Proceedings of Meetings on Acoustics

OCTOBER 08 2024

Vibration based method to evaluate floor-ceiling impact performance FREE

Sunit Girdhar ; John LoVerde; Wayland Dong; Benjamin Shafer

Check for updates

Proc. Mtgs. Acoust. 52, 040015 (2023)
https://doi.org/10.1121/2.0001961

View Online
Export Citation

Articles You May Be Interested In

Exploring Reciprocity method to measure radiated sound during a standard impact test
Proc. Mtgs. Acoust. (September 2022)

A dual-rating method for evaluating impact noise isolation of floor-ceiling assemblies
J. Acoust. Soc. Am. (January 2017)

Ceiling baffles and reflectors for controlling lecture-room sound for speech intelligibility
J. Acoust. Soc. Am. (June 2007)

27 May 2025 23:14:45

ASA
LEARN MORE
Advance your science and career as a member of the
Acoustical Society of America

ASA ACOUSTICAL SOCIETY OF AMERICA

ASA POMA Proceedings of Meetings on Acoustics

Volume 52 http://acousticalsociety.org/

Acoustics Week in Canada

185th Meeting of the Acoustical Society of America

Sydney, Australia

4-8 December 2023

Noise: Paper 1pNSa3

Vibration based method to evaluate floor-ceiling impact performance

Sunit Girdhar, John LoVerde and Wayland Dong
Paul S. Veneklasen Research Foundation, Cypress, CA, 90630; sunit.girdhar@gmail.com; info@veneklasenresearchfoundation.org; wayland.dong@gmail.com

Benjamin Shafer
PABCO Gypsum, Tacoma, WA; ben.shafer@quietrock.com

27 May 2025 23:14:45

The existing ASTM measurement methods use radiated averaged Sound Pressure Levels to evaluate the impact performance of floor structures from a tapping machine input. In low-frequencies, where the acoustic modal density of residential rooms can be low, Sound Pressure Level measurements can be highly non-reproducible. Different microphone locations can lead to different measurements, making it more challenging to compare the performance of one assembly with another. Vibration measurements can assist in making these decisions. These authors have undertaken a long-term project to explore using vibration measurements from accelerations on the source and the receiver side floor assemblies to get additional performance information from assemblies, especially in low-frequencies. In this work, we use three different input methods and show that the vibration-based floor performance is not dependent on the type of input. This suggests that any input, such as a foot stomp, can be used as an input force, as long as the output and input side acceleration is measured.

Published by the Acoustical Society of America

© 2024 Acoustical Society of America. https://doi.org/10.1121/2.0001961

1. INTRODUCTION

Footstep noise is a common source of annoyance in multi-story residential buildings.[1–3] ASTM standards[4–6] are used within the US to evaluate the impact performance of floor-ceiling assemblies. The test uses a standard tapping machine as an impactor on the source room floor and measures the radiated Sound Pressure Level (SPL) in the receiving room. The ASTM standard states that the tapping machine is not designed to mimic footstep impacts. Yet, the method provides a useful way of evaluating and rank-ordering the impact performance of various floors.

The measurement procedure suffers from reproducibility issues at low frequencies. Kylliäinen et al[7] studied 40 test structures and observed sound pressure level standard deviations of up to 8 dB in the 50 - 100 Hz bands due to different microphone locations in the living room. Hopkins et al[8] observed approximately 4 - 5 dB variation due to different microphone locations in the receiving room and Oliva et al[9] used a simulation model to show up to 4 - 10 dB measurement variation from 40 to 160 Hz. Similar behavior can be observed in other studies.[10–14] High measured SPL variability can lead to a high variation in calculated single-number ratings such as IIC (Impact Insulation Class[6]) and LIIC (Low-frequency Impact Insulation Class[15]). This can make it difficult to evaluate, rank-order, and design the impact performance of floor-ceiling assemblies.

The ASTM E989 standard[6] defines the Impact Insulation Class (IIC) rating, calculated using the measured SPL from 100 Hz to 3150 Hz and the ASTM E3207 standard[15] defines the Low-frequency Impact Insulation Class (LIIC) rating, calculated using the measured SPL from 50 to 80 Hz. The LIIC was added to the ASTM portfolio in the last few years, primarily because footsteps have a lot of low-frequency energy content.[16] This makes it imperative to evaluate the radiated SPL due to impacts in frequencies below 100 Hz.[16–23] and it is important to study frequencies below 100 Hz with the standard test methods. The measurement variability, as discussed previously, is worse at lower frequencies due to the low density of room modes in the low-frequency bands.

The authors have undertaken a long-term project to develop a vibration-based measurement method to evaluate the impact performance of floor-ceiling assemblies. Floor acceleration is measured on the floor and the ceiling surfaces to better understand how the vibration travels through the assembly. The supposition is that measuring vibration may be a better or complementary method to evaluate low-frequency impact performance as it will not be significantly affected by receiving room modes.

Portions of this project have been presented at the InterNoise 2022 conference,[24] where the input forces from the tapping machine impacts and the standard ISO impact ball[25] were calculated using the measured acceleration on a floor with known impedance. The impedance was measured directly using a modal hammer, with the assumption that the floor impedance is independent of the type of impact excitation.

In this work, we will be evaluating this assumption. The acceleration measured on the ceiling and the floor surfaces from a modal hammer, tapping machine, and impact ball were compared to analyze the differences observed, if any, with different impactors.

The next section explains the assembly studied and discusses the measurement methods used.

2. METHODOLOGY

The floor-ceiling structure evaluated for this work was still in the construction stages so it does not have an underlayment or a finish floor. The tested assembly consists of an OSB (Oriented Strand Board) sub-floor, wood joist with batt insulation, resilient channel, and one layer of gypsum board. A sketch of the assembly is shown in Fig. 1. The room size was $4.3m \times 3.3m \times 2.7m$ ($14ft \times 11ft \times 9ft$).

27 May 2025 23:14:45

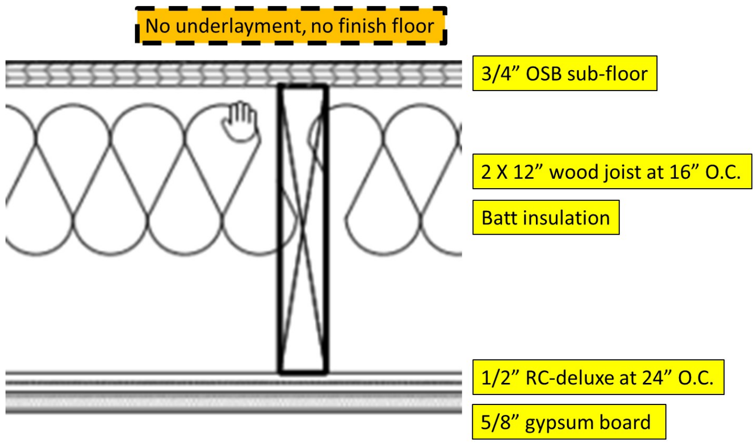

Figure 1: The floor-ceiling assembly evaluated in this work is shown above. The floor did not have any underlayment or a finish floor

For sanity check, the standard ASTM test according to E1007[5] was conducted and the single-number ratings were calculated based on ASTM E989,[6] E3207,[15] and E3222.[26] Figure 2 shows the measured SPL values using the solid red line, and the reference curves for ISR (Impact Sound Rating[6]) and HIR (High-frequency Impact Rating[26]) using the dashed and dotted black lines, respectively. The ISR, HIR, and LIR (Low-frequency Impact Rating[15]) ratings are shown in the bottom-right corner.

27 May 2025 23:14:45

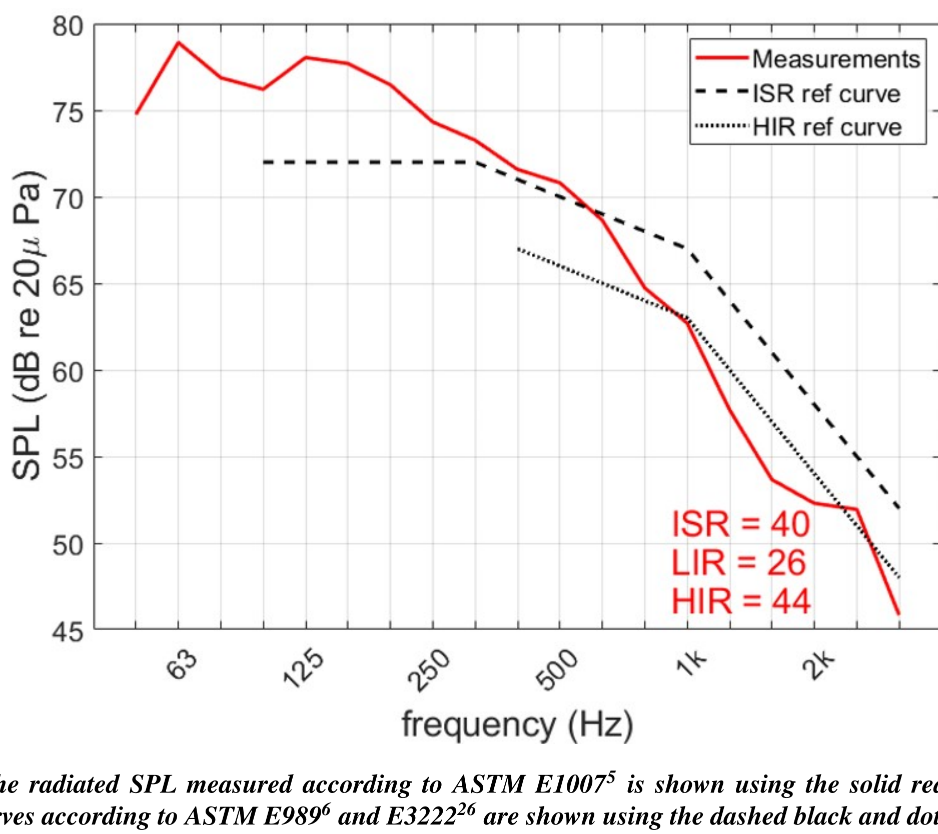

Figure 2: The radiated SPL measured according to ASTM E1007[5] is shown using the solid red lines and the reference curves according to ASTM E989[6] and E3222[26] are shown using the dashed black and dotted black lines, respectively. The three ASTM single-number ratings are presented at the bottom left corner of the graph

A PCB modal hammer (Model number 086D50[27]), along with the standard tapping machine and the ISO impact ball[25] were used as impactors on the source floor. The four locations, represented from sp1 to sp4, are shown using the blue circles in Fig. 3. The solid black lines are used to represent the room boundaries and the dashed black lines show the joist locations. Recall that the assembly did not have an underlayment or a finished floor, so the joists were easily located by the nail pattern in the subfloor.

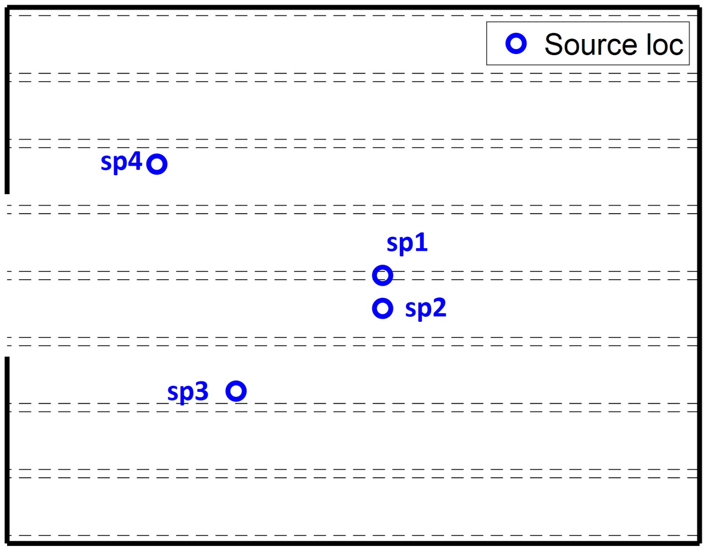

Figure 3: The blue circles show the four impact locations, represented using sp1 to sp4, for the test floor. The dashed black lines show the joist locations

27 May 2025 23:14:45

PCB 356A15 triaxial accelerometers were used for this work, but only the vertical channel was considered. Figure 4 shows the floor layout in the source room on the left and the ceiling layout on the right. Five accelerometers were mounted on the floor, represented using red squares, and three accelerometers were mounted on the ceiling, shown with green squares. Blue circles show the impact locations, only for reference.

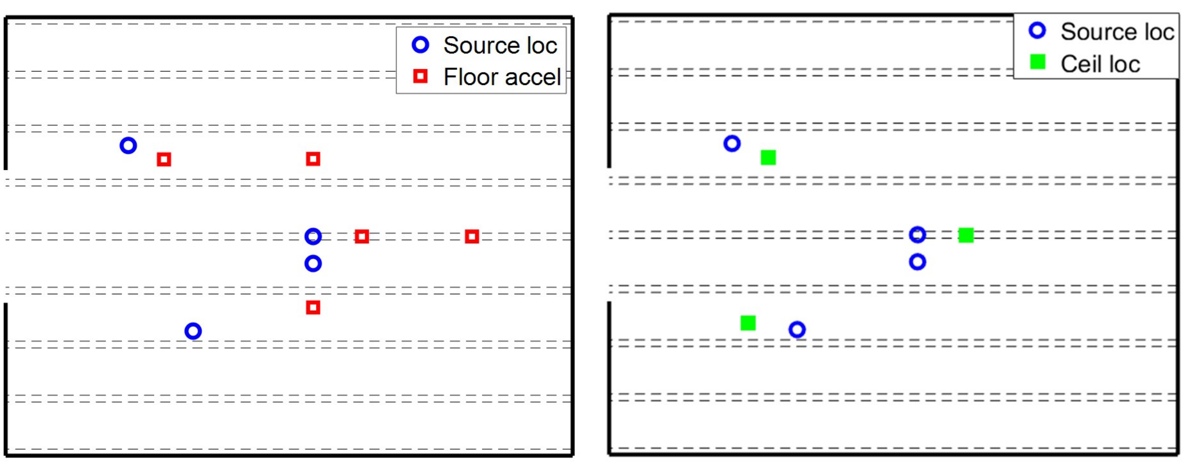

Figure 4: The floor locations are shown on the left and the ceiling locations are on the right. The accelerometer locations are highlighted with red and green squares, respectively, and the blue circles show the force locations, previously discussed in Fig. 3

Parts of this project have previously been presented at InterNoise 2022 conference,[24] where the impact forces from the tapping machine and the ISO impact ball were calculated by multiplying the acceleration of the tapping machine/ impact ball impacts by the inverse FRF (Frequency Response Function) measured with the modal hammer. This predicted force was averaged for all eight accelerometer locations to get the average tapping machine and impact ball force. This was compared to previously measured data and shown to have a good comparison.

The focus of this work was the vibration propagation through the floor-ceiling structure. The Frequency Response Function (FRF), which is the complex ratio of the acceleration to the input force,[28,29] was measured using a modal hammer to excite the floor. FRFs were measured from each impact location to each accelerometer position on the floor and ceiling as described in the previous section. For each source position, the FRF to the floor accelerometers and the ceiling accelerometers were averaged, and the ΔFRF is defined as the difference in decibels between the floor and ceiling average FRFs.

The vibration transmission was also measured using the acceleration level difference ΔL_a between the floor and ceiling, calculated from the averaged autopower spectra using all floor and all ceiling-mounted accelerometers.

3. RESULTS

Figure 5 compares the ΔFRF and ΔL_a for the four impact locations using the solid and the dashed lines, respectively. Four different colors are used to show four impact locations. For any given impact location, the ΔFRF and ΔL_a were similar for the entire bandwidth under study and nearly identical below 125 Hz. This is not a surprising result as phase is often not important in building acoustics quantities, which are mostly averages over space and time. Therefore, for the remainder of this analysis, we only consider the vibration level difference ΔL_a. This is convenient as it is considerably easier and quicker to measure than an FRF.

27 May 2025 23:14:45

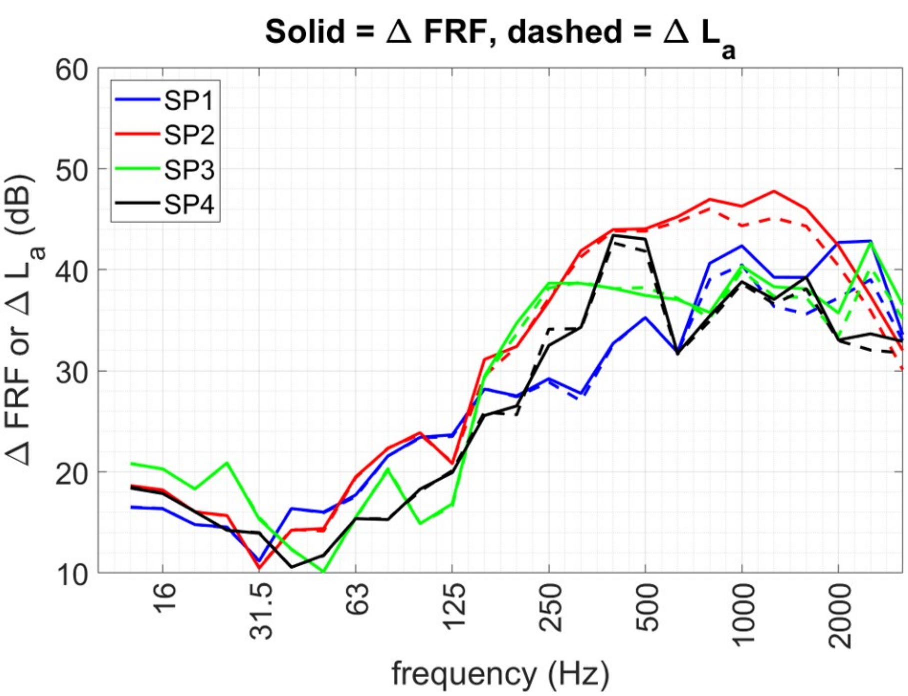

Figure 5: The Δ FRFs and ΔL_a for all four modal hammer impact locations are shown using the solid and the dashed lines, respectively. The two Δs are comparable to each other but high variation is observed for the four tapping machine positions

However, large differences are observed between different impact locations. As much as 15 dB variations are observed due to different impact locations from 16 Hz to 2000 Hz one-third-octave bands. Some differences might be expected, such as on the joist versus between joists, but such large variations are unexpected.

The ΔL_a spectra from all three impact sources for all four impact locations are shown in Fig. 6. The modal hammer, tapping machine, and impact ball are represented using the solid blue line, solid red line, and the dashed magenta line, respectively. For impact locations 2 and 3, the three impactors are comparable, but this is not the case for positions 1 and 4. For position 1, large differences are observed with the modal hammer, while for position 4, large differences are observed with the tapping machine, especially below 63 Hz and above 500 Hz. This may be due to the proximity between the impact location and the accelerometer locations.

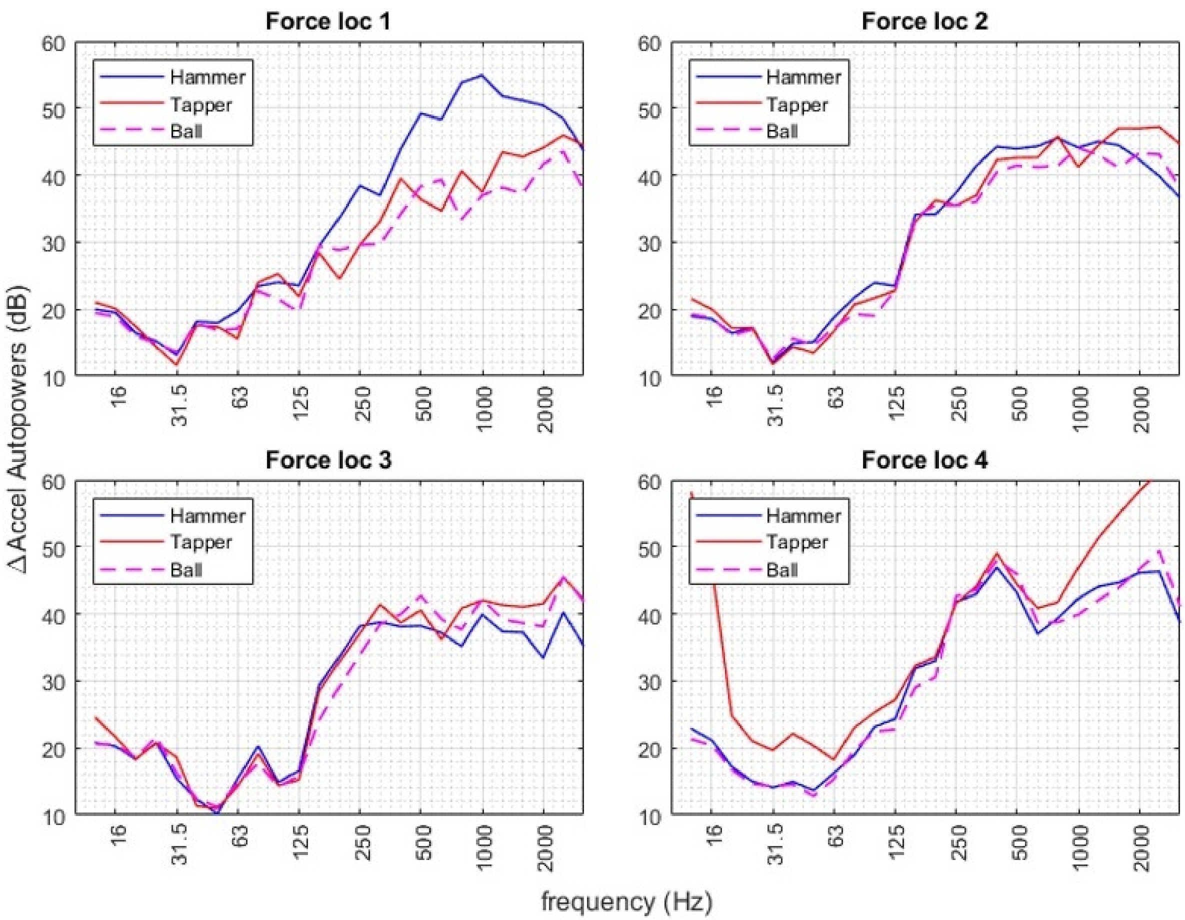

Figure 6: The ΔL_a (acceleration autopower spectra) for the four impact positions with the modal hammer (solid blue lines), tapping machine (solid red lines), and the impact ball (dashed magenta lines) show a good comparison for two of the four positions, but large differences for the other two positions are observed

Figure 7 highlights the 1st and the 4th impact locations as sp1 and sp4 (also shown in Fig. 3). Note that there is at least one accelerometer that is extremely close to these impact locations (red circles). Near-field effects of the force impact may be the reason for the discrepancies observed for these locations in Fig. 6.

27 May 2025 23:14:45

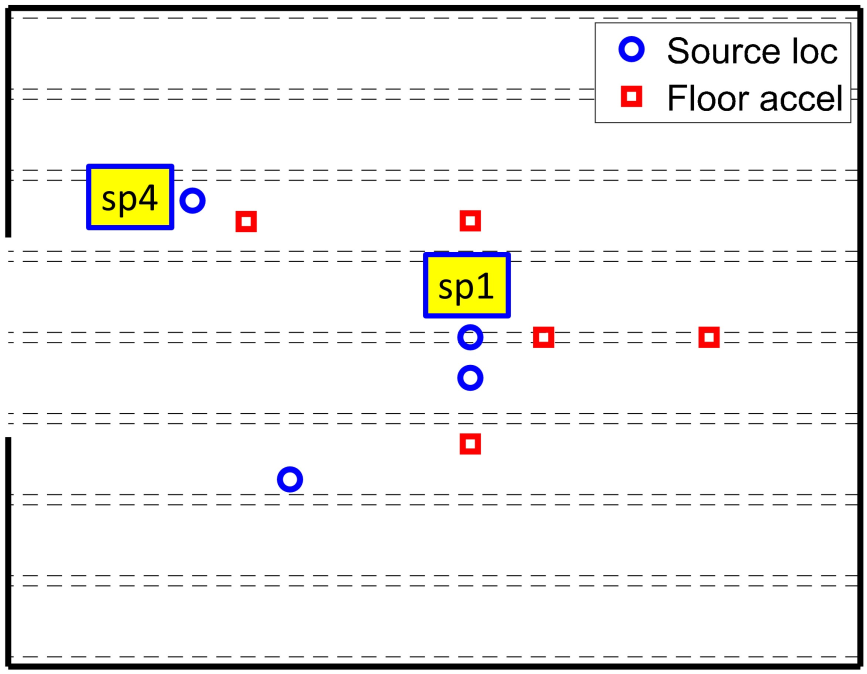

Figure 7: The Source Positions (sp) 1 and 4 are shown and they are extremely close to at least one accelerometer. The near-field effects from the impact may be causing the discrepancy observed in Fig. 6

27 May 2025 23:14:45

To avoid potential near-field effects on the data, the floor acceleration measured within 0.5 m of the impact locations was ignored and a new averaged floor acceleration was calculated. This was used to calculate the new ΔL_a spectra for all three input methods, which is presented in Fig. 8. The four locations are shown separately on four sub-plots, same as Fig. 6, and the three impactors are represented using the solid blue, solid red, and dashed magenta lines for the modal hammer, tapping machine, and the impact ball, respectively.

An improved comparison is observed for positions 1 and 4 when the near-field data is ignored. All four positions show good agreement between impact sources, except the tapping machine at position 4 above 1000 Hz. The focus of this work is low-frequencies so we can ignore this variation. Based on this data, it is safe to say that if the near-field acceleration is ignored, the choice of the impactor does not affect the vibration propagation from the impacted floor to the ceiling.

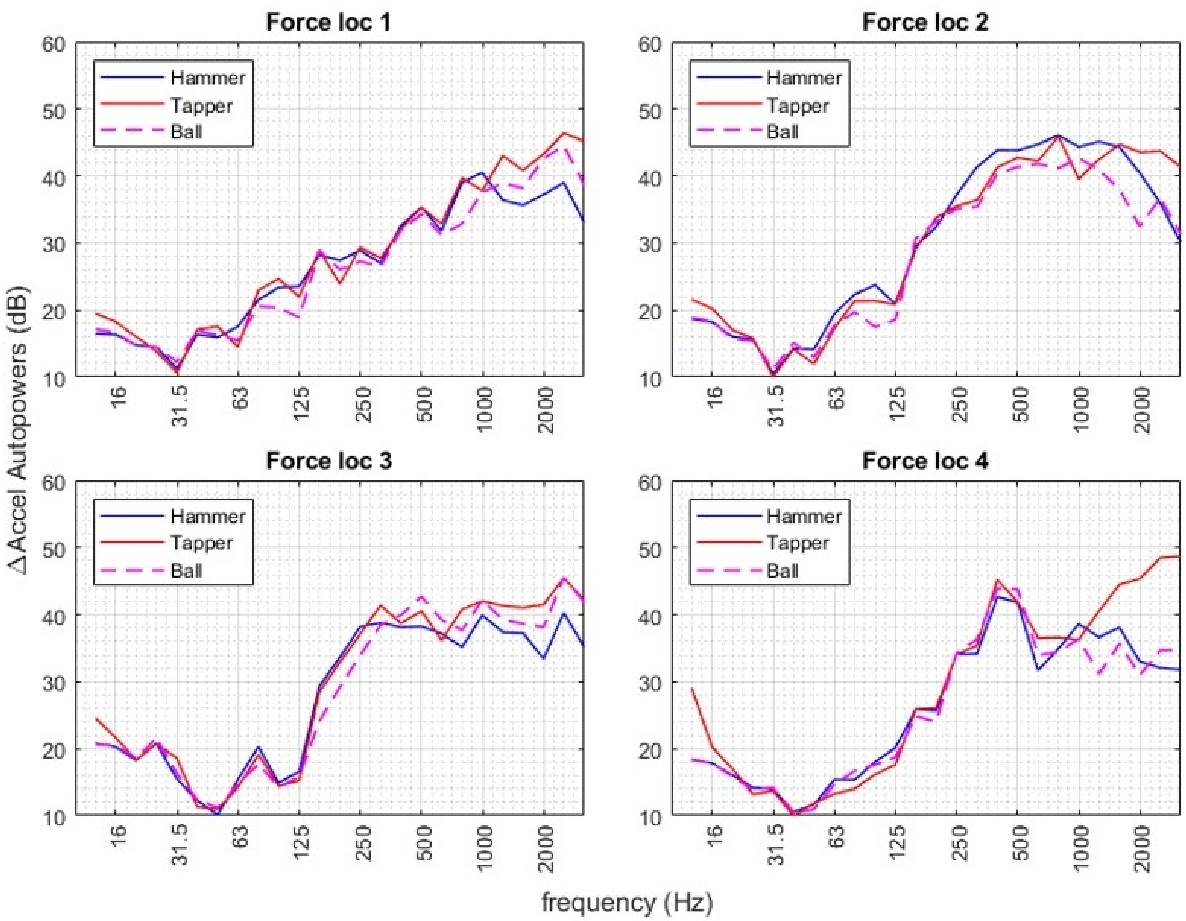

Figure 8: The ΔL_a (acceleration autopower spectra) for the four impact positions with the modal hammer (solid blue lines), tapping machine (solid red lines), and the impact ball (dashed magenta lines) after ignoring the floor acceleration measured within 0.5m of any impact locations shows an improved comparison, as opposed to Fig. 6

However, the variation observed due to different impact positions on the floor is unexpectedly high. Figure 9 shows the mean and the standard deviation in ΔL_a due to the impact location for the modal hammer, ignoring the near-field accelerometers. The solid curve in the middle is the mean value while the error bars represent one standard deviation on each side of the mean. Approximately 1.5 - 6.3 dB one standard deviation can be observed. Recall that this assembly doesn't have an underlayment or a finish floor, and the lack of load distribution may result in a greater variation due to impact location. More work is needed to better understand this behavior.

27 May 2025 23:14:45

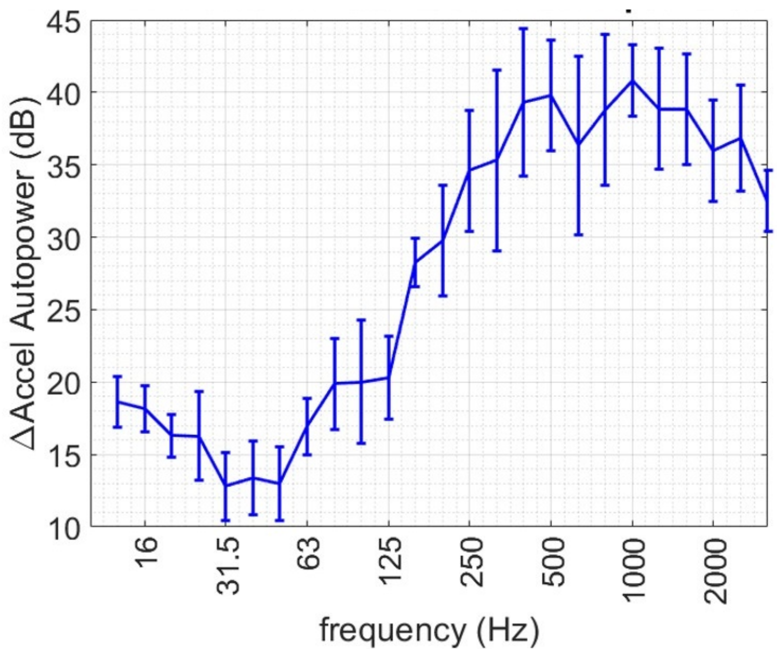

Figure 9: One standard deviation shown along the mean values for the ΔL_a (acceleration autopower spectra) due to all four input locations of the modal hammer shows approximately 1.5 - 6.3 dB variation

27 May 2025 23:14:45

4. CONCLUSIONS AND FUTURE SCOPE

The choice of impact source does not significantly affect the vibration propagation through the floor-ceiling assembly (although some differences were observed above 1000 Hz) as long as the floor accelerometers are a minimum of 0.5 m from the impact location. Assuming that this behavior also holds for real sources such as footfall, for example, then the tapping machine or any of the sources can be used to evaluate the vibration propagation through the assembly.

High variation in the vibration transmission was observed due to impact location, which was unexpected. More work needs to be done to better explain this behavior. If this is a true behavior of the structure, this has significant implications for the design of measurement methods to reduce uncertainty.

In the future, we will explore how the measured vibration propagation through the assembly compares with the radiated SPL and measured sound power in the receiving room. We also conducted a reciprocal test, where a speaker was used in the receiving room to generate an acoustic input for the assembly and the floor vibration was measured.

ACKNOWLEDGMENTS

The authors would like to thank their colleagues at the Paul S. Veneklasen Research Foundation and PABCO Gypsum for their support and all the productive and instructive conversations.

REFERENCES

[1] Kaj Bodlund. Alternative reference curves for evaluation of the impact sound insulation between dwellings. *Journal of sound and vibration*, 102(3):381–402, 1985.

[2] E Gerretsen. A new system for rating impact sound insulation. *Applied Acoustics*, 9(4):247–263, 1976.

[3] B. G. Watters. Impact-Noise Characteristics of Female Hard-Heeled Foot Traffic. *The Journal of the Acoustical Society of America*, 37(4):619–630, 1965.

[4] ASTM_E492-09. Standard Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine, 2016.

[5] ASTM_E1007-21. Standard Test Method for Field Measurement of Tapping Machine Impact Sound Transmission Through Floor-Ceiling Assemblies and Associated Support Structures, 2021.

[6] ASTM_E989-21. Standard Classification for Determination of Single-Number Metrics for Impact Noise, 2021.

[7] Mikko Kylliäinen, Lauri Talus, Jesse Lietzén, Pekka Latvanne, and Ville Kovalainen. Assessment of the low-frequency procedure in the field measurements of impact sound insulation between dwellings. *Applied Acoustics*, 185:108399, January 2022.

[8] C. Hopkins and P. Turner. Field measurement of airborne sound insulation between rooms with non-diffuse sound fields at low frequencies. *Applied Acoustics*, 66(12):1339–1382, December 2005.

[9] David Oliva, Valtteri Hongisto, Jukka Keränen, and Vesa Koskinen. Measurement of low frequency noise in rooms. *Finnish Institute of Occupational Health, Helsinki*, 2011.

[10] Sunit Girdhar, Wayland Dong, and John LoVerde. Evaluation of ASTM and ISO methods for measuring sound levels in building acoustics measurements. *Proceedings of Meetings on Acoustics*, 42(1):015005, December 2020.

[11] Wayland Dong and John LoVerde. Gauge Repeatability and Reproducibility Study of Airborne and Impact Insulation of Floor-Ceiling Assemblies. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 258(3):4578–4588, 2018.

[12] Wayland Dong and John LoVerde. Gauge Repeatability and Reproducibility Study of Field Testing of Floor-Ceiling Assemblies. *Proc ICSV25*, 2018.

[13] John LoVerde and Wayland Dong. Gauge repeatability and reproducibility studies of field testing of airborne and impact insulation in multifamily residences. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 259(5):4839–4847, 2019.

[14] ISO. 12999-1: Acoustics–Determination and application of measurement uncertainties in building acoustics–Part 1: Sound insulation. *Finnish standards association, Helsinki, Finland*, 2020.

[15] ASTM_E3207-21. Standard Classification for Determination of Low-Frequency Impact Noise Ratings, 2021.

[16] Warren E Blazier Jr and Russell B DuPree. Investigation of low-frequency footfall noise in wood-frame, multifamily building construction. *The Journal of the Acoustical Society of America*, 96(3):1521–1532, 1994.

[17] Rikard Öqvist, Fredrik Ljunggren, and Roger Johnsson. Walking sound annoyance vs. impact sound insulation from 20 Hz. *Applied Acoustics*, 135:1–7, 2018.

[18] Fredrik Ljunggren, Christian Simmons, and Klas Hagberg. Correlation between sound insulation and occupants' perception–Proposal of alternative single number rating of impact sound. *Applied Acoustics*, 85:57–68, 2014.

27 May 2025 23:14:45

[19] Mikko Kylliäinen, Jesse Lietzén, Ville Kovalainen, and Valtteri Hongisto. Correlation Between Single-Number-Quantities of Impact Sound Insulation and Various Noise Ratings of Walking on Concrete Floors. *Acta Acustica united with Acustica*, 101(5):975–985, 2015-09-15T00:00:00///.

[20] Th Mariner. Technical problems in impact noise testing. *Building Research*, 1:53–60, 1964.

[21] D Olynyk and TD Northwood. Subjective Judgments of Footstep-Noise Transmission through Floors. *The Journal of the Acoustical Society of America*, 38(6):1035–1039, 1965.

[22] T Mariner and HWW Hehmann. Impact-Noise Rating of Various Floors. *The Journal of the Acoustical Society of America*, 41(1):206–214, 1967.

[23] Birgit Rasmussen, María Machimbarrena, and Patrizio Fausti. COST Action TU0901–Building acoustics throughout Europe. *Volume 1: Towards a common framework in building acoustics throughout Europe*, 2014.

[24] