Modelling of airborne transmission in floor system including flanking transmission.

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Abstract

Predicting vibroacoustic performance in buildings in terms of sound insulation is a challenging task. As of today, no widespread standardised accurate method for predicting either impact or airborne sound insulation has been established. Rather, several software relying in the analytical methods proposed in the acoustic standard EN 12354-6:2000 are commonly used. In there, the overall in-situ performance of a structure is estimated through combining the individual performances of the elements present in the building and a general parameter $D_{n,T}$ is calculated. However, the complexity of the predictions increases with uncertainties related to factors such as craftmanship, frequency range involved and, above all, flanking transmission. Therefore, it is important to gain knowledge about the flanking transmission in buildings so that accurate predictions can be made in the early design phase of the building, which in turn saves also time and money for the actors involved. The aim of this investigations reported here is to model the airborne sound transmission in a floor system in order to gain knowledge about the different phenomena involved and eventually be able to enable accurate numerical sound insulation prediction models. Firstly, a 2D model was setup and its performance was analysed by comparing the direct transmission case (i.e. just the floor) with the case where flanking transmission occurs (i.e. floor-wall system). With the knowledge gained from the latter investigations, a 3D model was then created, and further developments of the predictive tools were performed so that the airborne transmission could be compared with existing in-situ measurements. The predictions stemming from the models showed correct tendencies, however further refinements and calibrations of the model (in terms of modelling the source as well as connections) are needed in the next steps so that the absolute values can be accurately predicted.

1. Introduction

One of the main hinders when developing sound insulation prediction tools (either airborne sound or impact sound) is flanking transmission. Estimations based on software relying in the analytical methods proposed in the acoustic standard EN ISO 12354:2017 and/or measurements performed in laboratory provide single number values (in terms of either airborne or impact sound insulation) that are very seldom reached on-site. The difficulty in foreseeing how junctions transmit sound and vibrations, together with the uncertainties involved in craftmanship, make sound insulation a challenging and daunting task. To that end, computer models can help, during the design phase of the building, potential problems with sound insulation, if accurate models can be created.

The performance of a structural system against airborne sound insulation is described in terms of a frequency dependent standardised sound level difference (in dB). The procedures for evaluating the performances as well as instructions on how to measure (both in situ and in lab environments) are described in the standards ISO717-1, ISO16283-1 and ISO10140-2. In there, measurements of sound pressure levels (SPLs) as well as reverberation times (RTs) are needed. The results obtained by use of sound level meters depend, especially in the low frequency range, in the evaluation positions, as the presence of a non-diffuse field (i.e. modal behavior of the room) can yield to values not being representative of the acoustic comfort experienced by dwellers. Therefore, gaining knowledge of the problem at hand is of crucial importance.

In the investigations presented here, a simple model is analysed with respect to flanking sound transmission. Modifications in a reference model were performed aiming at studying the relative differences between modelled results and thus gaining knowledge about the phenomena involved. To that end, a section of a concrete building was modelled as a reference case, subsequent modifications (in terms of e.g. adding floortopping, suspended ceiling) being performed one at the time in order to see how the airborne sound insulation varied.

2. Airborne sound insulation

In building acoustics, two types of transmission can be distinguished: impact sound transmission and airborne sound transmission. The main difference between both types of transmission is how the excitation is created. Whereas the former takes place when an object strikes directly the floor; the latter occurs when sound waves travel through the air and reach a building element, setting it into vibration. One the vibrations are produced in both cases, they travel throughout the element in question and radiate out to the other side of it through creating pressure differences that propagate and create noise.

In the investigations presented here, airborne sound insulation is dealt with. Sound Insulation is the ability of building elements or structures to reduce sound transmission. Typical airborne transmission sources are speech, HiFi systems (such as speakers), and appliances. The sound transmission path here is one in which the energy is carried for the most part by the air, and only to a minor extent via structural-borne waves. Airborne sound insulation procedures are described in the ISO717-1 and can be measured in a laboratory (following ISO10140-2) or in the field on a real construction (according to ISO16283-1). In the first case, the lab consists of two adjacent rooms, completely isolated one from another but they are connected only with a common surface, which is the partition under measurement. This way it is possible to measure only the direct transmission path, as the flanking transmission is disabled through controlling and isolating all the paths properly. The test rooms are reverberation rooms, so they offer almost perfect diffuse field conditions, which means equally probable distribution of the sound energy in all directions and equal SPLs in the room. However, field measurements often fall short of laboratory measurements since they offer more realistic results about the general behaviour of the test partition including any interactions with the rest of the structure, i.e. as flanking transmission comes into play (cf. Figure 1).

