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Impact and vibration transmission measurements of Masonite Beams AB test house.

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1 Introduction

Low-frequency impact sound is an important performance of multi-story timber buildings. Light weight timber buildings may achieve high sound insulation performance, however, there is a need of knowledge in the industry of how to best obtain efficient impact sound insulation measures. Today the industry and the building acousticians are measurement oriented, with a focus on measuring impact sound according to the regulations. One problem is that standard measurements are not able to efficient identify sound transmission paths, such as if direct transmission or flanking transmission is the weakest part of the design. In this study it is tested if an extended use of vibration measurements may better analyze the efficiency of the different test setups. Sound insulation and sound vibration transmission measurements were made on a state-of-the-art test house at Masonite Beams AB at Rundvik in Sweden, for one week (w. 27) in 2022. The test house is a lightweight design based on Masonite Beams building system with their I-beams. Prior to these test they have shown high impact sound insulation performance (Impact sound insulation sound class A in Sweden according to Swedish regulations, SS 25267). The test house is suitable to study different major design principles, such as resilient joint, suspended ceilings, increased mass on top of floor etc.

The aim is to extract knowledge about impact sound improvement measures and its sound transmission distribution, but also to evaluate the measurement and analyze method itself. There is a focus here in the low frequency range, since this is an especially important range for multi-story timber buildings.

2 Measurement setup

2.1 Impact sound measurements

Impact sound measurements are made according to SS 25267 and ISO 16283-2, as of the summer 2022. For the standard impact sound measurements, a Norsonic Nor140 handheld sound analyzer was used. For the excitation a standard ISO tapping machine is used (Norsonic Nor277). An omnidirectional speaker with a LAB.GRUPPEN E-series 8:2 amplifier was used for the reverberation time measurements.

2.2 Vibration measurements

To be able to measure and assess the transmission paths of impact sound, accelerometers are placed on floors, walls, and ceilings. The location of accelerometers is inspired by the AkuLite protocol, but also with additional accelerometers. For instance, points direct under the impact points at ceilings are added. Their purpose is to track the vibration magnitudes straight through the structure (direct transmission). The aim with the measurement points at walls and ceilings close to the ceiling joints is to compare the potential flanking transmission in relation direct transmission. The location of the sensors is shown in Figure 1 and Figure 2. The measurements are made with the assumption that the sound radiation of the walls and ceilings are proportional to the vibration levels of these surfaces. Excitations are made with the ISO tapping machine but also with a modal force hammer, to measure Frequency Response Functions (FRFs), see Figure 3.

The acceleration results spectrums from the accelerometer measurements are recalculated to velocity spectrums in decibels. The reference level for decibels is set to 50 nm/s. Presenting the results in velocity have some benefits. First, the velocity is better related to energy content in the vibrations, which is difficult to judge from accelerations spectra. Second, volume velocity of a vibrating surface is related to the radiated sound. We do not know the radiation efficiency of the measured surfaces, but knowing the velocities give us a strong connection to sound radiation. Also, for an infinite surface vibrating in perfect phase, the reference level 50 nm/s would give directly the radiated and measurable sound pressure level in the standard unit 20 µPa. The purpose is to better understand and relate the vibration levels to the sound pressure levels that the vibrations cause.

The measurements are made with two Siemens LMS Scadas measurement system (20 channels + 12 channels) synchronous connected. For the excitation a standard ISO tapping machine is used (Norsonic Nor277) for vibration transmission measurements and a modal hammer (Dytran DY 5803A) is used for the Frequency Response Function (FRFs) measurements. The FRF-measurements results are not included in this public report.

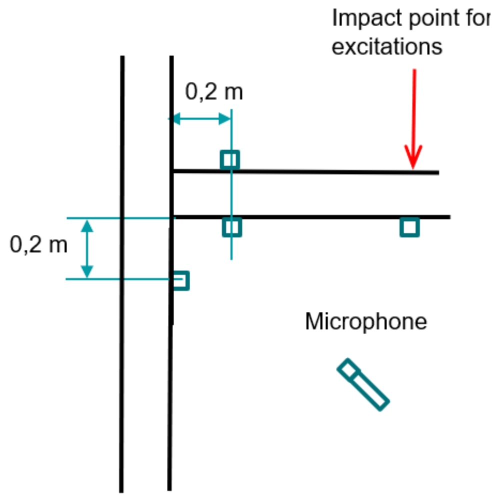


Figure 1. Location principle of accelerometers on the floor, ceiling below excitation points, the ceiling close to the wall at the flanking corner and corresponding at the ceiling close to the wall.

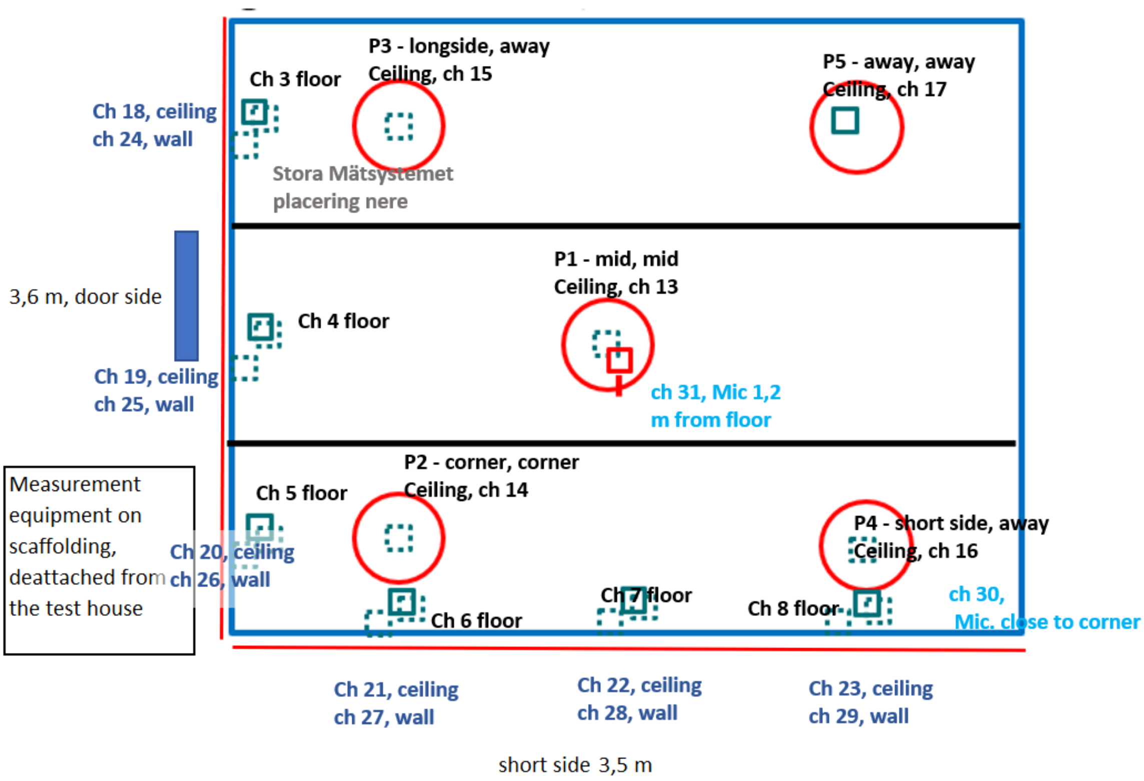


Figure 2. Schematic locations of the different accelerometers in relation to floor directions and building directions. The view is seen from above.

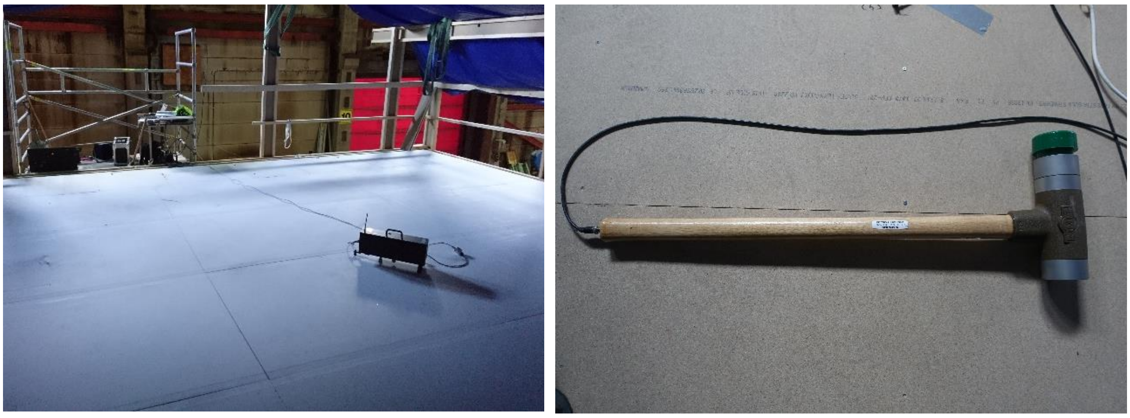


Figure 3. Left photo shows the tapping machine measurements (excitation point 1), and the force hammer is shown in the photo to the right.

3 The setup of the test house.

The measurements on the structural test house were made at Masonite Beams AB in Rundvik, Sweden. The test house, the preparations and the ideas of the setups tested is made by Tommy Persson and Alfred Wikner at Masonite Beams AB. The test house consists of the main parts, important for impact sound transmission. Full scale walls and floor structures for having realistic transmission of direct sound transmission and flanking transmission via connections and then to radiating connected surfaces. The conceptual design and dimensions are shown in Figure 2 and Figure 4. The exterior of the test house during the trials are seen Figure 5. The interior at the measurements with all the sensors mounted is seen in Figure 6.

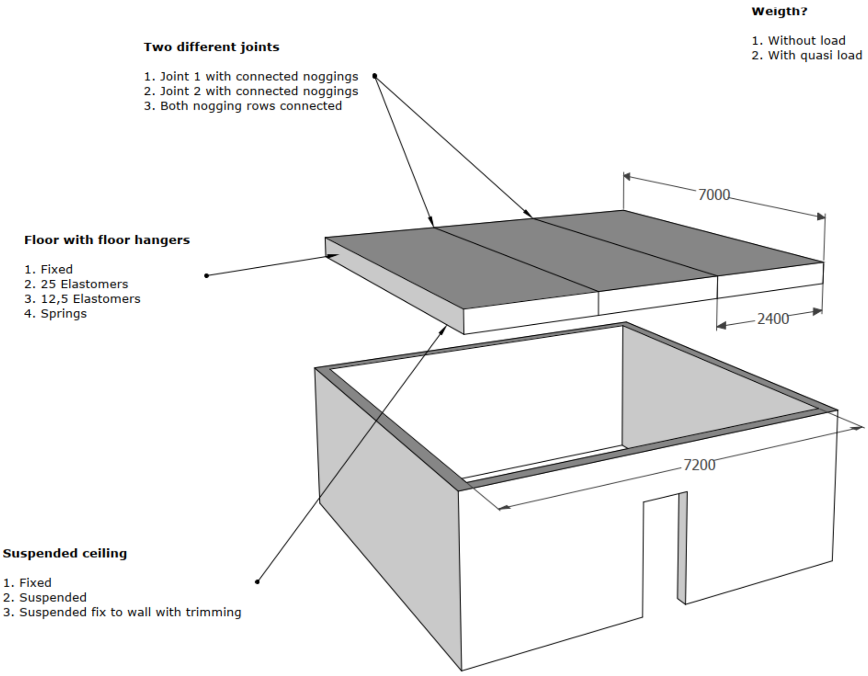


Figure 4. Concept drawing of the test house.

