Measured transmission functions from structure-borne sound sources in a timber-frame construction

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Summary
The aim of prEN 15657-2 is to provide engineering methods to estimate the structure-borne sound power input from machinery in situations where the source mobility matches or is lower than the receiver mobility. This situation often affects lightweight constructions such as timber-frame buildings. To estimate the sound pressure level in a room that is adjacent or distant from the room containing the source, the installed structure-borne sound power has to be propagated across at least one junction in the timber-frame construction. However, at present there are no generic, validated calculation models due to the complexity and the large variety of timber-frame constructions. A simplified approach to investigate and compare the structure-borne sound transmission is to treat the framed construction as a black box and only consider one parameter, a transmission function which is the ratio of the sound pressure level in the receiving room to the injected structure-borne sound power level. To get information about the variation of this transmission function in different timber-frame constructions, measurements were made in both the laboratory and the field. Experimental results are presented showing the variation due to different building configurations and the effect of the excitation position on the transmission function.

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1. Introduction

Sustainable and energetically optimized buildings are becoming ever more important, particularly timber-frame buildings. These typically incorporate mechanical service equipment such as heating devices, heat pumps or ventilation systems. Such appliances act as structure borne-sound sources in the building and can cause annoyance to the occupants. For this reason it is necessary for consultants and architects to be able to predict the sound pressure levels caused by service equipment at the design stage. In the frame document of prEN 15657-2, methods are described to calculate the structure-borne sound excitation for typical mobility conditions in lightweight buildings, where the source mobility can be equal or lower than the receiver mobility. However, at present there are no engineering methods available to predict the structure-borne sound transmission in lightweight buildings due to their complexity and the large variety of framed building constructions. Due to a lack of experience, there is uncertainty in the resulting sound pressure levels and their spread due to the variation of the construction or the position of fixing points of the machinery. To collect and compare data describing the structure-borne sound propagation and radiation in lightweight constructions a simplified approach is to focus on the ratio of the input and output quantities (e.g. [1]). In this paper, the transmission function between the input structure-borne sound power and the sound pressure level in the receiving room was determined experimentally for different situations in the laboratory and in the field. The results of this study are presented to give an idea of the variation of the transmission due to different influencing factors as described above.

Figure 1. Experimental setup at each excitation point. The force was applied with an impulse hammer between a pair of accelerometers.

2. Experimental work

In the following sections the basic measurement principle to determine the transmission function is described as well as the application of this principle to measurements in the laboratory and field.

2.1. Basic measurement principle

A calibrated impulse hammer was used to excite the structure with a single transient and to record the input force. To provide a flat force spectrum over a broad frequency range, the hammer had an aluminium tip. Since the structure-borne sound power was chosen as the input quantity, it is necessary to know the structural response at, or as an approximation close to the point of excitation. The structure-borne sound power input can then be determined from the real part of the cross-spectrum between the force and the velocity at the driving-point according to equation 1. The structure-borne sound power level was then calculated according to equation 2 with $P_0 = 10^{-12}\,W$.

$$P = \mathfrak{Re}(\tilde{F} \cdot \tilde{v}^*) \tag{1}$$

$$L_W = 10 \cdot log\, \frac{P}{P_0} \tag{2}$$

In this study a pair of accelerometers was used to estimate the velocity at the driving-point. Each accelerometer had a mass of 3.2 grams and was fixed with a thin layer of bees wax to the surface of the structure. The excitation point was in between the accelerometers as shown in figure 1.
The sound pressure as the output quantity was measured at various microphone positions in the receiving room.
In the receiving room there are few room modes below 50 Hz and the input force spectrum is dropping towards high frequencies; hence the results are presented between the 50 Hz and the 2000 Hz one-third octave bands.
All measurements were carried out with a multi-channel FFT analyser. All active channels for the force, acceleration and sound pressure were triggered with the hammer input (using a short pre-trigger) and filtered with the same FFT-window length to reference the transient energy to the same fraction of time for all quantities. The window length was determined by the sound pressure signal which had the longest decay time. At each excitation point, ten hits were carried out and averaged with problematic hits (e.g. double hits) identified in time domain and rejected before further processing.
The power input was calculated in narrow bands and then summed to give one-third octave bands as well as the sound pressure.
The measurement positions for the sound pressure were chosen according to [2] and [3] including corner positions for the 50 Hz, 63 Hz and 80 Hz one-third octave bands. Following these recommendations, the mean sound pressure level in the receiving room is

