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MITIGATION OF FLANKING NOISE IN DOUBLE-PLATE PANEL STRUCTURES BY PERIODIC STIFFENING—FINITE ELEMENT ANALYSIS IN THE LOW-FREQUENCY RANGE

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Abstract: *The present analysis focuses on flanking noise transmission within a two-wall structure of finite size. The walls are lightweight panel structures, each consisting of two plates with internal ribs. A finite-element model is utilized, assuming that the studs are fully fixed to the plates. Further, the air enclosed in the cavities within the structure is taken into consideration, whereas the external air has been disregarded. A fully coupled analysis is performed in which solid finite elements are adopted for the structure, whereas the acoustic medium within the panel is discretized into fluid continuum elements. The computations are carried out in frequency domain in the range below 500 Hz and the load acts as a concentrated force on one side of one of the panels. The responses of the same panel as well as the adjacent wall are studied.*

The position of the load relative to the stiffeners is important. Hence, analyses are carried out for different positions of the load. It has been found that the ribs have a significant impact, not only on the flanking noise but also on the direct radiation of sound from the wall on which the external force has been placed. Furthermore, the response changes when the air inside the wall panels is disregarded.

1 INTRODUCTION

Noise transmission within building structures is one of the main concerns in current time. For heavy structures, e.g. concrete buildings, statistical energy analysis (SEA) has been found to provide a reliable framework for prediction on noise transmission [1]. For example, Nightingale [5] found that a full wave SEA model of the junction produced useful results regarding the transmission of vibrational energy via flanking junctions from the point of excitation on a finite periodic rib-stiffened plates using SEA. However, SEA has limited validity for lightweight structures such as wooden floors with joists spanning in one direction or double-plate panel walls with vertical ribs [2, 12]. The periodic nature of the stiffening provides a nonhomogeneous modal density due to the formation of stop bands. Thus the vibrations are not diffuse and the number of modes in certain frequency bands may be limited. Hence, other methods of analysis must be employed.

As an alternative to SEA, the finite-element method (FEM) can be used [17] to describe flanking transmission in dwellings. Numerical simulations can reduce the cost of experiments and may also improve the design of sound insulation. However, modelling of lightweight structures is complicated, since such structures contain various materials and junctions as well as a relatively strong coupling to the acoustic medium compared to heavier structures such as concrete walls and decks. Furthermore, the FEM has limitations when it comes to the high-frequency range. Small elements must be employed in order to obtain an adequate discretization of the waves propagating in the structure and the acoustic medium. This results in a huge number of degrees of freedom, leading to long computation times.

Some research has been done in which sound transmission in the low-frequency range through lightweight structures has been predicted with numerical methods [6, 7, 14]. For example, Motoki [9] investigated sound radiation from a double-leaf structure under point force excitation, applying the load on a lightweight interior leaf connected to a massive exterior leaf. It was deduced that redesigning the interior leaf does not provide a significant reduction of the radiated sound power. In order to reduce the sound radiation, it is required to take damping mechanisms into account, e.g. acoustical damping.

Currently, there is also an increasing interest in periodic structures for better sound insulation. By a theoretical study, Takahashi [3] found that the spacing between ribs and the stiffness of the connector as well as the use of thick rigid materials all have a significant importance regarding the minimization of sound radiation from periodically connected infinite double-plate structures.

The current paper focuses on flanking noise transmission between two adjacent walls forming an L-shape with a rigid connection at the joint. The analyses concern the dynamic response to point-force excitation with the load applied at different positions on the source wall. The walls are identical, and with reference to the work by Hongisto [16] it is expected that flanking noise transmission can be very strong. Hence, a study is made of the energy transmission at various frequencies within the low-frequency range below 500 Hz. The findings of the paper indicate that the FEM can be applied to predict flanking noise in lightweight building structures with periodic stiffening.

Since flanking noise is the main consideration, the acoustic medium in the adjacent room is not modelled. However, the influence of including the air enclosed within the cavities inside the panel has been examined. The distribution of energy between the structure and the air has been analysed. The commercial code ABAQUS has been employed to model the double-plate panel structure using elements available in the ABAQUS/Standard library [19]. Material damping was introduced in the structure, whereas no damping was assumed in the air. For comparison, an analysis was performed in which the structural damping has been disregarded.

The aim of the paper is to get a better understanding of flanking-noise behaviour within two adjacent panels having couplings between the internal acoustic medium and the structure. Section 2 represents the model of the double-panel lightweight wall structures, whereas the results are discussed in Section 3 and concluding remarks are given in Section 4. Direct transmission of noise through a similar panel structure is analysed in a companion paper by Dickow, Domadiya, Andersen and Kirkegaard.