Figure 5. The test houses at the measurements with the scaffolding as a platform for the measurement system. The test house walls are standing on gravel. The test house is located within a large industrial building at Masonite Beams in Rundvik. The scaffolding is not connected with the test house structure.

Figure 6. The measured, receiving room below (here at the gable wall direction, at the last measurement setup number 8).

The eight different setups in the measurements consist of the following main versions:

1. Start version, only suspended ceiling in action.
2. Suspended ceiling hangers relate to screws and washers (from ceiling beneath) to floor joists ("short circuit" of dampening function).
3. Connecting the floor elements to each other, by gluing and screwing the particleboards to the floor joists.
4. Release the ceiling screws, making the ceiling suspended again.
5. Nogging rows glued and screwed with lath across the floor elements to create a composite action perpendicular to the load bearing direction (see picture).
6. The entire floor structure is mounted elastic by using elastomers under the supports (floor hangers) to the walls.
7. Adding a "floating" layer of 15 mm floor gypsum on the floor particleboards.
8. Fastening of OSB strips in the corners, on the walls adjacent to the ceiling, to represent cornices.

The major changes in the test setup are shown in the Figure 7 to Figure 13 below.

Table 1. The different measurement configurations, 1 indicates measure that is active and corresponding 0 for disabled measures.

Measurement Setup	Floor gypsum	Connected nogging rows	Joints between floor elements	Suspended ceiling	Elastomers in floor-wall connection	Cornices
1	0	0	0	1	0	0
2	0	0	0	0	0	0
3	0	0	1	0	0	0
4	0	0	1	1	0	0
5	0	1	1	1	0	0
6	0	1	1	1	1	0
7	1	1	1	1	1	0
8	1	1	1	1	1	1

Figure 7. Mounting of the first layers of gypsum boards, test setup version 1. The laths which the gypsum boards are fastened to are suspended (you may note a small distance between the laths and the structural beams above).

Figure 8. Test setup version 2, fastening the gypsum boards against the ceiling joists with screws and washer to take away the suspended ceiling effect.

Figure 9. Test setup version 3, gluing and screwing of the particleboards to the joist in the floor.

Figure 10. Test setup version 5, Screwed and glued lath to create composite action of nogging rows. Second gypsum layers added before measurements.

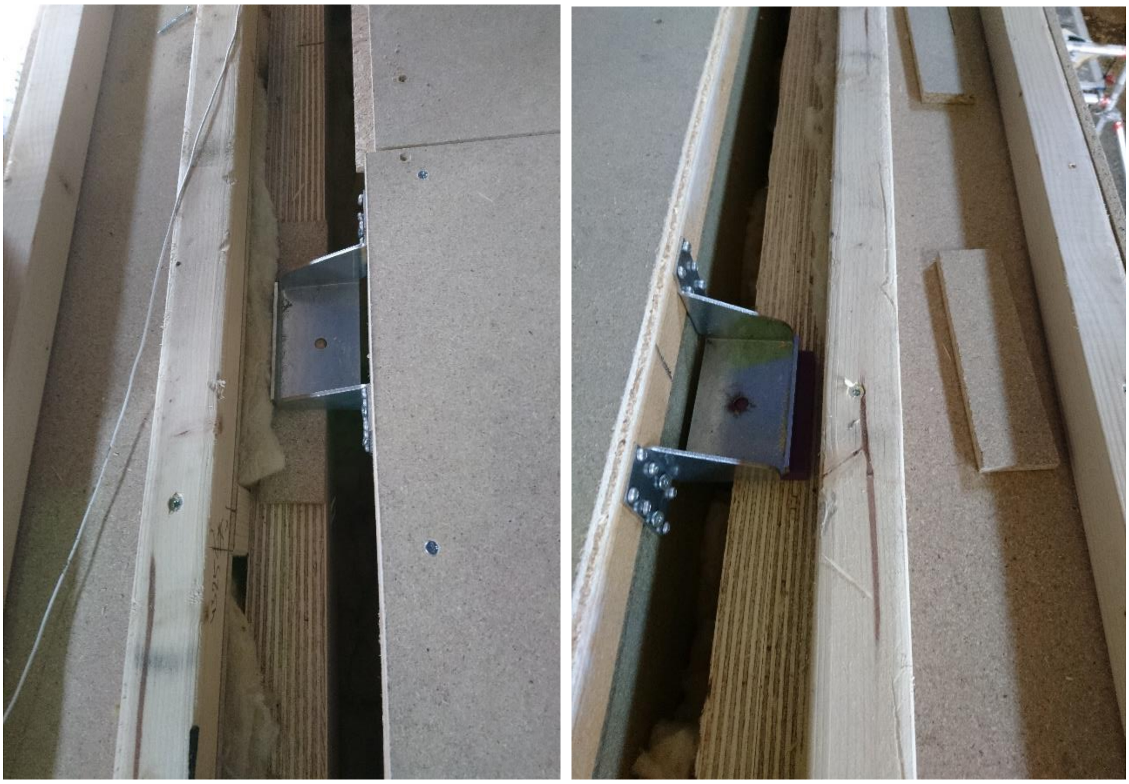


Figure 11. Test setup version 6, adding elastomers at the floor hangers, to study the effect on flanking transmission. Left photo is of the test setup 1-6 and the right show after the elastomer is mounted.

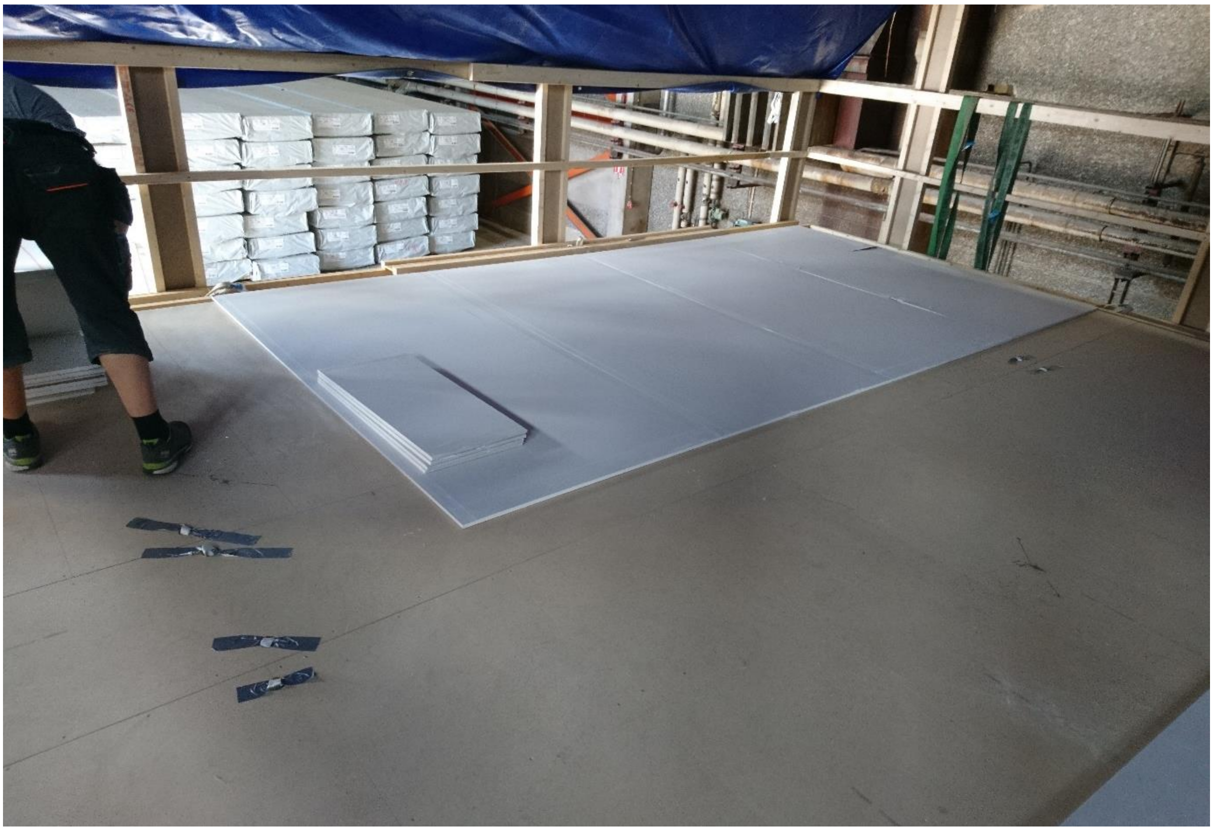


Figure 12. Test setup version 7, adding a layer of “floating” 15 mm gypsum on the particleboards.

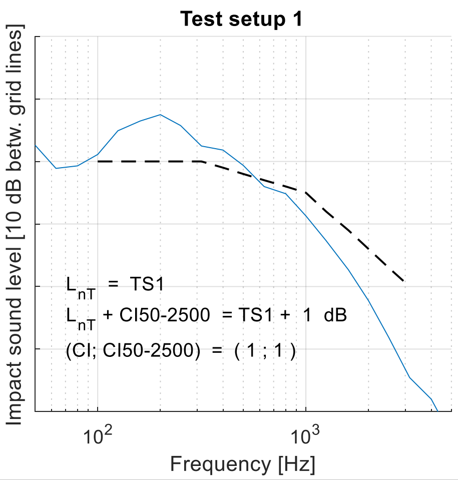
Figure 13. Test setup version 8, OSB strips fastened in the corners to represent the use of cornices.

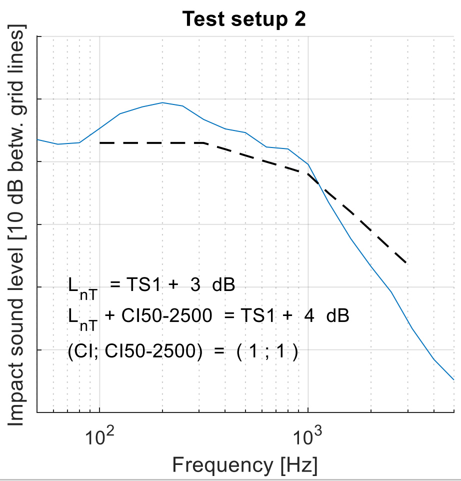
4 Results

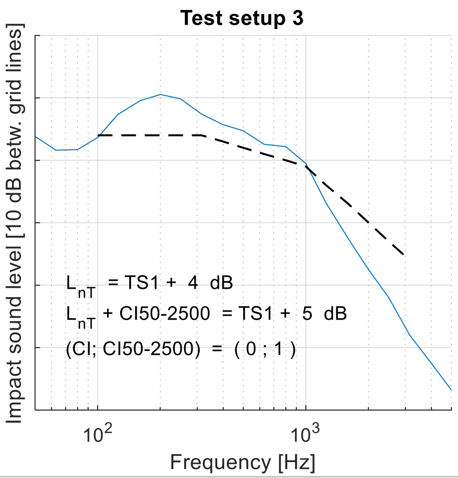
4.1 Impact sound measurements

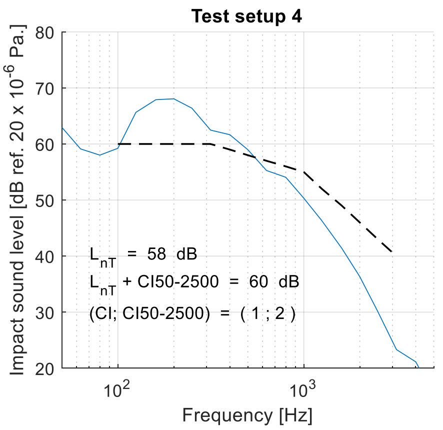
Standard impact sound measurements were made according to ISO 16283-2 with the ISO tapping machine and handheld sound analyzer. The speaker system used for the reverberation was research equipment with sound level on the lower side. This made the measured dynamic range on the lower side and the standard deviation of the reverberation measurements was large. However, all measurements are made with the same equipment in the receiving room below. This makes the relative dB results accurate between the different measurement cases. Results are presented with correction for reverberation time (standardized). It should also be noted that reverberation time corrections are under revision for the Swedish standard SS 25267 describing the sound requirements for dwellings in Sweden. Since absolute performance values is more sensitive from a competition point of view, how the design relates to relates to requirements levels, the absolute values are not presented. The relative decibel values are presented, which makes the relative performance between the different setups comparable. Test setup 1 becomes the reference level, to which every other setup is compared. The diagrams within the same type of results (neighboring diagrams with the same layout) have the same axis limits, although the absolute levels are not presented.

