relatively stronger). Thus, movement of the air will be affected much more by the two structurally independent plates coupled to either side of the air cavities and vice versa. In order to verify this hypothesis, a fourth case have been considered, in which there is still no structural coupling between the plates, but furthermore the air is not coupled to the structural parts either. It is seen that the air related modes now appear in groups as expected.

4.2 Diffuse field excitation

A convergence study of the number of seeds needed in ABAQUS to adequately approximate a diffuse field has been done. The results show (see Figure 7) that for the given structure convergence seems to be fairly good when using 30 seeds for the approximation. Similar results are seen when examining the model including air inside the cavities.

4.3 Frequency response

The frequency response for the panel with air inclusions is compared to the panel without air inclusions in Figure 8. It is seen that the two configurations yield nearly identical results for the given frequency region. The peaks located at the first three structural modes of the panel are slightly lower in frequency when the air is included. This is due to the added mass of the air. Aside from this, only a very small difference is seen around 135 Hz where a group of air-related modes occurs. From an overall perspective the air inclusions do not show significant behavior in this frequency range.

When examining the response of the uncoupled case (see Figure 9), more peaks are seen as more modes are present. The overall acceleration level is quite similar to the coupled case. This does not quite match the expectations as the main transmission path is now broken. However, the calculations are for a constructed case where the enclosed volumes of air are still rather small having relatively (to the properties of air) rigid boundaries. Because of this, the air inclusions show a spring like behavior. At low frequencies the displacement is relatively large, meaning that the stiffness of the air enclosures becomes significant, resulting in the observed behavior.

5 CONCLUSION

Using a finite element approach, the effect of including an acoustic medium in the cavities of a double-plate single-stud lightweight wall/floor panel has been examined in the low frequency range. It is seen, that the air inclusions contribute to the mode count of the panel as they provide groups of modes related to the pressure field in the cavities. These modes, however, have very little effect on the frequency response when exciting the panel using an approximated diffuse sound field. The significance of the air-to-structure couplings depends strongly on the stiffness of the structure and it is expected, that the effect of the air-inclusions will be more pronounced for a limp structure. In the case of no structural coupling the sound transmission surely depends on the air-inclusions, as these constitute the only transmission path between the two plates.

Furthermore, it has been shown, that when shell elements are used rather than solid continuum elements for modeling the plates, the panel becomes slightly stiffer due to the reduced degrees of freedom. However, the same modes occur – only shifted slightly in frequency.

It has been demonstrated that for the model at hand a diffuse field approximation in ABAQUS converges and that using 30 seeds gives reasonably good results.

The present paper merely presents the introductory steps in a larger research project on sound transmission in lightweight building structures. Along the line of the model presented here, future work includes adding a sound field in the receiving room in order to predict the transmission loss, making a more efficient diffuse field excitation, investigate elastic couplings between plate/stud, investigating screw connections and other coupling properties. The greater goal being a better understanding of the different parameters affecting the sound transmission of such structures. This understanding is needed in order to develop a simplified prediction tool like [1] to be used with lightweight building structures.

5.1 Acknowledgements

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