2 PROBLEM DESCRIPTION

Lightweight structures are usually constructed in panels with plates on stud or joist frames. To reduce the transmission of sound, frames are usually designed with single or double studs or constructed with layers of foam or another viscoelastic material. In the present case, single-stud double-plate panels have been considered. The structure consists of two identical panels forming an L-shape such that there is a direct structural coupling between the two panels. Furthermore, the plates are directly attached to the frame with no inclusion of elastic or viscoelastic layers. The aim of the study is to investigate the flanking noise transmission between the two walls under different circumstances. Thus, analyses are carried out with and without inclusion of the acoustic medium enclosed in the cavities within the panels. Further, different positions of a point force on one of the panels have been considered (see Figure 1), and the influence of structural damping is investigated.

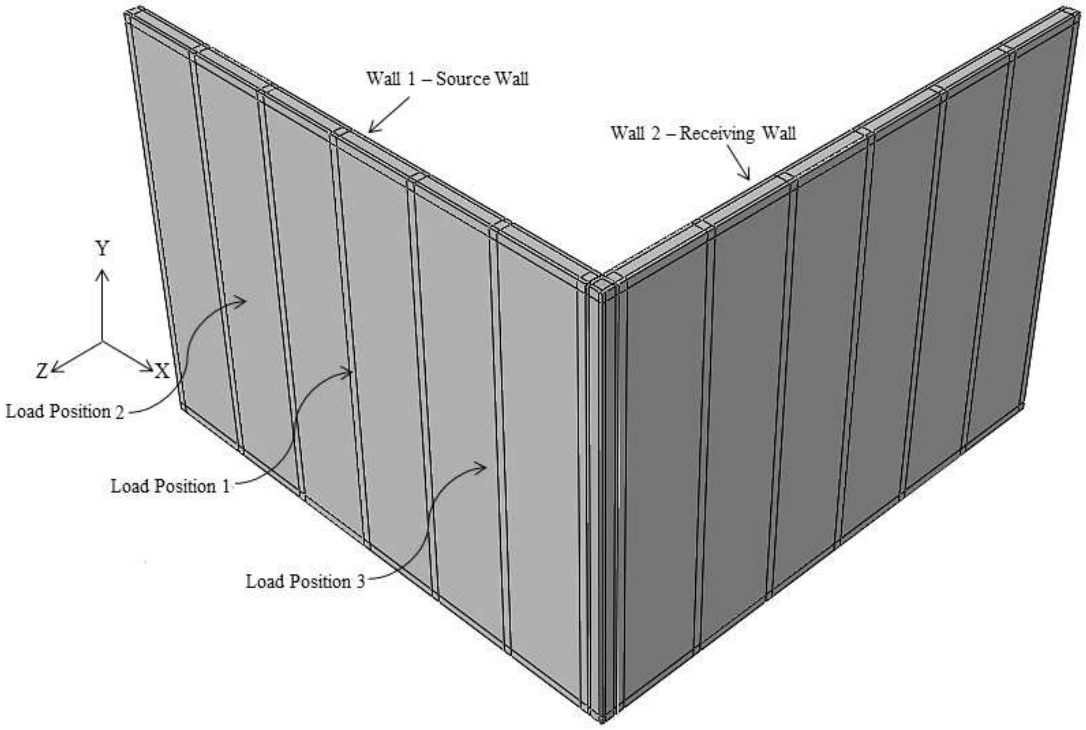


Figure 1: Complete geometry of two-wall structure.

2.1 Geometry and materials

The structure consists of two panels which are identical in sense of materials and geometry. Each panel consists of two plates mounted on a frame structure with six acoustic cavities (see Figure 1). The stud dimensions are 50 mm by 60 mm and the plate thickness is 20 mm. The total wall dimensions are 3350 mm (width) by 2600 mm (height) by 100 mm (thickness). The studs are placed with a distance of 550 mm (centre-to-centre). Homogeneous and isotropic materials are assumed. The material properties are:

- Timber (plates and frame): Young's modulus 14 GPa, Poisson ratio 0.35, mass density 550 kg/m^3. Damping is set to 1% of the stiffness (frequency-independent structural damping).
- Air (acoustic cavities): Bulk modulus 141,360 Pa, mass density 1.2 kg/m^3. No damping is introduced in the air inclusions.

It should be noted that the external air has not been included into the computational model, i.e. the acoustic medium surrounding the walls has been disregarded. Introduction of the surrounding air has an anticipated effect of reducing the Eigen frequencies of the structure due to the added-mass effect, and at the same time damping will occur due to radiation of sound.