$$L_p = 10 \cdot log\, \left(\frac{\sum_{i=1}^{n} \tilde{p}_i^2}{n \cdot p_0^2} \right) \tag{3}$$

above the 80 Hz third octave band and

$$L_{p,LF} = 10 \cdot log\, \left(\frac{10^{0.1 \cdot L_{p,corner}} + 2 \cdot 10^{0.1 \cdot L_p}}{3} \right) \tag{4}$$

for the 50 Hz, 63 Hz and 80 Hz third octave bands with $p_0 = 2 \cdot 10^{-5}\,Pa$.
To account for potential airborne flanking transmission, the sound pressure level difference between the source and the receiving room was determined with an airborne source. Hence any airborne flanking could be quantified and, if necessary, corrected by measuring the sound pressure level in the source room during the hammer measurements. In addition, the influence of background noise in the receiving room was also taken into account. Both influencing factors showed very little or no contribution in the results.
It was necessary to normalize the measured sound pressure level to a reference room with an equivalent absorption area of $A_0 = 10\,m^2$ to allow comparison of different transmission functions. The sound pressure level induced by the structure-borne sound excitation is then given by

$$L_{sn} = L_p + 10 \cdot log\, \left(\frac{A}{A_0} \right) \tag{5}$$

above 80 Hz and

$$L_{sn} = L_{p,LF} + 10 \cdot log\, \left(\frac{A}{A_0} \right) \tag{6}$$

for the lowest three one-third octave bands in the considered frequency range.
Knowing the input structure-borne sound power and the resulting sound pressure level, the transmission function can be calculated in decibels as suggested in Annex C of ISO 15657-1 [4].

$$L_H = L_{sn} - L_w. \quad (7)$$

2.2. Laboratory setup

As part of an ongoing research project, a lightweight test rig was built in the Laboratory for Sound Measurement LaSM at the University of Applied Sciences in Rosenheim. In this mock-up a T-junction was formed by a bare timber joist floor and two timber frame walls. The construction comprises a single layer of sheathing material without insulation material in the cavities. The timber framework was designed by the German timber house manufacturer Regnauer and represents a common construction. The cross sections of the frame elements are 24 cm x 6 cm for the floor joists and 9 cm x 6 cm for the studs that form the framed walls. The spacing is 62.5 cm for both the floor joists and wall studs. The sheathing material is 19 mm chipboard with tongue and groove connections. In the lower floor the test rig forms a receiving room with a volume of approximately 50 m^3. With this setup, it was possible to measure both diagonal and horizontal transmission.
In the receiving room the reverberation time was adjusted to be approximately 0.5 s over the entire frequency range of interest. To determine the transmission function, the sound pressure level was measured at six microphone positions. Four positions in the centre area of the room and two positions in room corners. The mean sound pressure level was then calculated according to equation 3 and 4. To account for a possible airborne flanking transmission, an additional microphone was placed in the source room during excitation with the impulse hammer. For this transmission suite, both the diagonal and horizontal paths were investigated.
The main aim of the laboratory measurements was to investigate the influence of varying the excitation position on the transmission function. Therefore a number of positions was chosen on the upper wall (diagonal transmission) and the lower wall (horizontal/direct transmission) to represent different fixing points that could be used for service equipment. For diagonal transmission the distance to the nearest stud as well as the distance to the T-junction was taken into account. For horizontal transmission, the direct path was assumed to be dominant; hence the dependency on the distance to the nearest stud was investigated for this situation only.