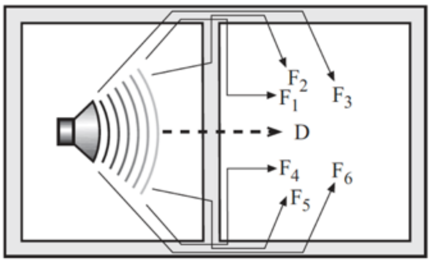

Fig.1 – Airborne sound transmission. "D" denotes direct transmission whereas the "Fi" indicate the different flanking paths involved.

When measuring airborne sound insulation, a noise is emitted in the sending room, measuring the frequency-dependent SPL that is produced in both the sending ($L_{p,send}$ [dB]) and receiving ($L_{p,rec}$ [dB]) rooms and then calculating the sound level difference D(f) simply as $D(f)=L_{p,send}(f)-L_{p,rec}(f)$. After that, and aiming at being able to compare sound insulation properties of floor or walls installed in different constructions, one needs to take into account several parameters of the receiving room, namely the area of the dividing partition/wall (S[m^2]), as well as the volume (V[m^3]) and sound absorption properties (A[m^{2}Sabine]) which is related to the reverberation time T_{60}[s] of the receiving room (i.e. the time that it takes for the sound to decay 60 dB after the source is shut off). In doing so, measurements are normalised to a reference absorption value of A_0=10 m^2 or standardised reverberation time of T_0=0.5 s, yielding the following indicators:

$$\text{Sound reduction index (lab): } R(f) = L_{p,send}(f) - L_{p,rec}(f) + 10\log\left(\frac{S}{A(f)}\right)$$

$$\text{Apparent sound reduction index (field): } R'(f) = L_{p,send}(f) - L_{p,rec}(f) + 10\log\left(\frac{S}{A(f)}\right)$$

$$\text{Normalised level difference (field) } D_n(f) = L_{p,send}(f) - L_{p,rec}(f) + 10\log\left(\frac{A(f)}{A_{0(10m^2)}}\right)$$

$$\text{Standardised level difference (field) } D_{n,T}(f) = L_{p,send}(f) - L_{p,rec}(f) + 10\log\left(\frac{T_{60}(f)}{T_{0(0.5s)}}\right)$$

Both D_n, D_{nT} and R' are used in situ. However more and more countries are using $D_{nT,w}$ since it has been shown that it relates better to the experienced sound insulation due to the fact that It refers to a reverberation time of of 0.5 s which is normal in furnished dwellings (R' is scaled to the partition area and absorption area in the receiving room which can create strange numbers in the field when big rooms, for example). The relation between the quantities are described in EN ISO-12354. According to the latter standard one can predict either R' or $D_{n,T}$, depending on how the requirement is stated in each country, and then convert the quantities taking into account the volume of the receiving room and the surface of the partition according to

$$D_{n,T}(f) = R'(f) + 10\log\left(\frac{0.32V}{S}\right)$$

The application of the latter formulae yields a curve (in third octave bands) of the indicator in question against frequency. Since it generally describes a reduction sound index; the higher it is the better the floor (or wall) performs against airborne sound insulation. A single number to present the results and compare products is useful and often calculated according to the procedures described in ISO 717-1 (the weighted value is where the curve meets the 500 Hz shifted reference curve and the unfavourable deviation is 32 dB). This is where the weighted term comes in; thus we can have: weighted sound reduction index (R_w) weighted apparent sound reduction Index (R'_w), weighted level difference (D_w), weighted standardized level difference ($D_{nT,w}$). The D_w value is identical to $D_{nT,w}$ when T_{60}=0.5 s. Spectrum adaption terms can be additionally added to the weighted indicators depending on the type of excitation dealt with (e.g. traffic, see ISO 717-1). In here, and since the receiving room is the same in all cases, focus is put into the sound level difference D(f) in order to compare the cases under study.

3. Finite element model

More specifically, two rooms (made of concrete walls and a concrete floor) and dimensions 4x3x2.5 m^3 were modelled and stacked on top of each other (mimicking for example a part of a modular building). Both a 2D model (Fig. 2) and a 3D model (Fig. 2) were developed; the aim being that the 2D model allowed analysing higher up in frequency (due to computer power limitations). The transmission from the upper room (hereafter "sending room") to the room below (denoted "receiving room") through the floor structure, underlying ceiling (when present) and surrounding walls was investigated. Acoustic-structure interaction was included, thus accounting for resonant transmission through air cavities, e.g. between the floor structure and the suspended ceiling.