2.2 Computational model

The panel is modelled in the commercial FEM package ABAQUS using solid continuum finite elements for the structure and fluid continuum elements for the air inclusions in the finite cavities. 20-node brick elements with quadratic spatial interpolation of the displacement (structure) and pressure (acoustic medium) are adopted with a mesh size of 50 mm. The mesh size has been chosen based on the wavelengths of waves propagating in the model at the higher frequency of interest—in this case 500 Hz.

The mesh is generated in such a way that nodes constituting the plate mesh align with the nodes on the frame structure. All structural contact points are connected using tie constraints in the *x*, *y* and *z* directions. Three-dimensional solid continuum elements have no rotational degrees of freedom, i.e. only displacements are considered. However, due to the local piecewise second-order interpolation of the displacements, the model adequately describes bending in the plates with a single element over the thickness direction.

The fluid–structure coupling is generated by using tie constraints within ABAQUS [19]. The two walls are connected by a column with cross-sectional dimensions of 100 mm by 100 mm and consisting of the same material as the remaining structure. Finally, the panels are fixed along the entire outer edge, i.e. at the top and bottom of the walls as well as the ends of the two adjacent panels.

2.3 Method of analysis

Two analyses have been performed on the present lightweight structure: 1) Modal analysis; 2) analysis of the steady state response to point excitation. In the modal analysis, the real Eigen frequencies were determined with and without air inclusions inside the panel structure. The Lanczos solver implemented in ABAQUS was applied in order to account for the structure–fluid coupling. In case of the steady state response to point excitation, direct steady state analysis was performed. Currently, mode-based analysis in ABAQUS does not support simultaneous modelling of fluid–structure coupling and structural damping. The steady state response analysis has been done under five different specifications of the model and load:

1. Transmission from wall 1 to wall 2 with air inclusions (load position 1),
2. Transmission from wall 1 to wall 2 without air inclusions (load position 1),
3. Transmission from wall 1 to wall 2 with air inclusions (load position 2),
4. Transmission from wall 1 to wall 2 with air inclusions (load position 3),
5. Energy deviation on receiving wall with and without damping (load position 1).

The three different load positions are considered in order to quantify the influence of the load position on the transmission to the adjacent wall, i.e. the flanking noise transmission. Material damping is introduced within the two panels, but as indicated by item 5 above, a comparison is made with an alternative model without structural damping. In addition to the total transmitted energy, the relative distribution of energy between the structure and the enclosed acoustic medium is also investigated at wall 2 for the three different loading positions.

3 RESULTS AND DISCUSSION

3.1 Eigen modes and Eigen frequencies

The undamped Eigen modes and corresponding Eigen frequencies of two panel structures with and without air inclusions were extracted using ABAQUS. Figure 2 shows the accumulated number of modes occurring below a given frequency in the interval 0 to 500 Hz. In the case with no internal air inclusions, only structural modes are present, and below approximately 420 Hz the modal density is low with the first mode occurring at approximately 95 Hz (see Figure 3). Beyond 420 Hz, the modal density increases significantly due to local modes of resonance in the plate fields between the studs.

When the air inclusions inside the panel are introduced into the computational model, Figure 2 shows that the number of modes increases dramatically. The first modes occur at about 67 Hz. However, these are not structural modes but modes related to resonance of the air in the cavities inside the panel. These “bubble modes” appear in bunches of 12 since there are 12 cavities in the structure. Due to the coupling between the structure and the acoustic medium, some spreading is present in the Eigen frequencies related to a bunch of “bubble modes”. However, since the coupling is weak in the present case at low frequencies, the frequencies are closely spaced as indicated by Figure 2 and the first two subfigures of Figure 4. With the inclusion of the air, the first structural mode in the panel structure is reduced from 95 Hz to about 80 Hz as an effect of the added mass (see Figure 2). A similar observation can be made for the subsequent structural modes up to about 340 Hz. At higher frequencies, there is a rapid increase in the number of modes, i.e. a higher modal density, within the panel. Further, a clear distinction between structural modes and “bubble modes” cannot be made, thus indicating a higher degree of structure–fluid coupling at higher frequencies.