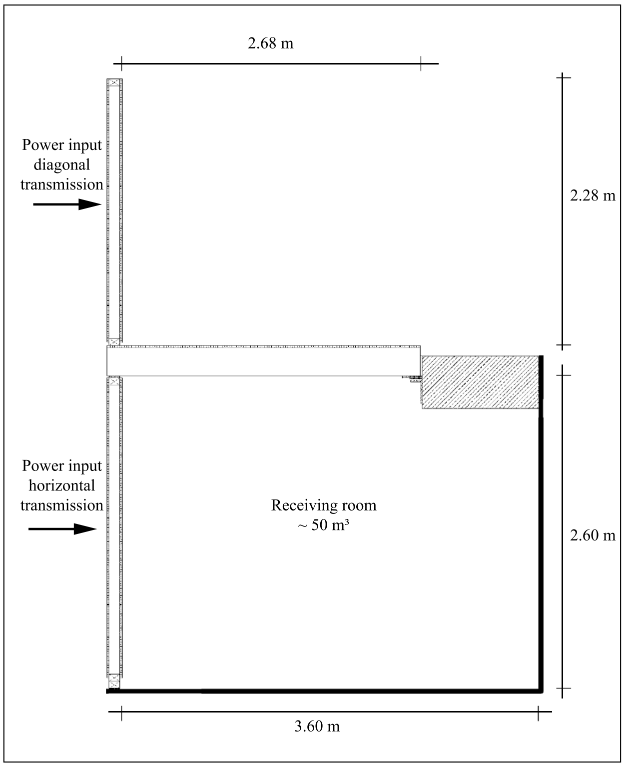

Figure 2. Sketch of the test rig.

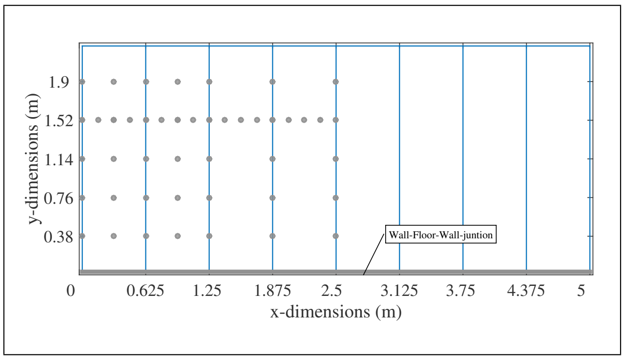

Figure 3. Excitation positions on the framework wall in the lightweight test rig that were used to measure diagonal transmission (n=45).

2.3. Field measurement setup

The field measurements were carried out in a single family house. In contrast to the laboratory situation, the timber frame construction was more complex. The walls were covered with one layer of 15 mm plasterboard on side and a 15 mm OSB panel in combination with 15 mm plasterboard on the other side. The cavities were filled with fibre insulation material. The timber joist floors were covered with a floating screed. The ceiling was constructed with 15 mm plasterboard on a wood batten construction that was screwed to the floor joists. The cavities of the floors were also filled with fibre material.
Due to the limited time that was available on site, the number of measurements was reduced in comparison

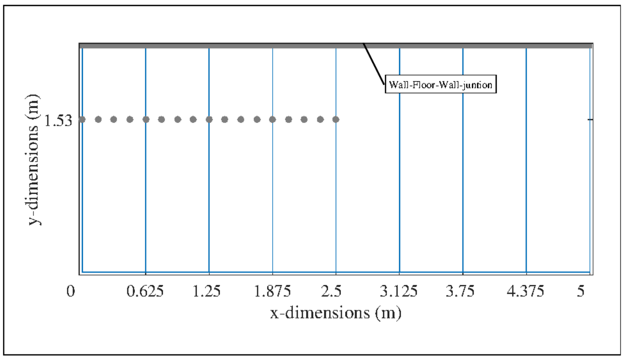

Figure 4. Excitation positions on the framework wall in the lightweight test rig that were used to measure horizontal transmission (n=17).