The reference model (where flanking transmission is not present, see Fig. 2a and Fig. 2c) is comprised of 10 cm thick massive concrete walls and the floor was considered to be a 20 cm concrete slab. During the parameter studies performed, other materials were included as part of the structure (e.g. floortop made of plywood, gypsum boards on the wall surfaces…) as it will be explained afterwards. All materials used for the structural components are listed in Table 1 together with their properties. The plywood and the concrete were modelled as linear isotropic materials.

Air	Concrete	Plywood	Gypsum
K=141000	E=25E+9	E=12.5E+9	E=10.7E+9
ρ=1.2	ρ=2300	ρ=710	ρ=574
c=340	υ=0.2	υ=0.3	υ=0.2
	η=0.03	η=0.01	η=0.01

Table 1. Material properties. E[Pa] denotes the Young modulus, K[Pa] the bulk modulus, ρ[kg/m^3] the density, υ[-] the Poisson's ratio and η[-] the structural loss factor.

All parts were meshed with tetrahedral elements using quadratic interpolation. The mesh sizes both for the structural and the acoustic parts were decided based on the wavelengths expected to occur at the highest frequency of interest, namely 3150 Hz in the 2D case and 1000 Hz in the 3D case (here computer power limitations hindered going higher up in frequency). In order to simulate the "existence" of extra levels above and below than the two modules studied, fixed constraints were assumed, as shown in Fig. 4.

In order to address airborne sound insulation, noise has to be produced in the sending room in order to see how much the floor structure reduces before sound is radiated into the receiving room. Modelling the loudspeaker is a complex task and there is unfortunately no one general solution to it. Loudspeakers by different manufacturers are very different; they have different directivities and also sound source distributions (i.e. different parts of the surface of a loudspeaker could radiate differently and also the loudspeaker does not radiate equally in all directions). However, since in this first preliminary study relative differences are of interest rather than absolute matches with measurements (just tendencies are to be caught and understood, a monopole source was considered to be accurate enough for the investigations presented here. A monopole is a source which radiates sound equally well in all directions. The simplest example of a monopole source would be a sphere whose radius alternately expands and contracts sinusoidally. The monopole source creates a sound wave by alternately introducing and removing fluid into the surrounding area. Three monopole sources were modelled in the sending room, at the positions indicated in Fig. 2b and 2c. A frequency sweep between 20 and 3150 Hz (in the 2D case) and 1000 Hz (in the 3D case) was performed in steps of 1 Hz, the SPL[dB] being evaluated in third octave bands at a uniform grid (see Figure 3) both in the receiving ($L_{p,rec}$) and the sending ($L_{p,send}$) rooms. An energetic average of all the evaluation points (*n* in total, each with its SPL $L_{p,i}$) in each room was performed according to:

$$\overline{L_p}(f) = 10\log\left(\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{L_{p,i}}{10}}\right)$$

The sound level difference then being extracted according to:

$$\mathrm{D}(f)[\mathrm{dB}] = \overline{L_{p,send}}(f) - \overline{L_{p,rec}}(f)$$

3.1. Case studies

As mentioned above, modifications on a reference case were performed aiming at studying the relative differences in terms of airborne sound insulation between the different cases. All cases studied are listed in the table below.

Name	2D/3D	Comments
REF (1a)	✓ / ✓	Bare concrete floor and discontinuous concrete walls (no flanking transmiss.)
2a	✓ / ✓	Same as the REF but considering continuous walls (i.e. flanking transmission)
2b	✓ / ✓	Same as 2a with a 0.05 thick plywood topfloor (and a 3 cm gap with the walls)
2c	✓ / ✓	Same as 2b with the long walls made of plywood instead of concrete
2d	✓ / ✓	Same as 2c with a 0.1 m thick concrete-suspended-ceiling (cavity 0.05 m)
2e	✓ / ×	Same as 2d with gypsum linings on all the walls.

Table 2: All cases studied (see Fig. 5 for graphical illustration of all cases).

4. Results

The results in terms of sound level differences for the 2D and 3D models are shown in Fig. 6 and Fig. 7 respectively. Some other extra cases were simulated, but their results are not shown for the sake of simplicity, since they did not contribute with much extra information. For example, different thicknesses and materials of the floor system were tried as well as different connections (of varying stiffnesses) between walls and floors. Only the most relevant results are shown.