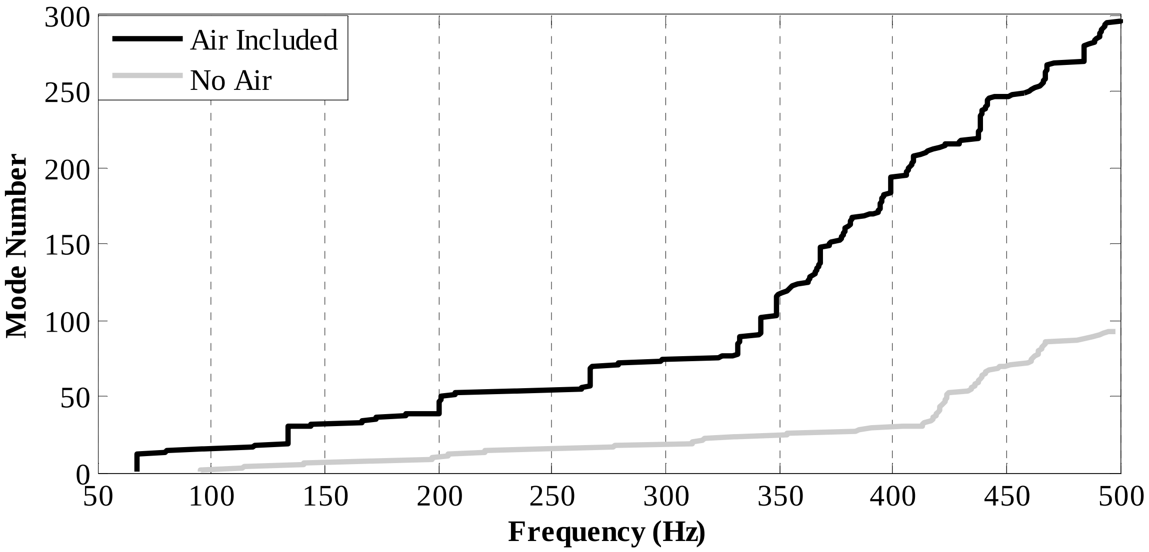
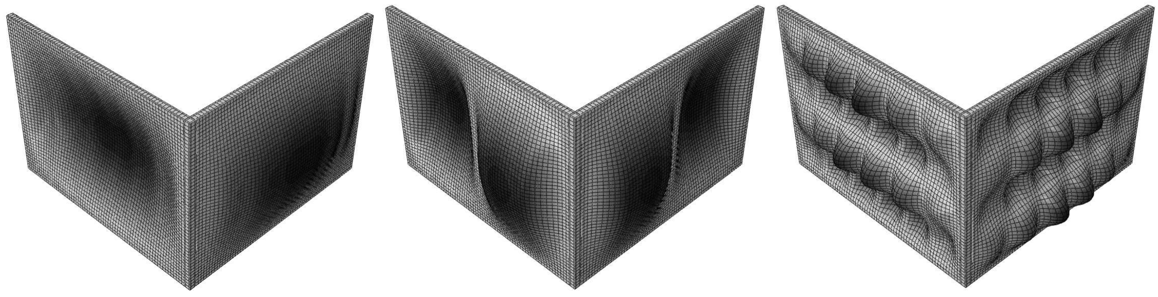
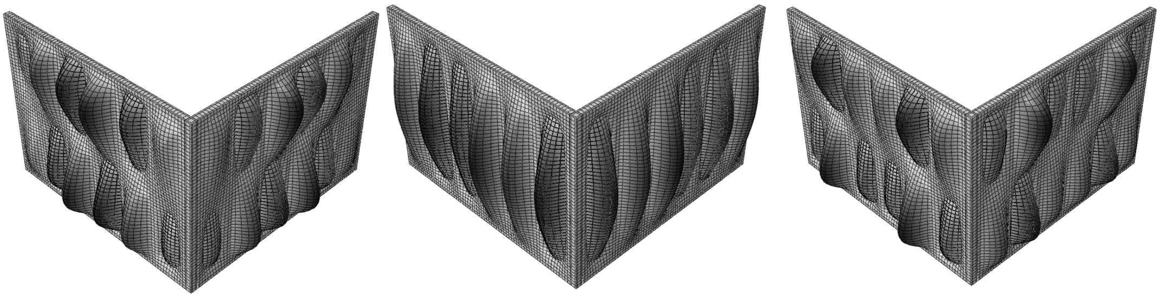


Figure 2: Eigen frequencies within whole panel with and without air inclusions.



Mode at 94.94 Hz   Mode at 114.92 Hz   Mode at 413.13 Hz

Figure 3: Structural modes at different frequencies in the model without air inclusions.



Mode at 67.11 Hz   Mode at 67.12 Hz   Mode at 364.73 Hz

Figure 4: “Bubble modes” generated due to resonance in the air inclusions.