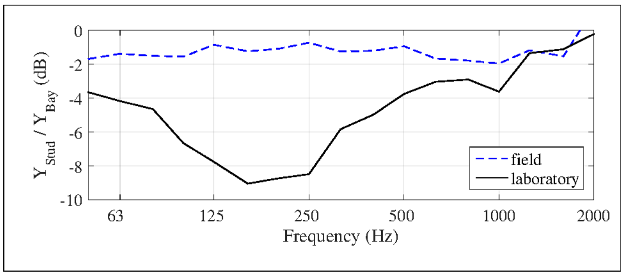

Figure 5. Ratio of the driving-point mobility above a stud an in a bay for the field and the laboratory construction.

to the laboratory with only two microphone positions used in the central zone of the receiving room which increased the uncertainty towards low frequencies. However the data in the mid and high frequency range is reliable. Again, a possible airborne flanking transmission was taken into account as well as the influence of background noise.
An average value was determined from five hits at each position. Two excitation positions were used; one above a stud and the other in a bay as the driving-point mobility was significantly different at low frequencies for the simple laboratory construction. However this did not apply for the field construction due to additional layers of sheething material. In figure 5 the ratio between the mobility above a stud and in a bay is shown in decibels for a field and the laboratory construction.

3. Results of the experimental study

This experimental study investigates the spread of transmission functions due to the variation of excitation position, the transmission path and the construction.

3.1. Laboratory results

For the laboratory measurements the dependency on the excitation point was investigated with 45 excitation positions for diagonal transmission and 17 for horizontal transmission as shown in figures 3 and 4.

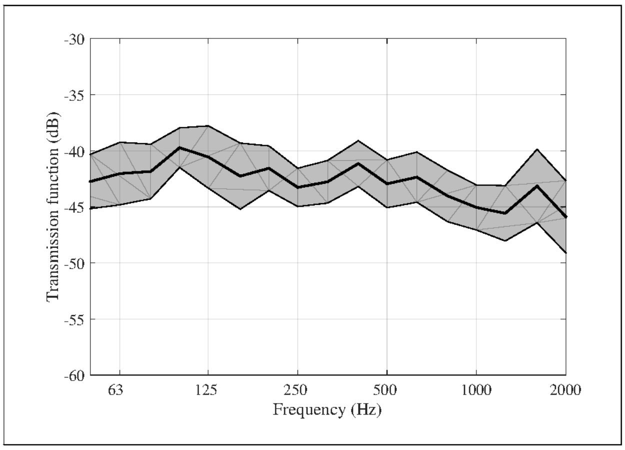

Figure 6. Mean transmission function ± one standard deviation for diagonal transmission in the laboratory setup.

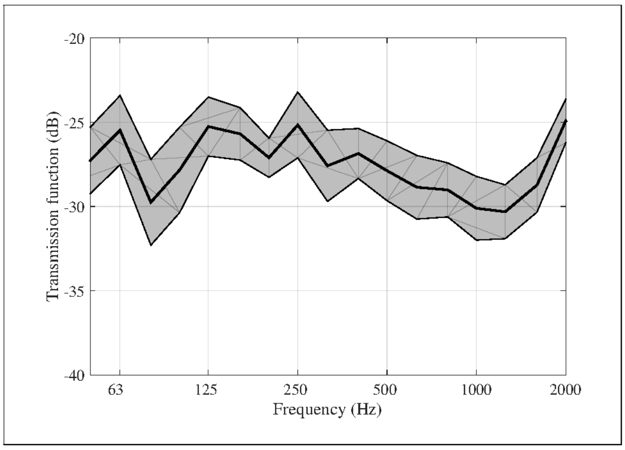

Figure 7. Mean transmission function ± one standard deviation for horizontal transmission in the laboratory setup.

3.1.1. Evaluation of diagonal and horizontal transmission

For diagonal transmission, the result is shown in figure 6. The transmission function has a relatively flat spectrum between 50 Hz and 500 Hz, above which there is a slight decrease with increasing frequency. There is a slight peak in the 1600 Hz band due to the critical frequency of the chipboard. For horizontal transmission, the mean transmission function is shown in figure 7. The transmission function has a similar spectral shape to diagonal transmission but offset by approximately 15-20 dB.

3.1.2. Effect of different excitation positions

Different excitation positions were chosen above the studs to investigate the variation in the transmission function for diagonal transmission. This allows evaluation of the variation in the transmission function due to different distances between the excitation point and the junction line between the walls and

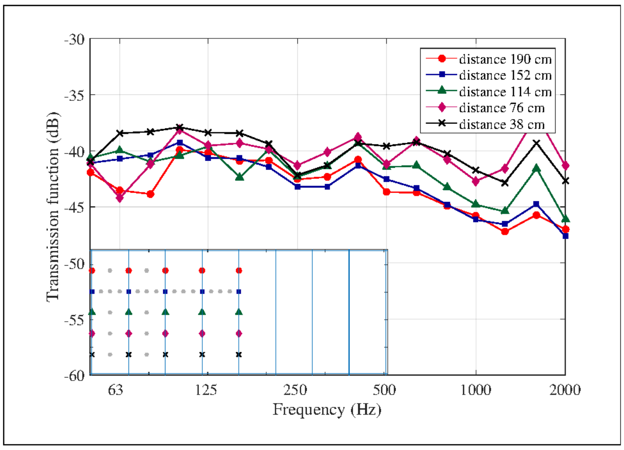

Figure 8. Dependency on the distance to the junction; stud positions

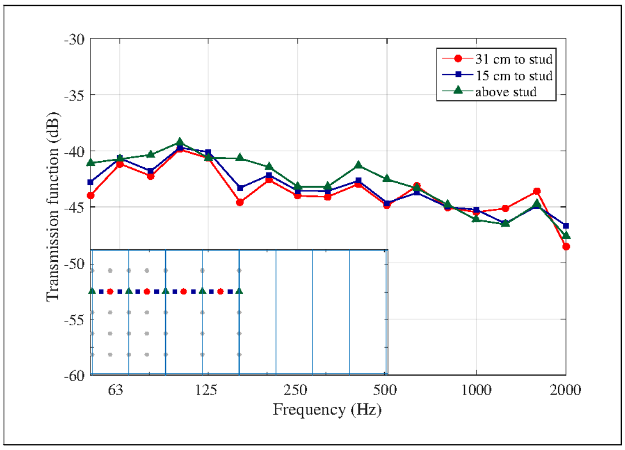

Figure 10. Dependency on distance to studs; diagonal transmission

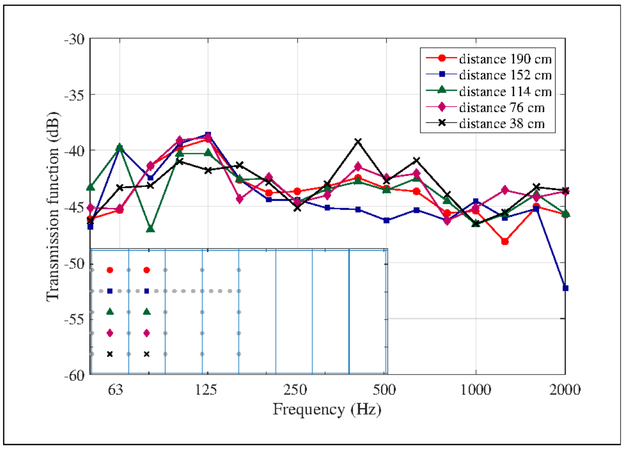

Figure 9. Dependency on the distance to the junction; bay positions

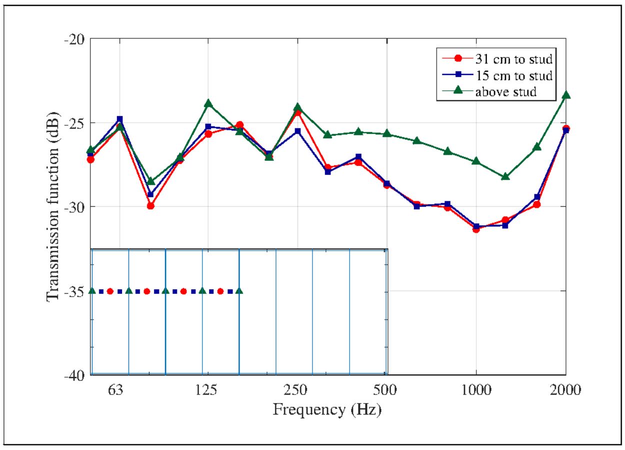

Figure 11. Dependency on distance to studs; horizontal transmission

floor. Five different distances have been investigated with five positions at each distance in order to calculate an average transmission function. The same evaluation was carried out for excitation positions in bays which were exactly in the middle between two studs. Two excitation points were used at each of the five distances. The averaged transmission functions are shown in figure 8 for the stud positions and in figure 9 for the bay positions. For both situations there are differences of only a few decibels between the five different distances. Although the differences that can be observed tend to fall into a logical rank order. The positions closer to the junction have higher values. This can be observed for both the stud and the bay positions. Since the cavities are not filled with insulation material, the difference between the bay positions tends to be negligible. If the airborne sound field in the cavities was damped, with fibre material, larger differences might occur. For clarity, the standard deviation is not included in the plots. However the spread in figures 6 and 7 indicates that the difference between the different excitation positions will be overlapped by one standard deviation.

For diagonal and horizontal transmission, a row of positions perpendicular to the studs was measured. On this line the positions can be combined in three groups. The first group contains positions above studs, the second group contains positions at a distance of 31 cm from the centre line of the studs and the third group contains positions in the middle of each bay. For horizontal transmission the line was chosen such that the stud positions were very close to the screws that fix the chipboard panels to the studs. The averaged curves for these three groups of positions are shown in figure 10 for diagonal transmission and in figure 11 for horizontal transmission. For diagonal transmission, the three curves are similar across the entire frequency range of interest. For horizontal transmission, the three curves are similar below 315 Hz but at higher frequencies the stud positions have the highest values. This is likely to be explained by a structure-borne transmission path across the studs that is more efficient than the path involving the sound field in the cavity, even though the chipboard becomes increasingly decoupled from the studs at higher

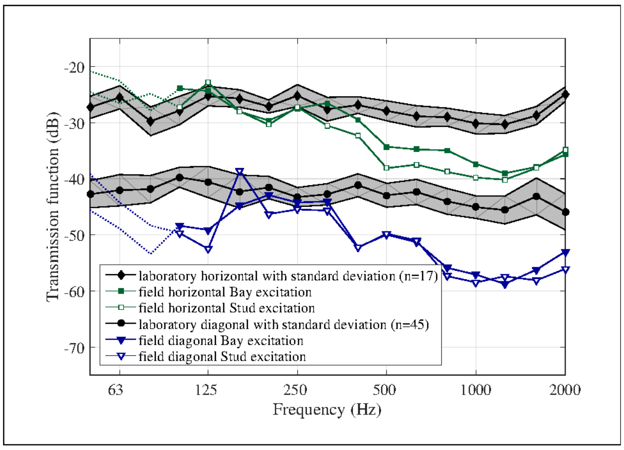

Figure 12. Comparison of different paths and constructions

frequencies ([5] and [6]). By comparing the results for diagonal and horizontal transmission it appears that with increasing complexity of the transmission paths, the influence of the excitation point diminishes.

3.2. Comparison of different paths and constructions

In the laboratory study the differences between various excitation points were investigated on one construction. To assess the field situation this data will now be compared to transmission functions determined in a real building. The measured transmission functions are shown in figure 12. For the field measurements the low frequency range is excluded since only two microphone positions were used which led to a greater uncertainty in this frequency range. For every transmission path in the field measurement the two excitation positions (one above a stud and one in a bay) are shown separately.
For both the horizontal and the diagonal transmission, the values are quite similar in the low and mid frequency range, whereas towards the high frequency range, the real building transmits less sound. Similar findings have been made in [7]. This might be explained by the lack of insulation material in the cavities of the walls in the laboratory setup. In the field measurement, horizontal transmission shows more dependency on the excitation point than diagonal transmission.
In this comparison it should be noted that in the field measurement, flanking paths are likely to have been included that were not present in the laboratory setup. However, in both the laboratory and field measurements there appears to be a fixed offset between horizontal and diagonal transmission.

4. Conclusions

For structure-borne excitation of timber-frame constructions, this paper investigated a transmission function defined as the ratio of the sound pressure level in the receiving room to the injected structure-borne sound power level. The experimental study has shown that the location of the excitation point does not have a significant effect on the resulting sound pressure in a receiving room. Comparison of different transmission paths in the building configurations considered indicates a constant shift in the transmission function between the horizontal and the diagonal transmission. To confirm these findings, more field data will be measured.

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