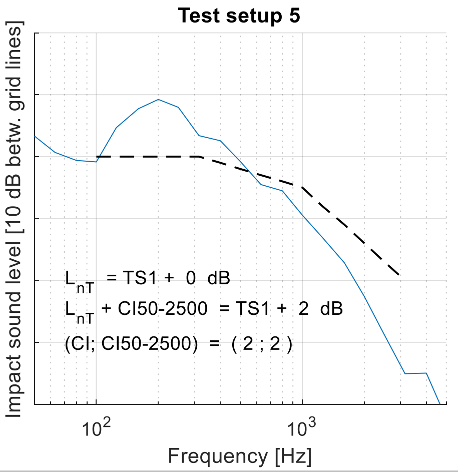
Table 2. Standardized impact sound level measurement, relative results.

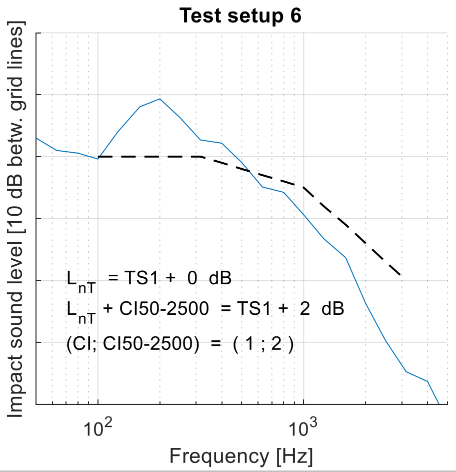


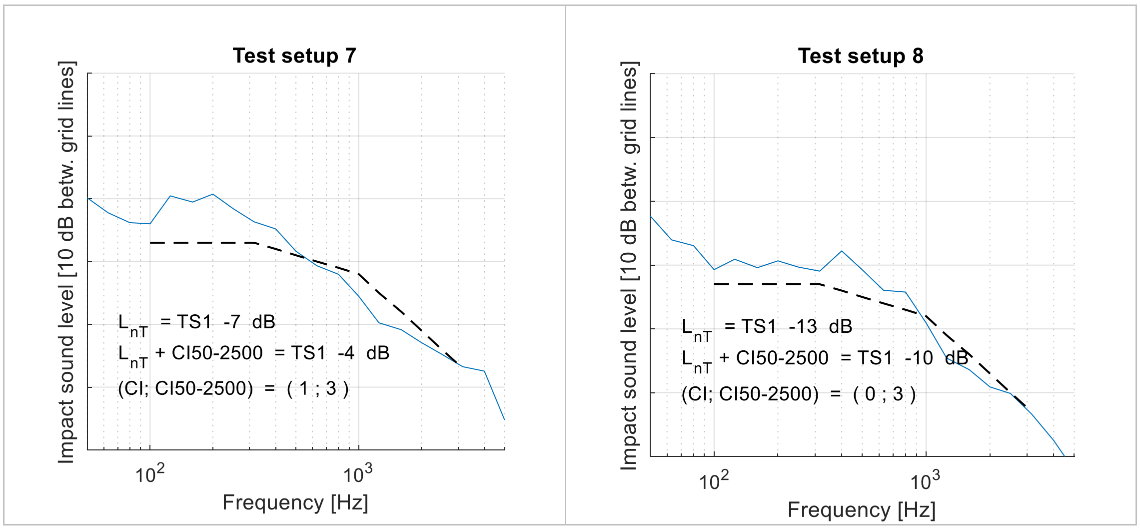












In Figure 14 is the single values for impact sound insulation according to Swedish regulation SS 25267, presented. The measures that affect the weighted single values are first the suspended ceiling with about 3-4 dB. The suspended ceiling is activated in setup 2 and disabled in setup 4, which clearly affects the results. It is seen that the added layer of gypsum (setup 7) and the cornices (setup 8) is what really improve theses weighted single values.

Table 3. Measured reverberation times used in the corrections.

1/3 Oct. frequency band [Hz]	T – Reverberation time [s]
50	1,55
63	1,11
80	2,42
100	2,70
125	1,74
160	1,14
200	0,72
250	0,60
315	0,76
400	0,90
500	0,92
630	0,97
800	1,00
1000	1,03
1250	1,08
1600	0,96
2000	0,93
2500	0,93
3150	0,86
4000	0,83
5000	0,78

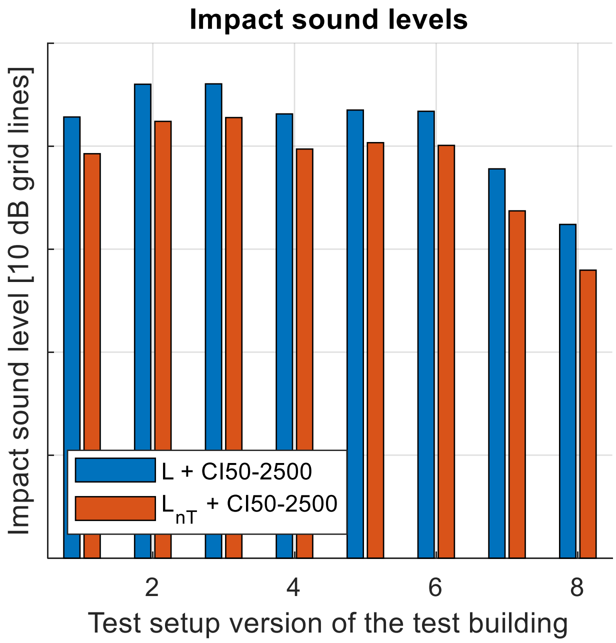


Figure 14. Measured, relative, averaged impact sound level before reverberation correction and standardized impact sound level (reverberation time corrected).

4.2 Vibration measurements

The measurement results are referenced to the accelerometer location in Figure 1 and in Figure 2.

4.2.1 Tapping machine measurements

The measurements contain large amount of data. The data is visualized in different categories of spectrums to help understand the results. First, all accelerometers for one measurement are plotted. This is done in Figure 15 and Figure 16 for the first excitation with the tapping machine in the middle of the floor, for test setup 1. It is seen that (see Figure 2 for reference to channels and excitation points) the highest levels occur at the channel 4 sensor in the middle along the door side, at the area where the joist floor is supported. For the accelerometers on the ceiling, it is seen that the accelerometer in the middle, directly under the where the tapping machine is in this measurement, by a small margin have the highest levels of these accelerometers. For the ceiling 0.2 m from the walls (Figure 16) it is seen that middle on the door side have the highest vibration levels in general, at least above 100 Hz. For the walls 0.2 m from the ceiling (Figure 16) it is seen that middle on the door side as well have the highest vibration levels in general, at least above 100 Hz. The levels indicate that for the first setup the flanking transmission to the door side should be a significant transmission path. The results are logical in general, the highest levels are located closest to the excitation, directly under at the ceiling and at the door side in the middle where the floor is supported. It is clearly seen that there is less vibration transmission perpendicular to the carrying direction of the floor.

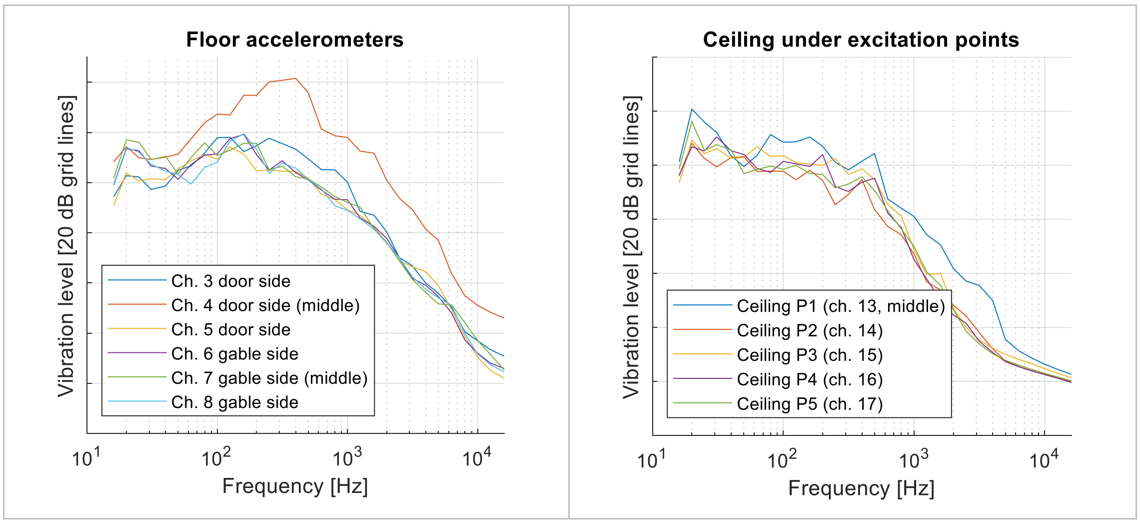


Figure 15. The results of all the accelerometers for one impact point, here in the middle of the floor (P1, in Figure 2), test setup 1. Left diagram shows the accelerometers on the floor. The right diagram shows the accelerometers at the different points at the ceiling in the room below.

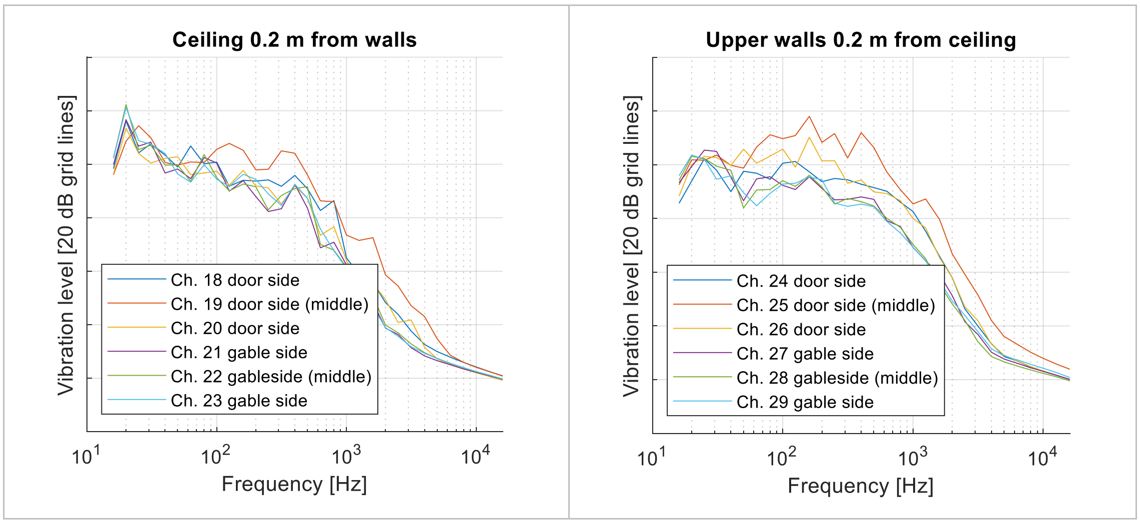


Figure 16. The results of all the accelerometers for one impact point, here for the floor (P1, in Figure 2), test setup 1. Left diagram shows the accelerometers on ceiling 0.2 from the wall, in the room below, and the right diagram shows correspondingly the accelerometers on ceiling 0.2 from the wall.

In Figure 17 it is seen the difference when the tapping machine is located on the two out of five points nearest the wall where the accelerometers are located, compared to when the two points located most far away from the measured sides. It is seen that there is a larger difference on the door side. That is on the sides where the floor is most structurally supported.

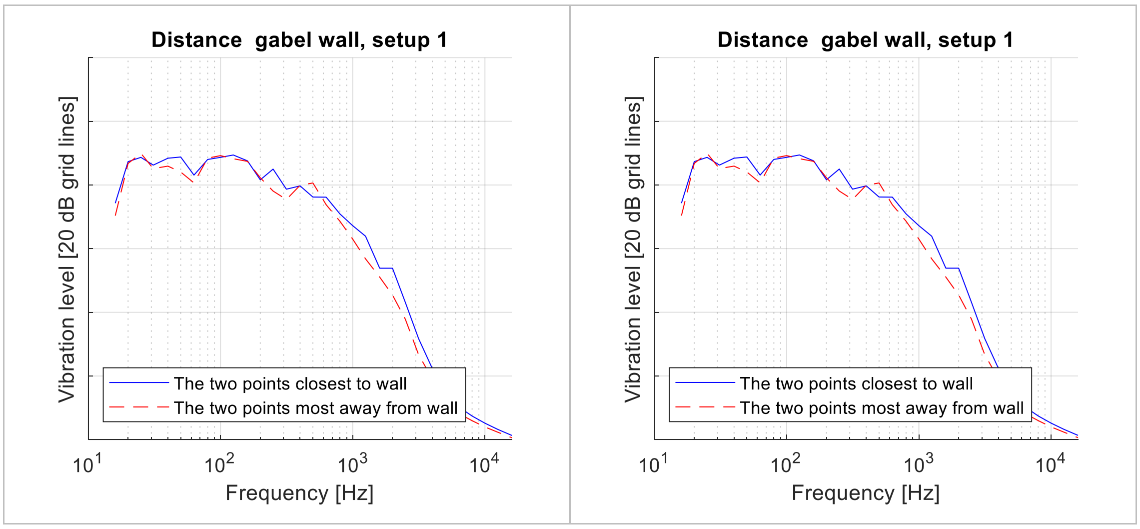
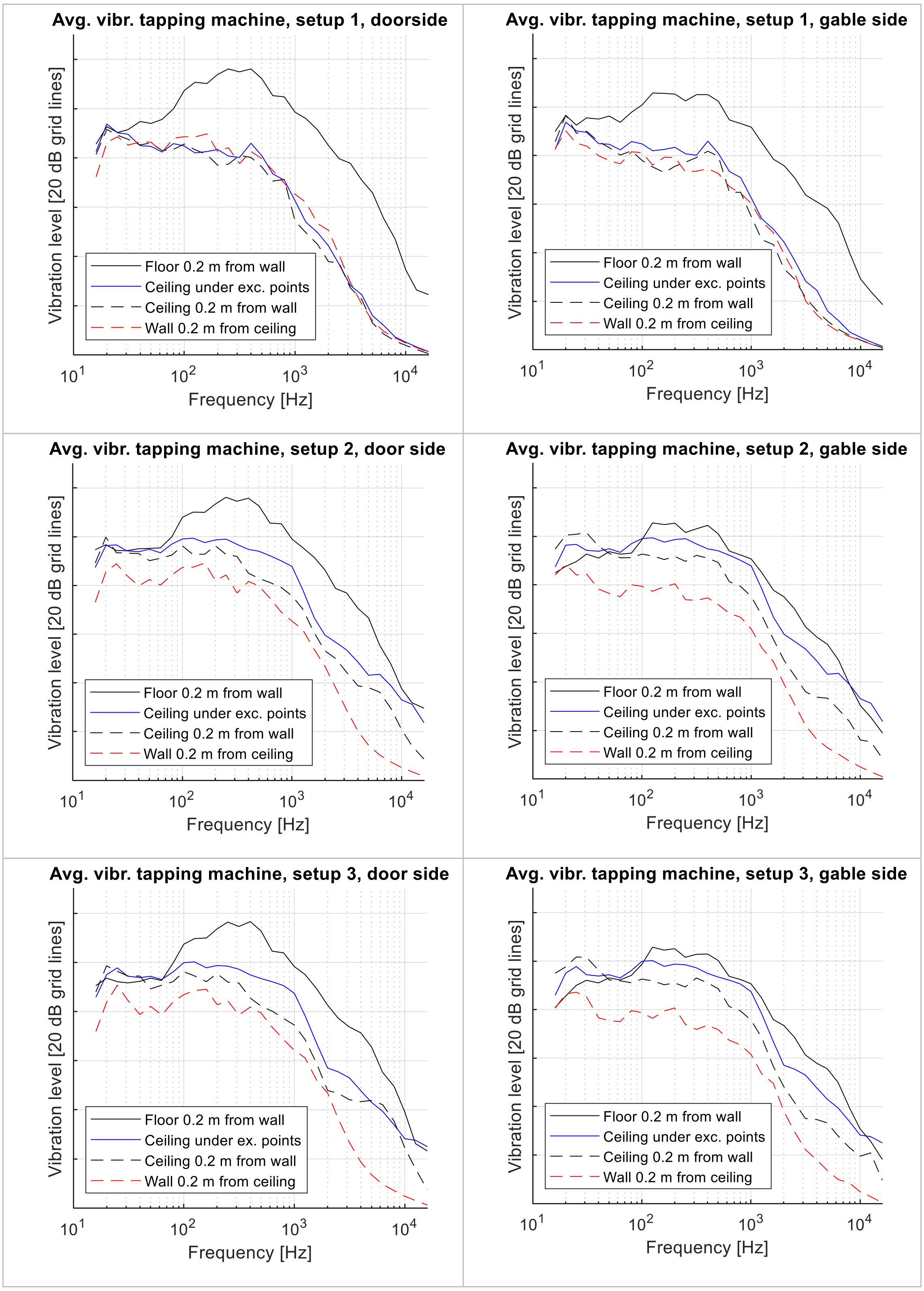
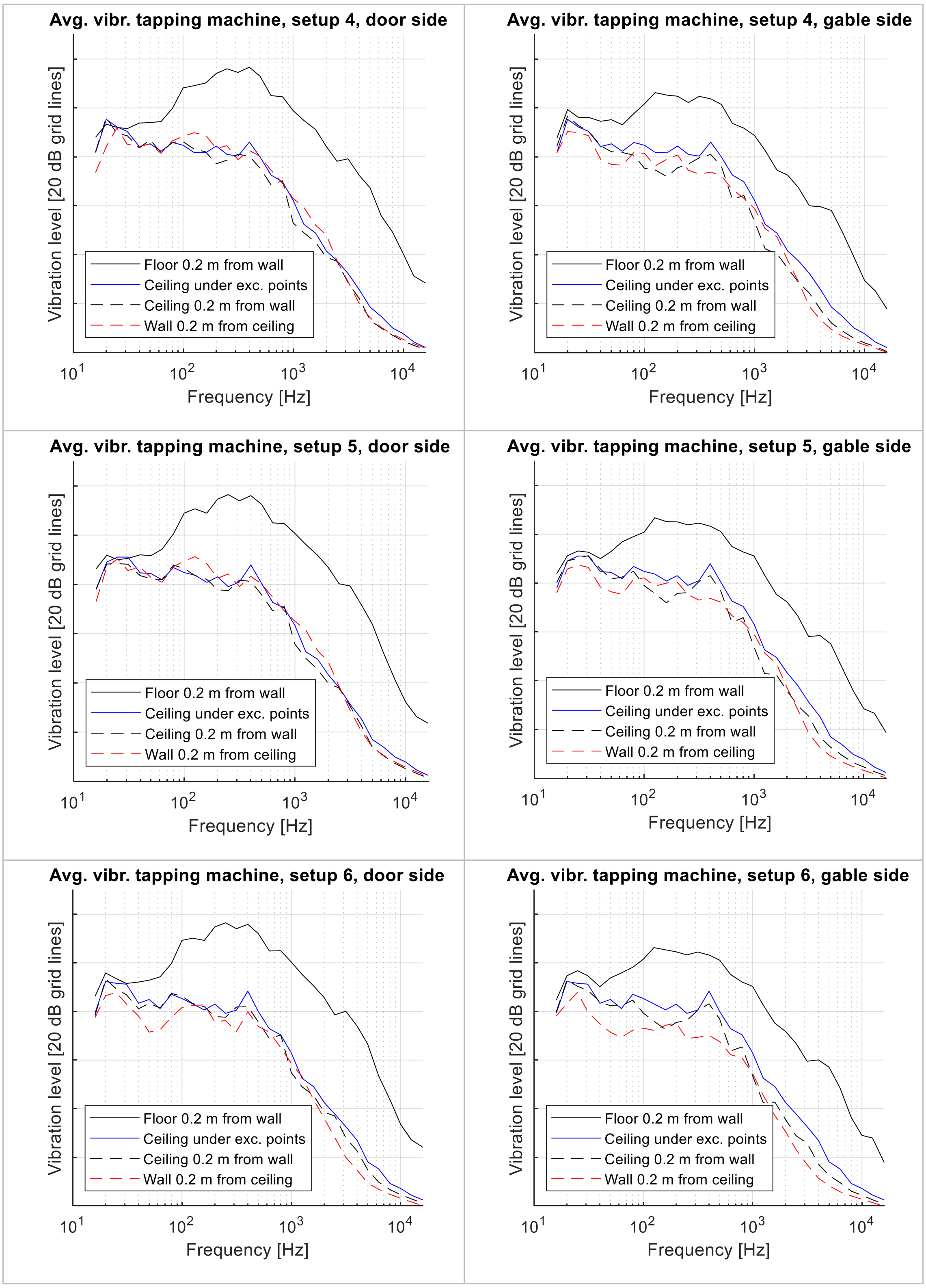


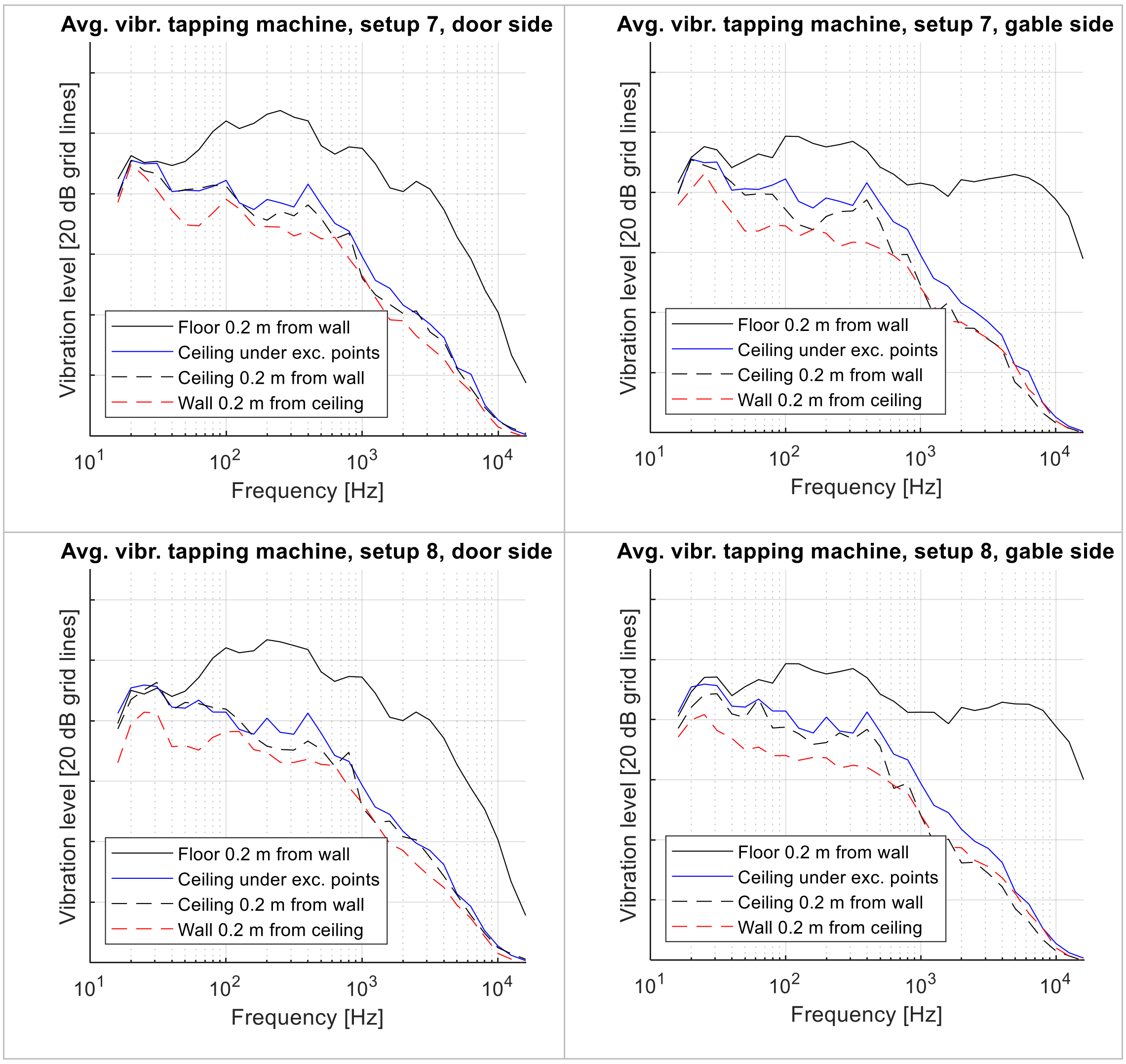
Figure 17. Results for Setup 1. In the left diagram, all the accelerometers located on the long side (door side) wall, 0.2 m from ceiling, averaged for all tapping machine impact points. The right diagram is showing the short side wall, 0.2 m from ceiling (right side when standing at the door looking in).

All the tapping machine positions and the different categories of locations are energy averaged for each measurement setup to be able to relate the different transmission paths to each other. The averaged results for the different location categories of accelerometers are presented in Table 4. In the results it is for instance seen that when the elastomers are activated (setup 6, compare dashed red line with setup 5 when there is no elastomers), the wall vibrations are decreasing. However, the ceiling vibrations are unaffected and in similar level. This may be the reason for not having improved single value impact sound insulation result for the elastomers. The sound insulation is not better than its weakest link, i.e., the ceiling may still set the level for that setup.

Table 4. The averaged results for all the tapping machine locations and each sensor location category averaged, for each test setup.




Avg. vibr. tapping machine, setup 4, door side
Vibration level [20 dB grid lines]
Floor 0.2 m from wall
Ceiling under exc. points
Ceiling 0.2 m from wall
Wall 0.2 m from ceiling
10^1 10^2 10^3 10^4
Frequency [Hz]
Avg. vibr. tapping machine, setup 4, gable side
Vibration level [20 dB grid lines]
Floor 0.2 m from wall
Ceiling under exc. points
Ceiling 0.2 m from wall
Wall 0.2 m from ceiling
10^1 10^2 10^3 10^4
Frequency [Hz]
Avg. vibr. tapping machine, setup 5, door side
Vibration level [20 dB grid lines]
Floor 0.2 m from wall
Ceiling under exc. points
Ceiling 0.2 m from wall
Wall 0.2 m from ceiling
10^1 10^2 10^3 10^4
Frequency [Hz]
Avg. vibr. tapping machine, setup 5, gable side
Vibration level [20 dB grid lines]
Floor 0.2 m from wall
Ceiling under exc. points
Ceiling 0.2 m from wall
Wall 0.2 m from ceiling
10^1 10^2 10^3 10^4
Frequency [Hz]
Avg. vibr. tapping machine, setup 6, door side
Vibration level [20 dB grid lines]
Floor 0.2 m from wall
Ceiling under exc. points
Ceiling 0.2 m from wall
Wall 0.2 m from ceiling
10^1 10^2 10^3 10^4
Frequency [Hz]
Avg. vibr. tapping machine, setup 6, gable side
Vibration level [20 dB grid lines]
Floor 0.2 m from wall
Ceiling under exc. points
Ceiling 0.2 m from wall
Wall 0.2 m from ceiling
10^1 10^2 10^3 10^4
Frequency [Hz]



The energy averaged vibration data and the impact sound levels of tapping machine measurements are presented together in the same diagrams from Figure 18 to Figure 25, for the door side (and the ceiling which is the same for both presented cases) and correspondingly from Figure 26 to Figure 33. The measured sound level and the vibration levels are in most cases around the same levels. One exception is when the suspended ceiling is disabled (setup 2 and setup 3). Then the ceiling vibrations is a bit higher, although the measured sound insulation also is increased. What can be seen is that the characteristics of the measured sound levels are in high degree similar in its spectral characteristics (Figure 19 and Figure 20 black solid line vs blue solid line). This makes it likely that the ceiling vibrations dominates the sound radiation. For the later setups there is lower levels, especially above 100 Hz. For the lowest frequencies presented down to 20 Hz, it is seen that there is less attenuation. However, this lowest range is not included sound classification regulations.

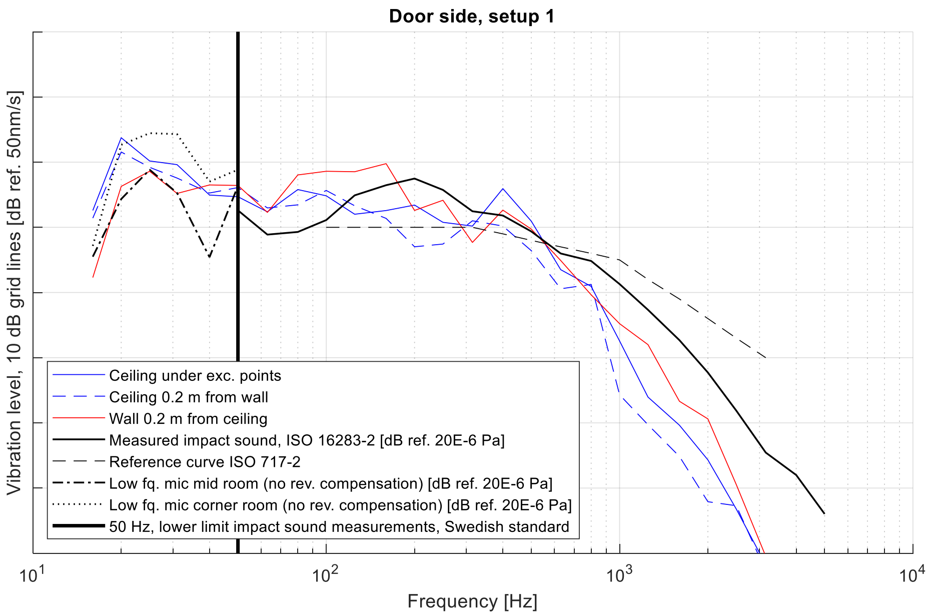


Figure 18. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the door side of the test building and for test setup 1.

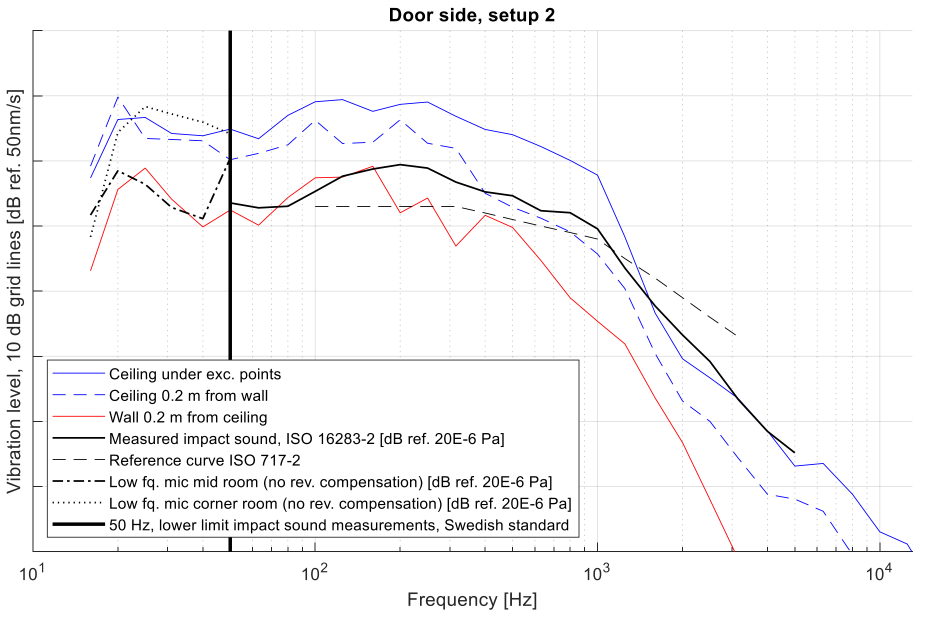


Figure 19. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the door side of the test building and for test setup 2.

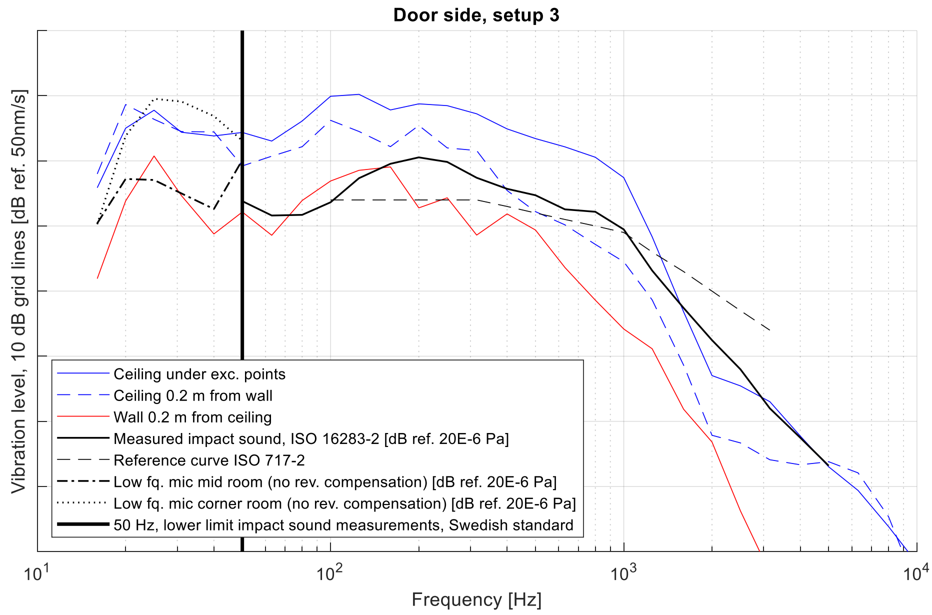


Figure 20. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the door side of the test building and for test setup 3.

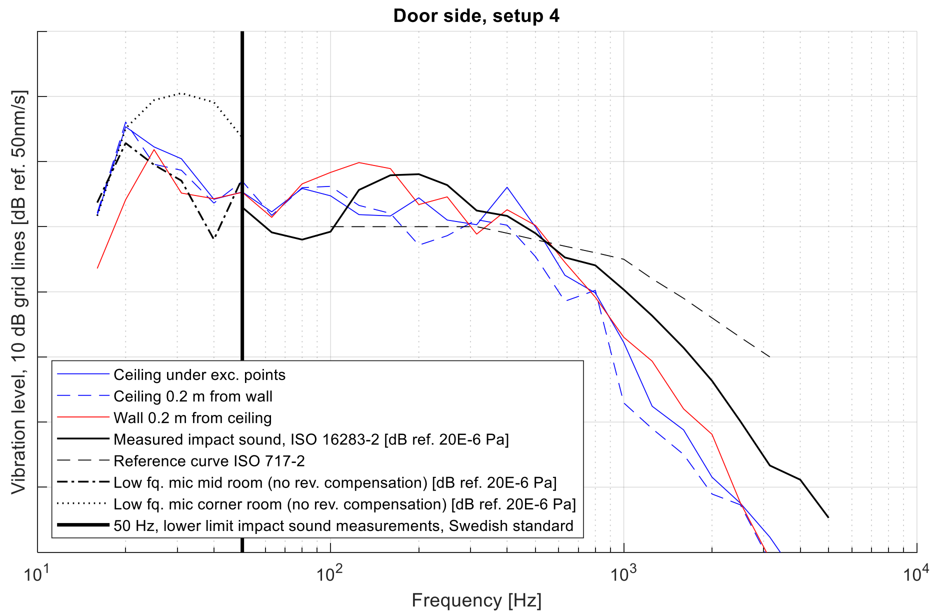


Figure 21. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the door side of the test building and for test setup 4.

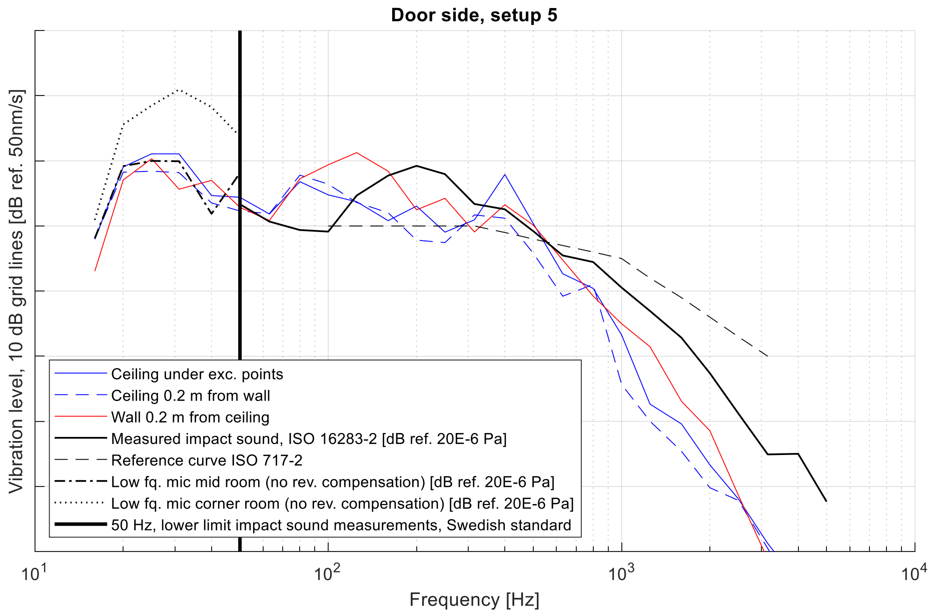


Figure 22. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the door side of the test building and for test setup 5.

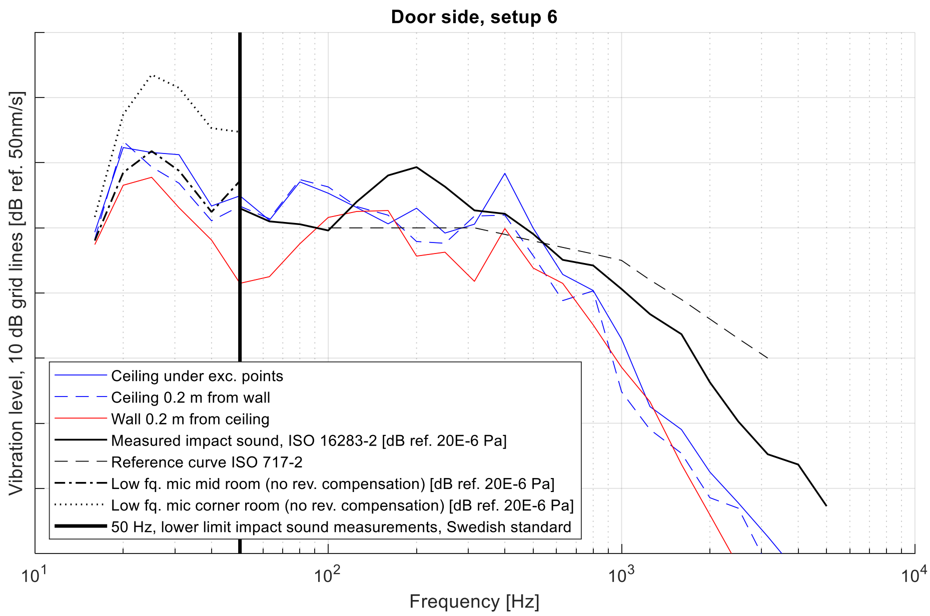


Figure 23. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the door side of the test building and for test setup 6.

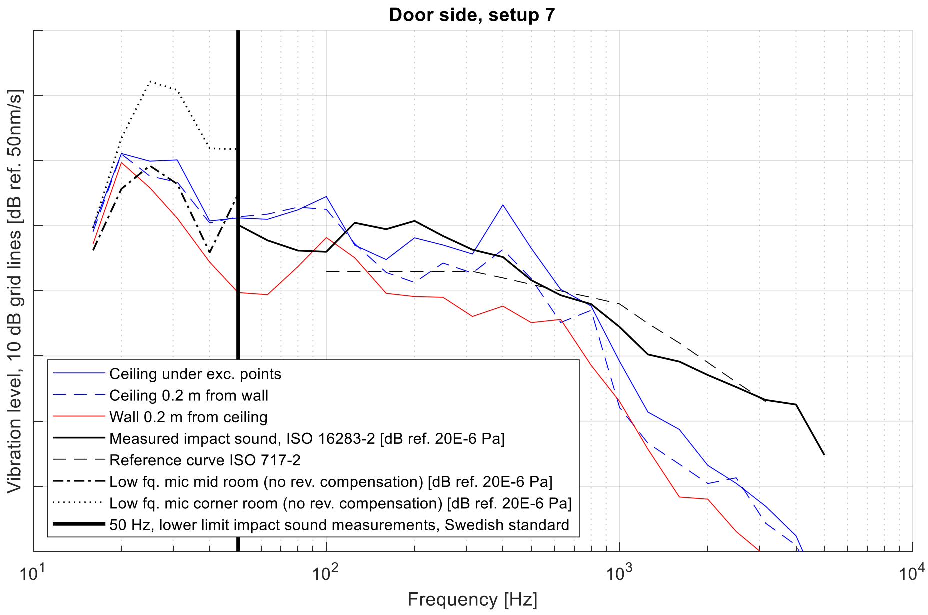


Figure 24. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the door side of the test building and for test setup 7.

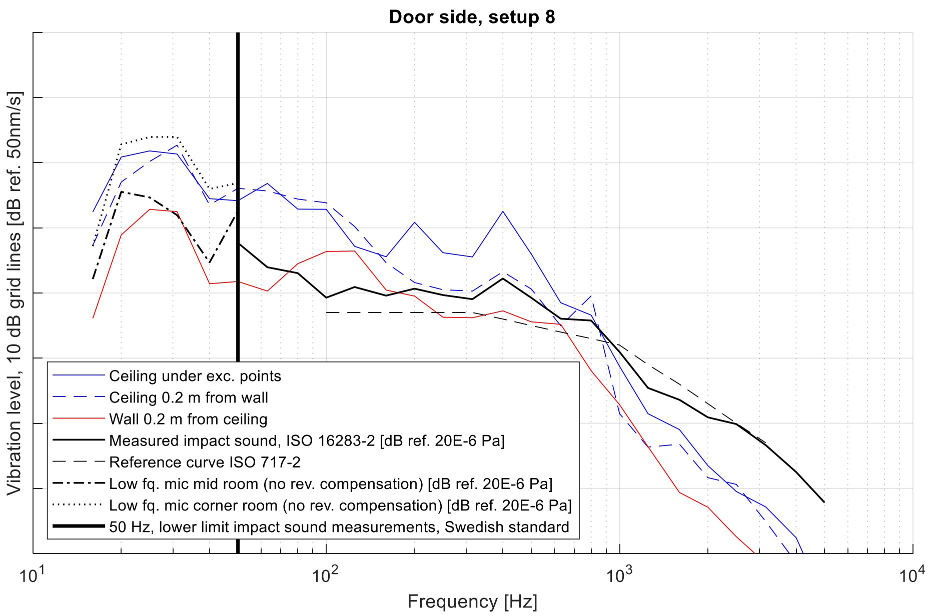


Figure 25. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the door side of the test building and for test setup 8.

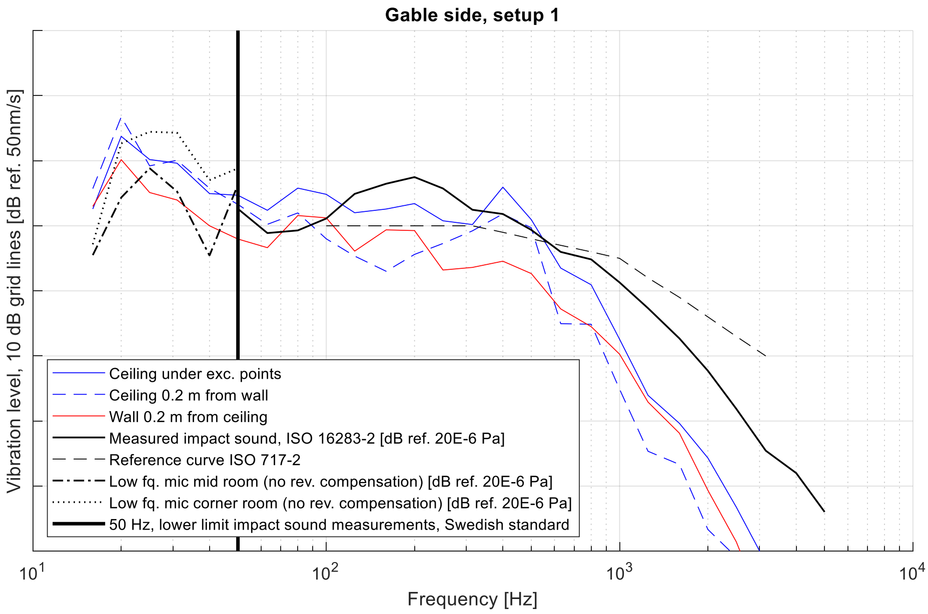


Figure 26. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the gable side of the test building and for test setup 1.

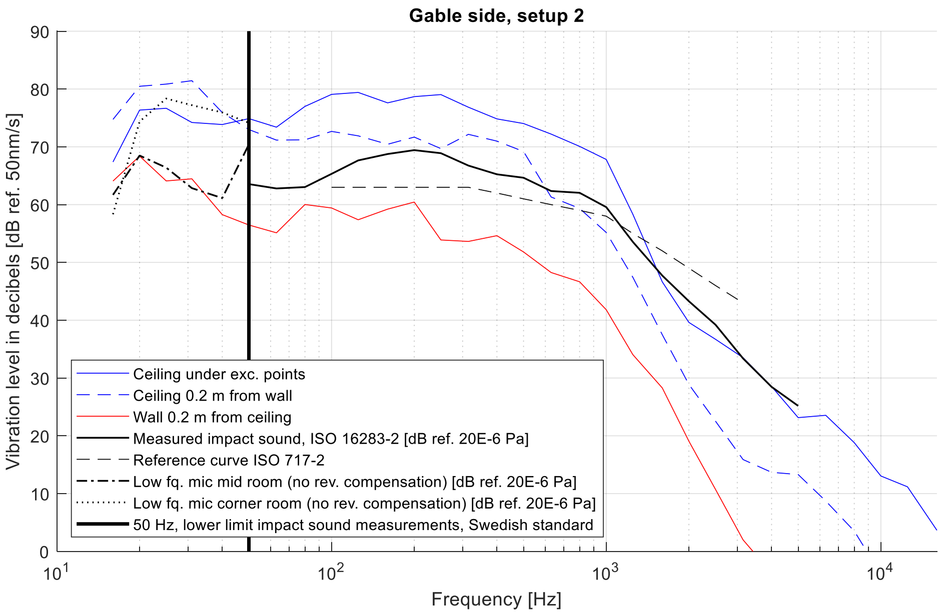


Figure 27. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the gable side of the test building and for test setup 2.

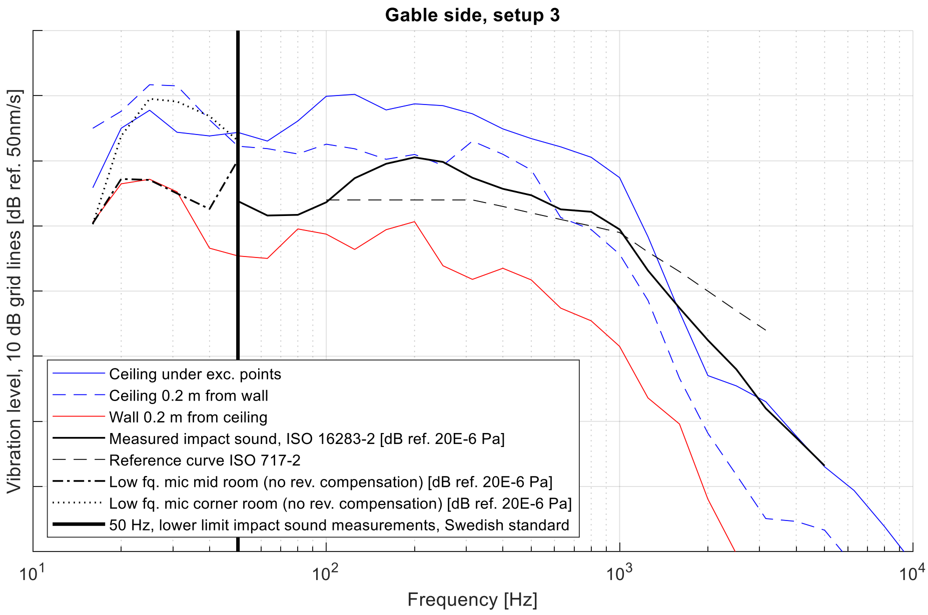


Figure 28. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the gable side of the test building and for test setup 3.

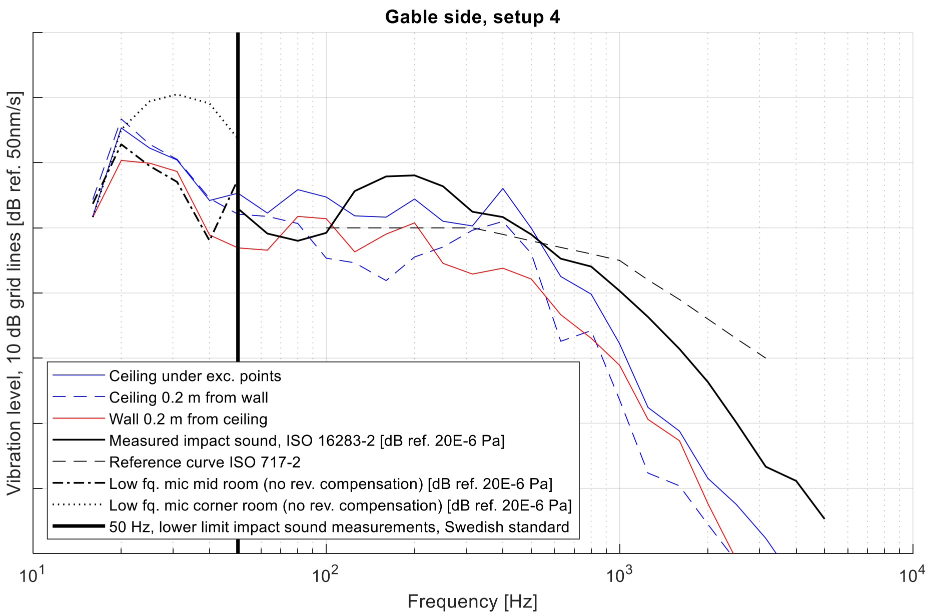


Figure 29. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the gable side of the test building and for test setup 4.

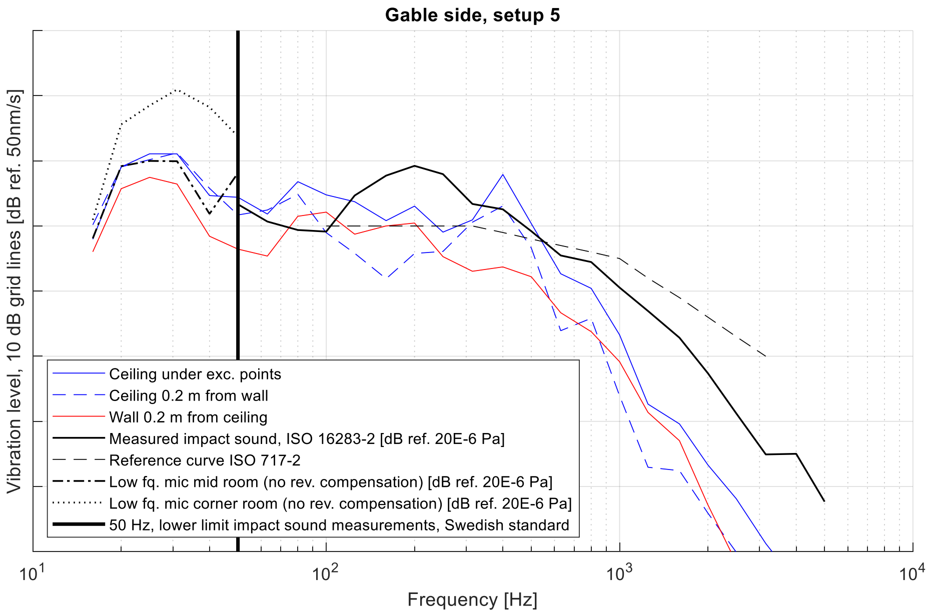


Figure 30. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the gable side of the test building and for test setup 5.

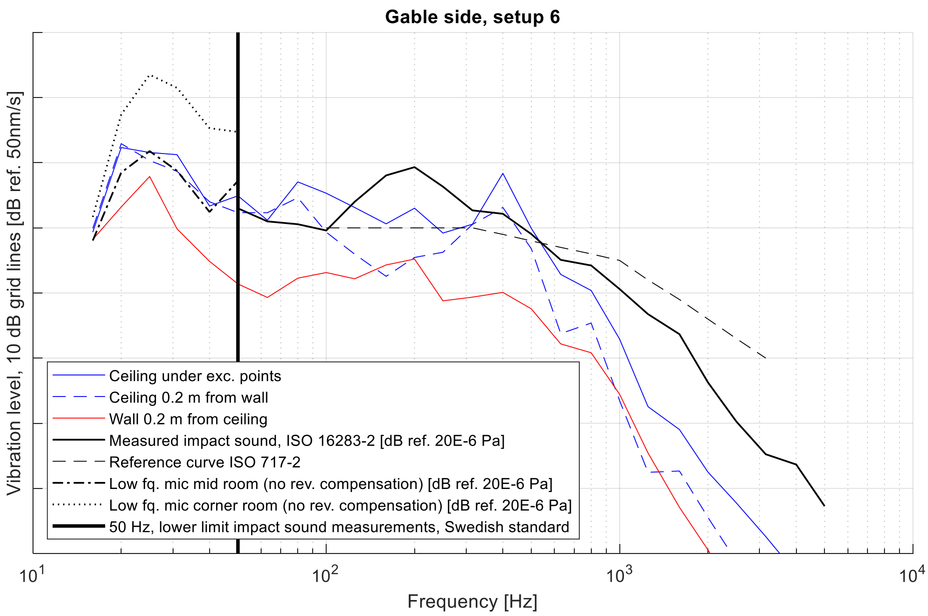


Figure 31. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the gable side of the test building and for test setup 6.

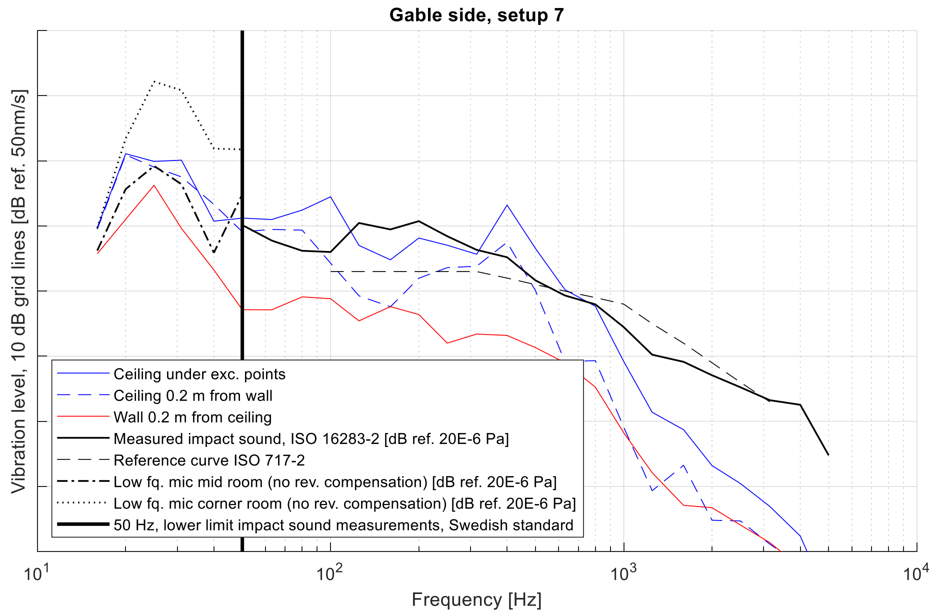


Figure 32. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the gable side of the test building and for test setup 7.

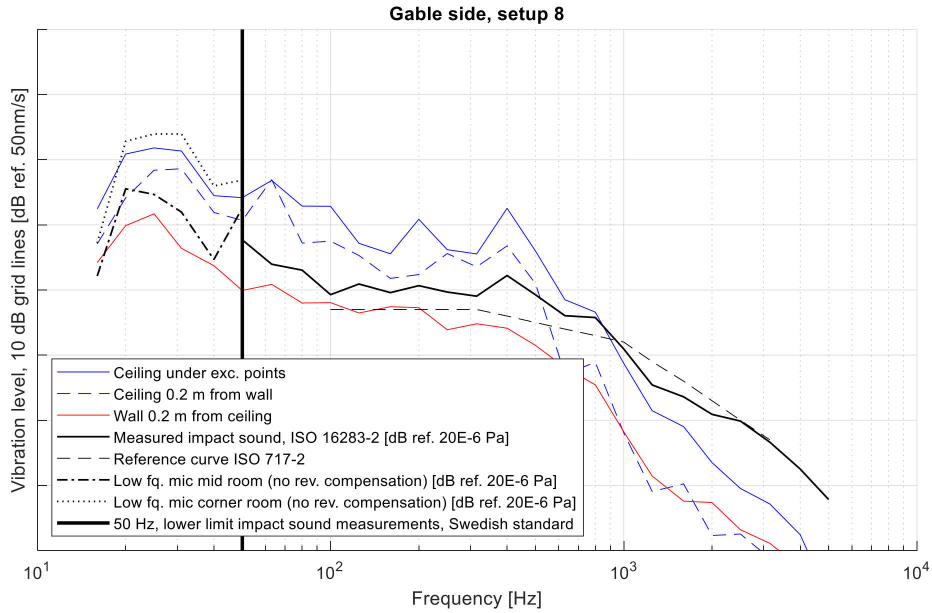


Figure 33. Measured impact sound levels presented with measured averaged vibration levels for the different locations, with the tapping machine. Here data is for the gable side of the test building and for test setup 8.

The weighing method used for calculation of the regulatory sound pressure level $L'_{nT} + C_{I,\ 50\text{-}2500}$, may also be used for the vibration levels. This makes it easier to relate the characters and levels of different vibration location categories to the measured impact sound levels. In Figure 34 to Figure 36 the measured impact sound levels are presented with each of the different energy averaged accelerometers locations, weighted in the same way. I could be seen that there is in general a similar pattern between the measured sound levels and the measured vibration levels, however it is not perfect. It seems likely that the dominating sound transmission, i.e., direct transmission and flanking transmission differs through the different setups.

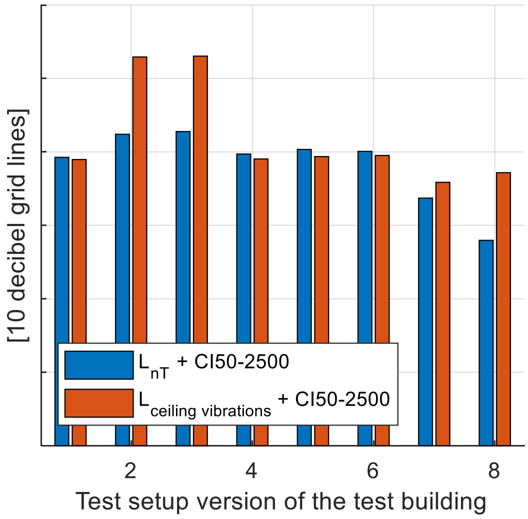


Figure 34. Diagram showing measured impact sound levels according to Swedish regulation, and the same when the averaged ceiling vibrations (dB ref. 50 nm/s) under the ceiling are weighted in the same way.

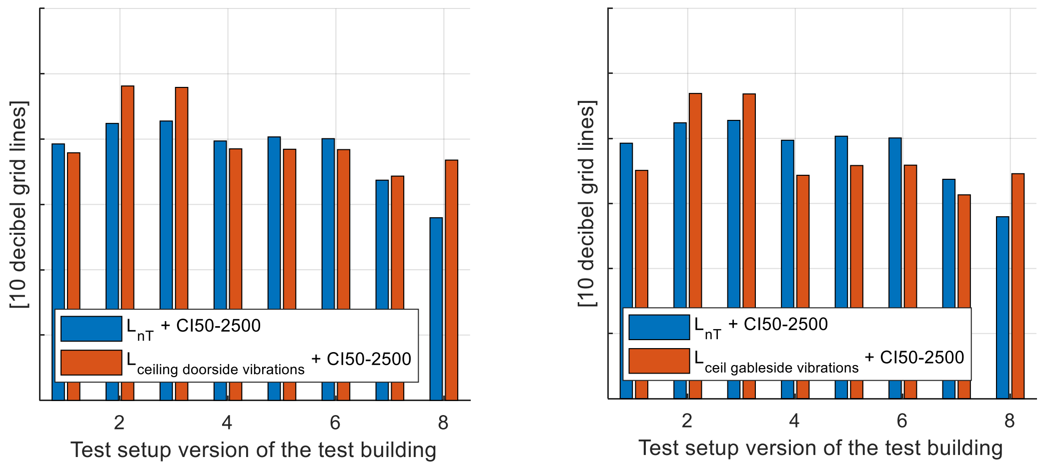


Figure 35. Diagram showing measured impact sound levels according to Swedish regulation, and the same when the vibrations (dB ref. 50 nm/s) under the ceiling are weighted in the same way. The left diagram shows the averaged ceiling 0.2 m from the wall on the door side. The right diagram shows the averaged ceiling 0.2 m from the wall on the gable side.

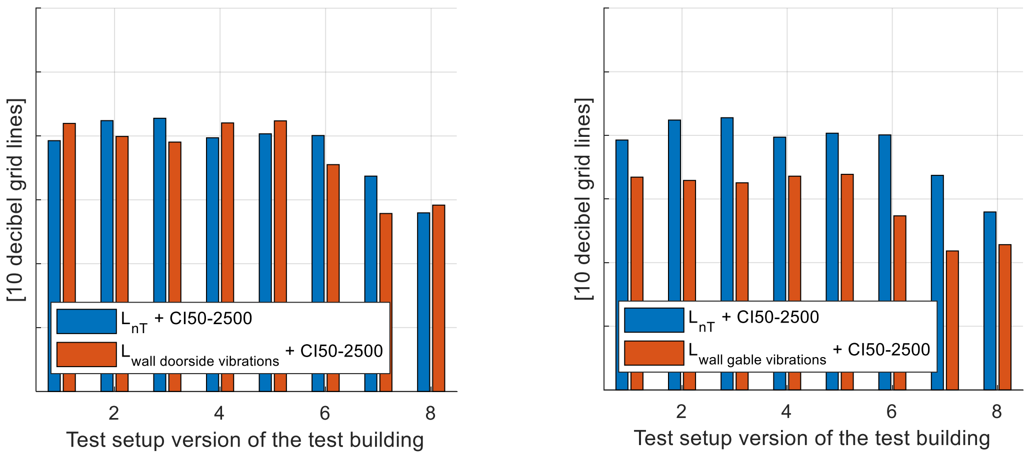


Figure 36. Diagrams showing measured impact sound levels according to Swedish regulation, and the same when the vibrations (dB ref. 50 nm/s) are weighted in the same way. The left diagram shows the averaged wall accelerometers 0.2 m from the ceiling on the door side. The right diagram shows the averaged wall accelerometers 0.2 m from the ceiling on the gable side.

5 Conclusions and discussion

The measurements show some interesting results. It is seen that suspended ceiling is a measure that improves the impact sound insulation with about 3-4 dB in relation to its adjacent setups (which may limit the improvement, the benefit may be larger than the measured difference if another weak link dominates these setups). It may be surprising that the elastic mounted floor does not improve in impact sound insulation. Studying the vibration diagrams, it is seen that the elastomers in fact improve, i.e., lower, the vibration levels in the wall. However, since the ceiling levels are higher and are unaffected in the ceiling, there is no real measured improvement of the sound insulation. If the direct transmission sound would be improved even further, then the elastomers are more likely to have a deciding effect on the achieved impact sound insulation.

For setup 7 added gypsum layers are put on the floor, both ceiling and wall vibrations are decreasing. Looking on the character (spectra) of the vibrations, the wall characteristics looks more like the impact sound, even though the walls have lower sound vibration levels on the measured locations (Figure 32). However, the measured locations may not be the ones with the highest amplitude on the walls. The accelerometers are put 0.2 m from the edges and edges are rather stiff points. It can not be ruled out that vibration levels are higher further from edges, i.e., lower on the walls. For the last setup 8, there is no measured vibration level decreasing and yet it has the lowest impact sound levels. It may indicate that the improvement for the last one is due to leakage is taken away (since there was a small gap between wall and ceiling until setup 8, cornices were added).

One could also notice that in the lowest frequencies, the difference in sound insulation between the accelerometers on the floor and corresponding in the ceiling below, is low. However, the vibration levels on the floor are rather low on the floor in the lowest frequencies. The number of trials made with the vibration measurement setup used here is few. However, it is common that the impact sound levels are the highest even below 50 Hz in timber buildings. These lower levels in the low frequencies are likely beneficial for the impact sound insulation. In these measurements, the range above 100 Hz to about 600 Hz, show the highest impact sound levels on the floor side. Higher frequencies are easier to attenuate compared to lower frequencies. Here is seen vibration differences exceeding 30-40 dB between the floor above and the ceiling below, from around 200 Hz and above.

The re-calculation of the measured acceleration vibration levels to velocity with a dB reference of 50 nm/s is useful. There is seen a clear connection between the measured vibration levels and the measured impact sound levels. Even though there is a strong connection, it is not perfect. The vibration levels commonly change in the same direction as measure improvement of do not change the exact the same amount as the impact sound levels change. It means that there is room for improvement of the measurement method. For instance, even though there are rather many accelerometers used in total in the measurements, there are rather few accelerometers used on each wall and floor measured. It means that it is not certain that the most critical points with highest vibration and / or sound radiations are measured. Also, here two walls and ceiling edges were measured out of the four. It assumes that there is high accuracy in symmetry to assume that the results are similar for the sides not measured. On the other hand, more accelerometers require increased efforts, more equipment, time, and costs. One potential change to consider is to alter the accelerometers on the floor to points on walls in the receiving room below, to have more data of the important radiating surfaces. Also, it would be beneficial to gain information about the radiation efficiency of the radiating surfaces in the receiving room. This would also help the evaluations.

1 Acknowledgements

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