3.2 Steady state response to point excitation

The steady state response of the panel structure to point excitation on one of the walls (the *source wall*) has been analysed for three different positions of the load (see Figure 1). The focus of the analyses has been put on the *receiver wall* in order to study the flanking noise transmission. Furthermore, for load position 1 (at the centre of the source wall), the energy transferred to the receiver wall was determined with and without the air inclusions in the two panels, and computations were made with and without structural damping.

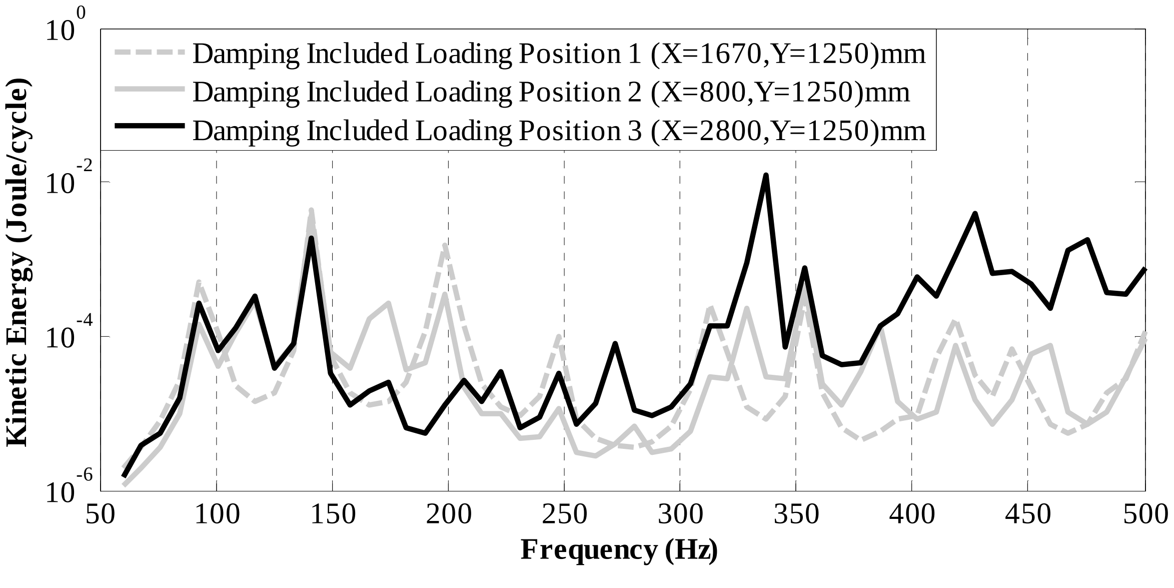


Figure 5: Kinetic energy per load cycle in whole model for the three different load positions.

Figure 5 shows a comparison of the kinetic energy per load cycle (absolute values) in the whole model for load positions 1, 2 and 3 and at 55 frequencies in the interval from 60 Hz to 500 Hz. It is noted that the models include the air inside the cavities as well as structural damping corresponding to 1% of the stiffness. At lower frequencies, peaks occur in the response near the structural Eigen frequencies. The point forces placed at load positions 1 and 2 provide nearly the same magnitude of response. With reference to Figures 1 and 3 this can be explained by the fact that the two loads act at positions leading to a similar strength of the excitation of the source panel within the first few structural modes of vibration. The analyses show that the peaks near 80 Hz and 200 Hz are slightly more pronounced for load position 1 compared to the two other load positions. This can be explained by the fact that a load applied to the centre of the source wall provides a stronger excitation of the first and third structural mode than a load applied near one of the ends of the panel. By contrast, the load applied at the centre of the source wall (i.e. at load position 1) acts near a node of the second mode, leading to a smaller response than observed for load positions 2 and 3.

For an excitation near 67 Hz it is expected that the load will induce strong vibrations in the “bubble modes”. This is not visible in Figure 5, which can be explained by the coarse frequency spacing combined with the fact that the “bubble modes” are weakly damped and almost uncoupled from the structural modes at lower frequencies. Hence, unless the “bubble modes” are excited very close to their resonance frequencies, they are not excited at all.

At higher frequencies, load positions 1 and 2 provide a significantly lower energy level than observed for load position 3—especially beyond 360 Hz. This can be explained by the longer distance from the load to the main part of the structure leading to a longer transmission path. Hence, the effect of structural damping is stronger. Moreover, the periodicity introduced by the ribs has an influence at the higher frequencies.

The kinetic energy transferred to the receiver wall with and without structural damping is presented in Figure 6 for load position 1. The structural behaviour with and without damping is almost identical in the low frequency range, but there is a reduction in the level of energy for frequencies beyond 260 Hz when damping is included, in particular near the resonance frequencies. If a higher frequency resolution is adopted, the peaks will go to infinity in the case without damping. At the higher frequencies, i.e. 400 to 500 Hz, the modal density is relatively higher than observed at lower frequencies. Hence, the influence of the structural damping is visible for all frequencies in the range.

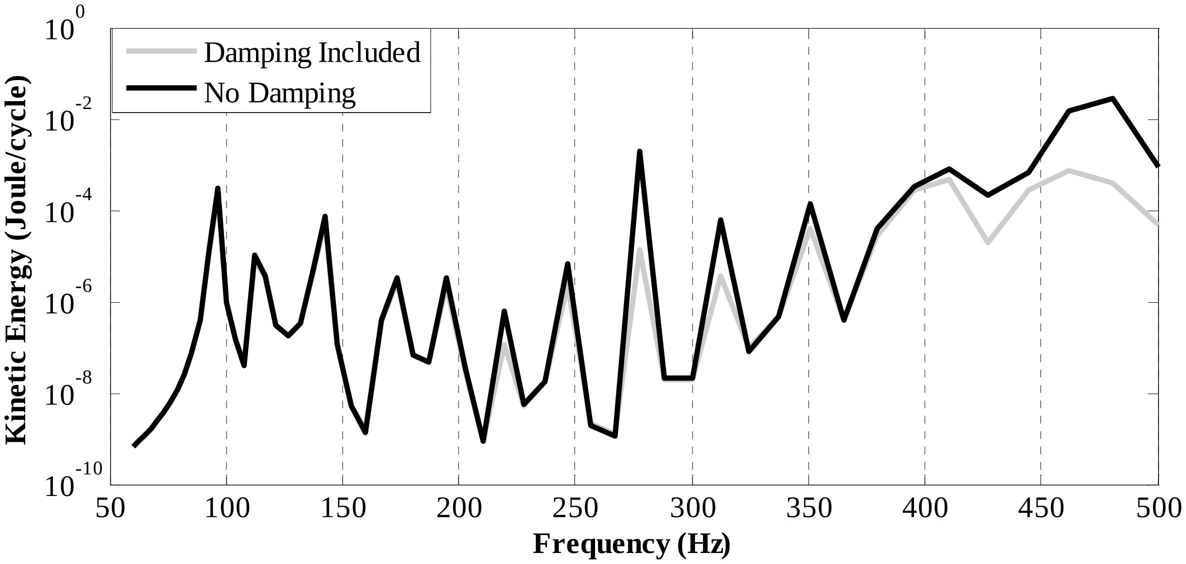
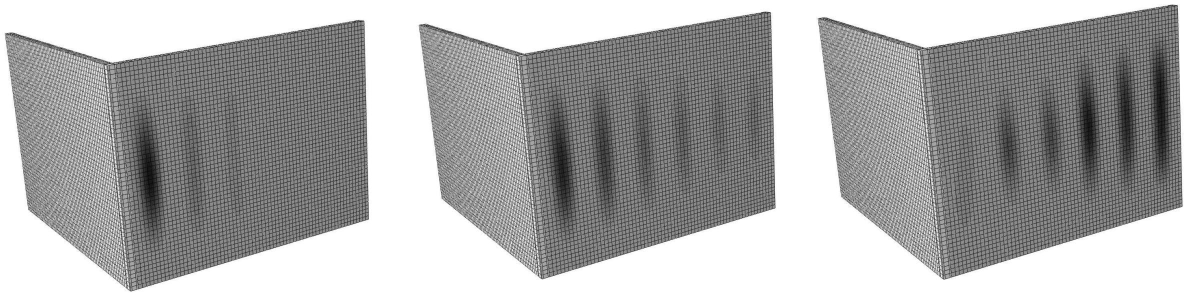


Figure 6: Energy transferred to the receiving wall with and without structural damping for load position 1.

Another interesting observation can be made regarding the response at frequencies above 350 Hz, where the modal density becomes higher. Thus, the total amount of kinetic energy transferred to the receiving panel may be similar for a number of frequencies in this interval. However, the local distribution of the energy over the receiving panel can be very different. This is illustrated in Figure 8 which shows the distribution of the kinetic energy at three different frequencies for the panel without air and with the point force placed at load position 1. At the frequency 394 Hz the main part of the energy is contaminated in the half of the receiver wall that is closer to the joint with the source wall. However, as the frequency is gradually increased to 410 Hz, the energy is transferred to the other end of the receiver wall.



Response at 394.1 Hz Response at 402.2 Hz Response at 410.4 Hz

Figure 7: Response at three different frequencies for the panel without air and load position 1. The shades of grey indicate the magnitude of kinetic energy per unit volume (darker shades correspond to more energy).

Figure 8 shows the kinetic energy transferred to the receiver wall with and without air inclusions for load position 1. An increase of the energy due to the inclusion of the air within the cavities is seen at almost all frequencies. Finally, Figure 9 shows the relative distribution of energy between the air and the structure in the receiver wall for all three different load positions. It is observed that the structure generally carries the main part of the energy in all three cases. The energy contained in the air is 1–3 orders of magnitude smaller, which corresponds well to the fact that the mass of the air is less than 1% of the structural mass. However, a strong fluid–structure coupling is seen for load positions1, 2 and 3, respectively, at the frequencies 200 Hz, 140 Hz and 340 Hz. Here, some of the “bubble modes” are excited.

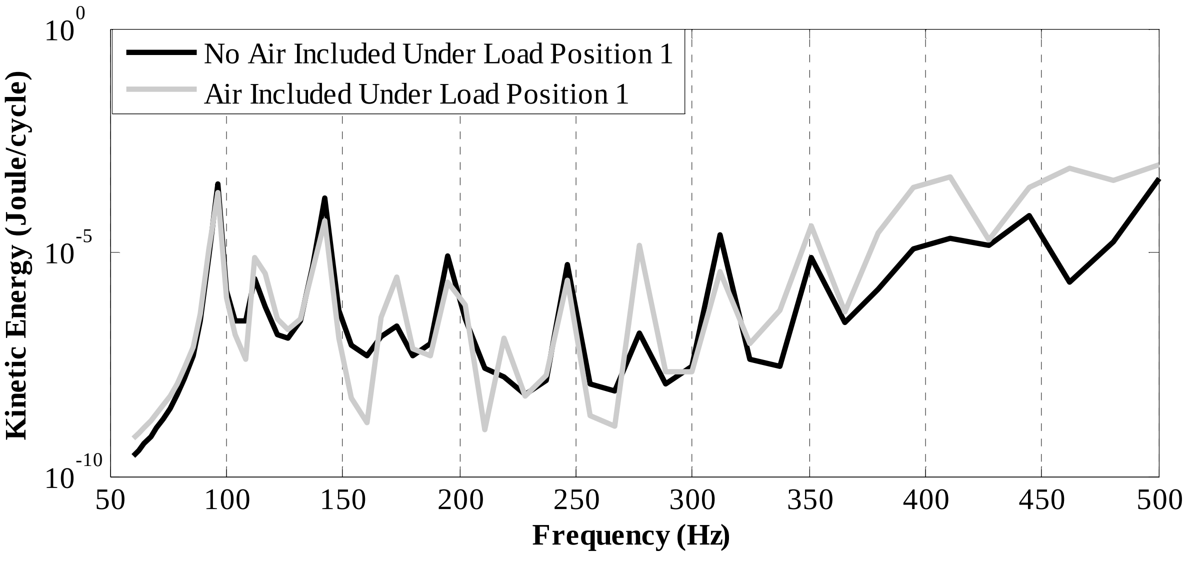


Figure 8: Energy transferred to the receiving wall with and without air inclusions for load position 1.

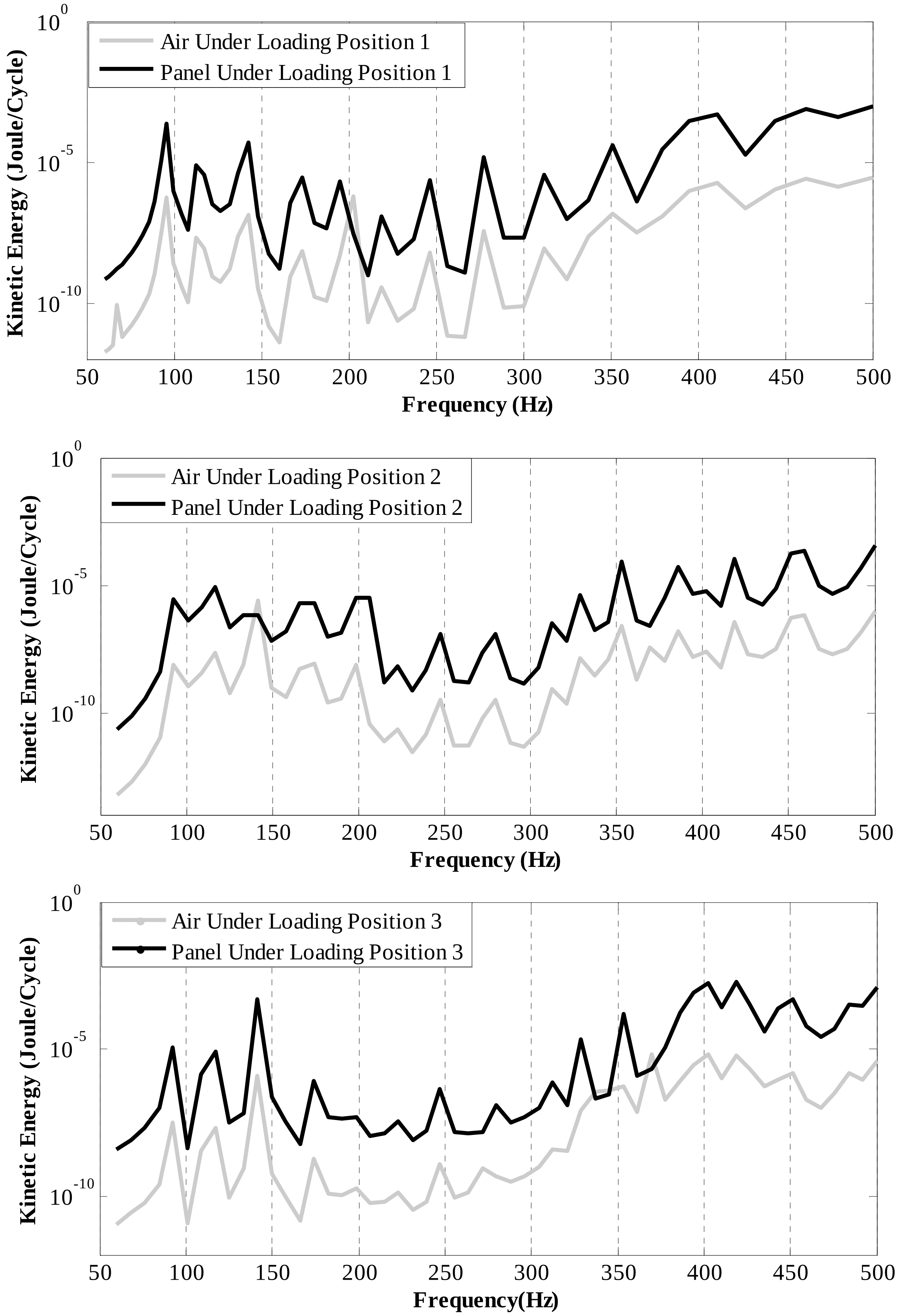


Figure 9: Distribution of energy between air and panel at receiver wall for three different load positions.

4 CONCLUDING REMARKS

Flanking transmission between two double-plate single-stud lightweight panels has been analysed under different conditions in the frequency range below 500 Hz. Slight differences have been observed in the Eigen frequencies depending on whether the air inside the cavities within the panels has been included or not. For example, the first structural mode with and without air inclusions occurs at 80 Hz and 95 Hz, respectively. The kinetic energy per load cycle within the whole structure was extracted for three different positions of a point force acting on one of the panels. It was observed that the energy level is highly influenced by the load position, especially at higher frequencies. Material damping as well as periodic stiffening may contribute to a decrease of the transmission when the load is applied on the source panel at a greater distance away from the receiver panel.

It is also seen that the energy present in the receiver wall is slightly increased when air is included within the panel structure. The structure still carries the main part of the energy and in most situations the coupling between the structure and the fluid is weak. Due to resonance of the air inside the cavities, “bubble modes” exist, but due to the weak coupling with the structure at lower frequencies, excitation of these modes will not lead to a significant excitation of the structure and vice versa. However, for certain combinations of the load position and the excitation frequency, a significant part of the energy is transferred to the air inside the receiver panel. At frequencies beyond 350 Hz the modal density becomes much higher than observed at lower frequencies and the structural and acoustic modes become mixed, indicating a stronger fluid–structure coupling with increasing frequency.

The present paper is a result of preliminary research in a larger research project on mitigation of flanking transmission in lightweight building structures. Future work involves a closer investigation of the influence of periodicity in the stiffening of lightweight structures. Further, the energy dissipation at junctions will be examined, and a sound field will be introduced in the adjacent room in order to predict the flanking noise behaviour of the structure. Comparisons will be made between panels with unidirectional ribs and with two sets of orthogonal stiffeners. The aim is to predict flanking noise behaviour via joints or as direct transmission between adjacent rooms.

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