Moreover, in Fig. 8 and Fig. 9, the coupling of the acoustic and structural modes and their potential influence in the sound field is shown. In the case shown as a matter of example (Case 2c), one can see how the material properties can play an important role. The difference in bending stiffness of the materials involve (plywood in the long walls contra concrete in the short walls, for the case shown) change the way the plate-like elements couple between them and their modal densities and thus its insulation behaviour. Further discussions about such issues are present in the next section.

5. Discussion and concluding remarks

In the results presented above, some expected results could be described. Higher mass (due e.g. to a floortopping), linings on the walls, the addition of a suspended ceiling… yielded better sound insulation properties. A bit unexpected though is the bad performance of the reference case (i.e. where no flanking transmission was accounted for). One would think that the sound reduction index should be higher than the other cases, but the fact that the structure is very light makes that direct transmission plays a bigger role than the flanking one. All in all, one can conclude that a floortopping together with a suspended ceiling is often desirable is a proper/acceptable sound insulation is to be achieved and thus enabling acoustic comfort inside dwellings. Moreover, and since the sound level difference is very much sensitive to the combination excitation-dynamic properties of the structure, one should take the latter into account, as it will be explained below.

Looking closely to the finite element results (i.e. the narrow band response of the structure), one can usually get further information about the structure's behaviour than the one gotten from the third-octave-band sound insulation performance, and it can be sometimes very much needed depending on the problem at hand. For example, it was seen that global modes often arise if the plate-like elements are of the same size and have the same material properties. A decoupling of the global modes of vibration occurs, for example when properties of some of the elements are changed (e.g. in *Case 2c*, where the long walls were considered to be made of plywood and coupled to concrete short walls). This can lead to marked changes in the sound insulation, since acoustic and structural modes can couple together and thus enhancing the radiated sound in the room in question (cf. Fig. 8 and Fig. 9). This is an aspect that designers should start looking at, as it can make a big difference in the acoustic performance of floor systems. Just in that manner one can, for example, avoid the fact that room modes lie on the same frequency as the structure global modes (or even local) and the excitation frequency, since otherwise high sound pressure levels in the receiving room could occur. Single number values are often looked at, but the fact that modes of vibration of the structure are triggered in different ways (the latter often depending on the use of the building in question and the loads present) can make two building structures with an identical single number descriptor behave in a totally different manner. Thus, suitable design of structural components (in terms of material, size and shape for example) can avoid high sound pressure levels in rooms and hence improving acoustic experience of dwellers.

The predictions stemming from the models showed correct tendencies, however further refinements and calibrations of the model (in terms of modelling the source as well as connections) are needed in the next steps so that the absolute values can be accurately predicted.

References

[1] CEN (2000), EN 12354-1 (ISO 15712-1:2005): Building acoustics – Estimation of acoustic performance of buildings from the performance of elements – Part 1: Airborne sound insulation between rooms, European Committee for Standardization, Brussels, Belgium.

[2] ISO (2013), ISO 717-1: Acoustics – Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation, International Organization for Standardization, Geneva, Switzerland.

[3] ISO (2010), ISO 10140-2: Acoustics – Laboratory measurement of sound insulation of building elements – Part 2: Measurement of airborne sound insulation, International Organization for Standardization, Geneva, Switzerland.

[4] ISO (2014), ISO 16283-1: Acoustics – Field measurement of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation, International Organization for Standardization, Geneva, Switzerland.

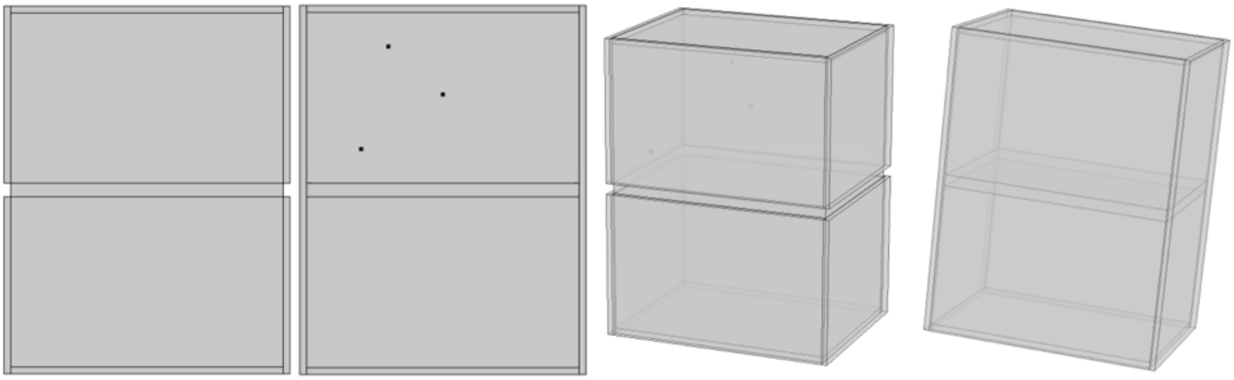

Fig 2. The simplest models studied (i.e. just a bare concrete floor considered). Figures 2a and 2c represent the cases (in 2D and 3D respectively) where flanking transmission is not accounted for, whereas in Figures 2b and 2d flanking transmission comes into play. In Figures 2b and 2c the loudspeaker positions are shown as black dots.

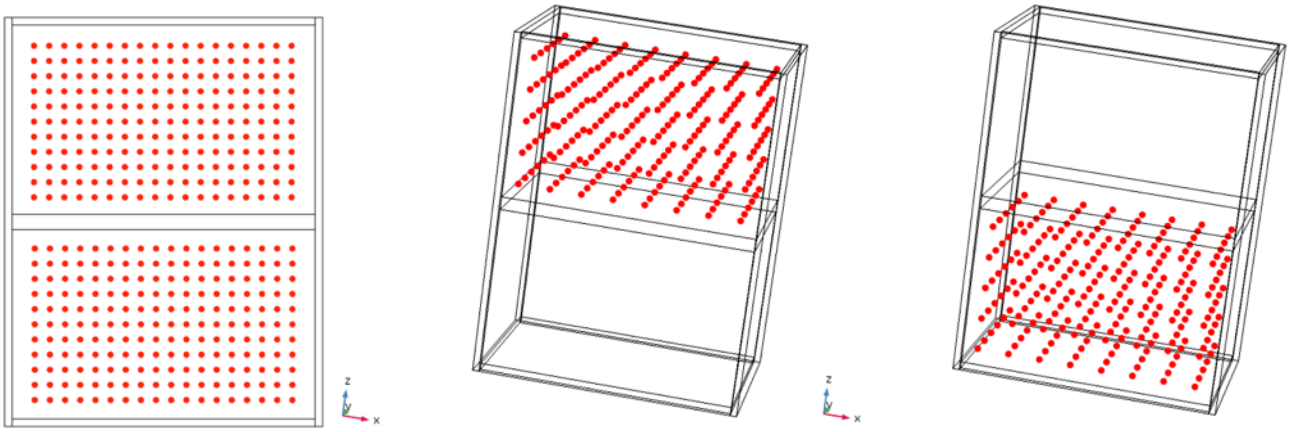

Fig 3. Evaluation points in both the sending and receiving rooms. The left picture depicts the 2D model, whereas the middle and the right figure show the evaluation points in the sending and receiving room respectively for the 3D model.

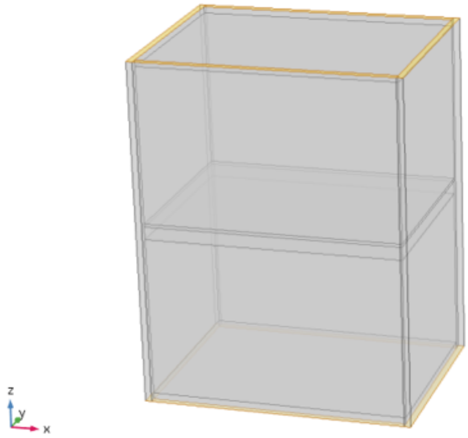

Fig 4. Fixed constraints (zero displacement) considered in the simulations. The model corresponds to the 3D "case b"

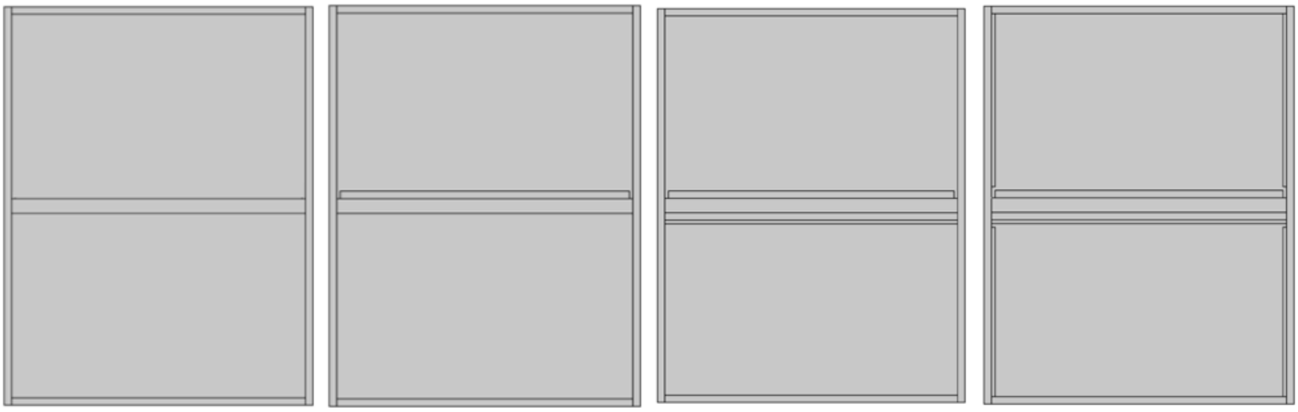

Fig 5. Cases under study. (4a) Case 2a; (4b) Case 2b; (4c) Case 2c and 2d (with concrete and gypsum linings); (4d) Case 2e. For the sake of simplicity, only the 2D models are shown.

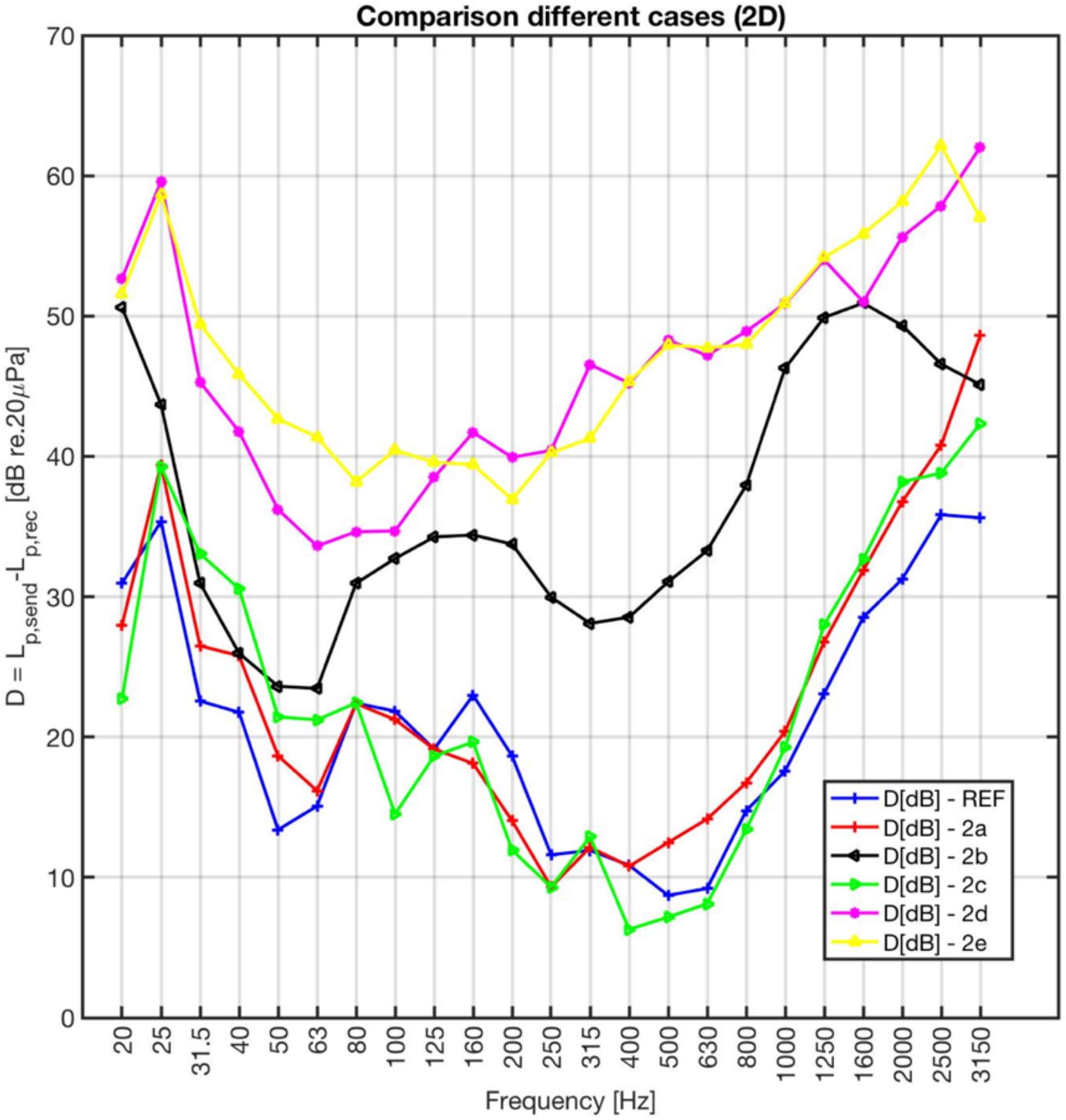

Fig 6. Level difference of the 2D cases under study.

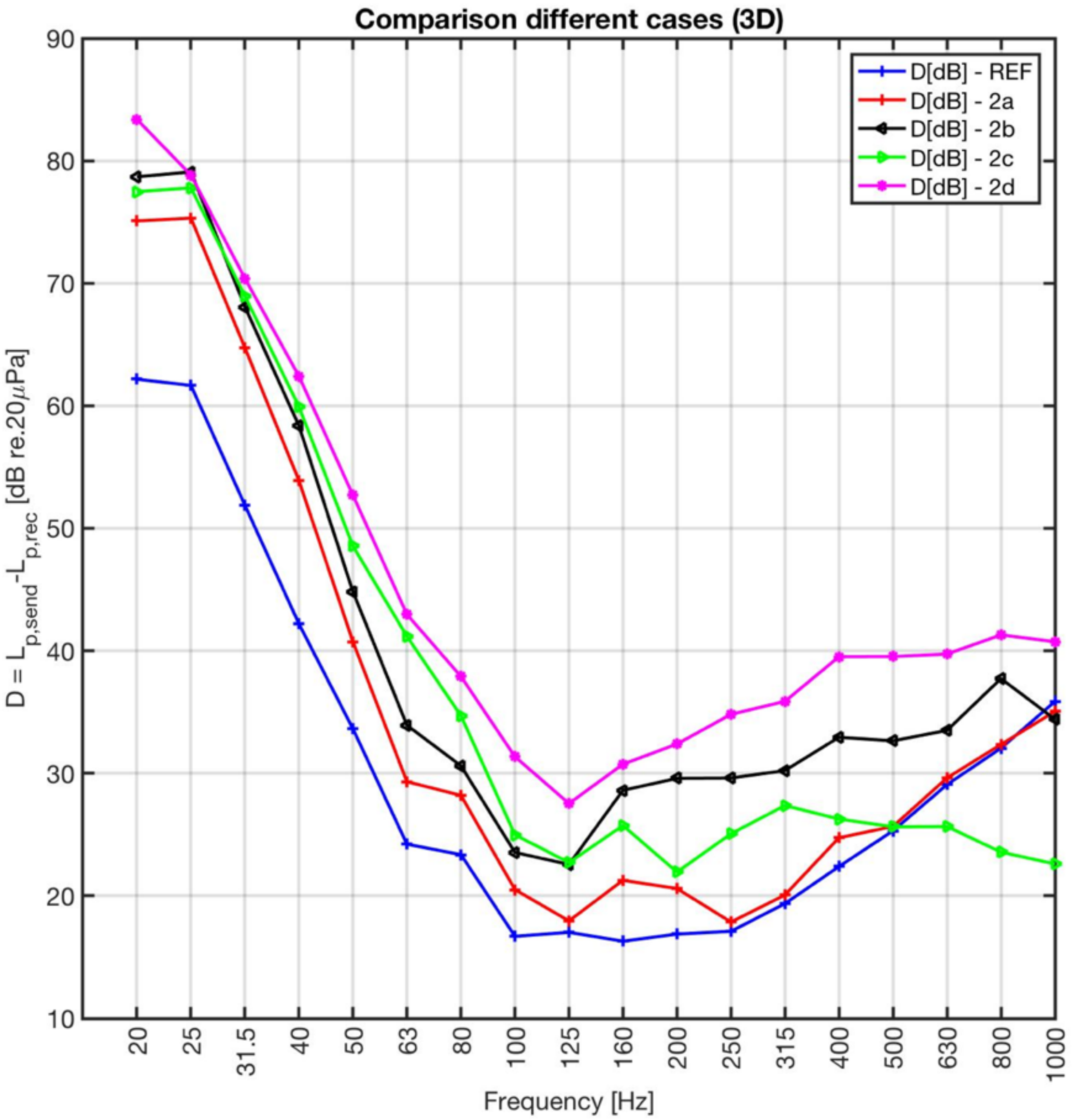

Fig 7. Level difference of the 3D cases under study.

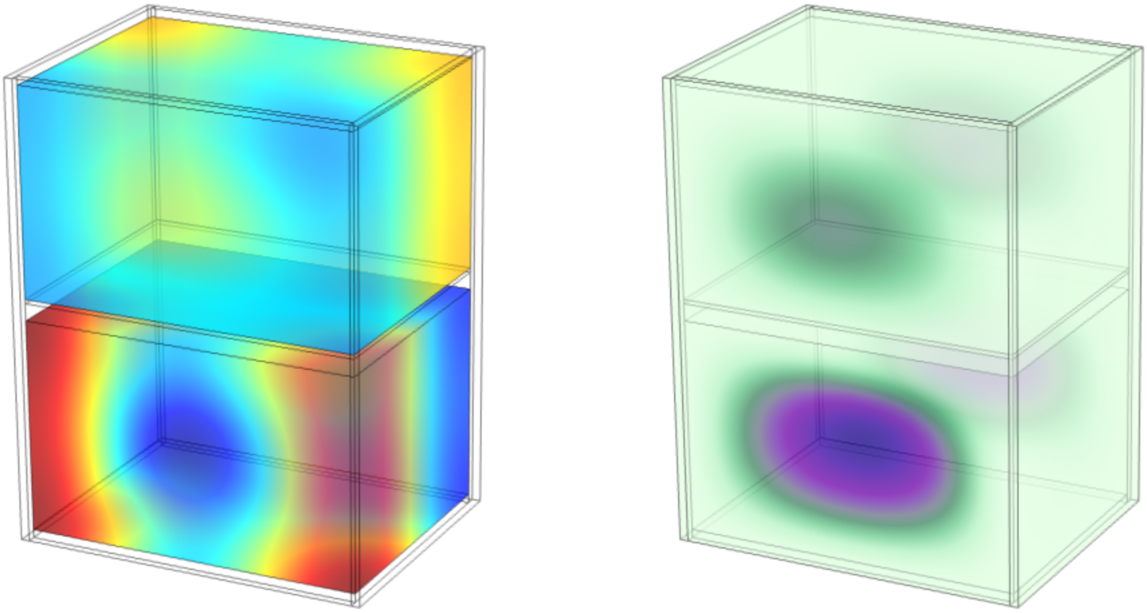

Fig 8. Acoustic modes (left) and coincident structural mode (right) at 83 Hz for the Case2c (3D).

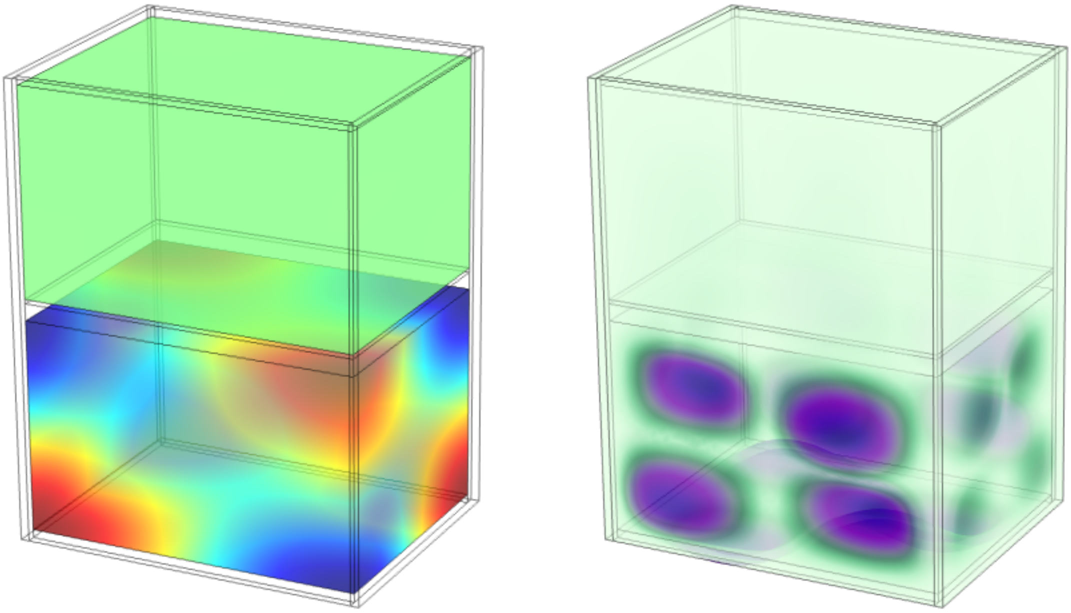

Fig 9. Acoustic modes (left) and coincident structural mode (right) at 99 Hz for the Case2c (3D).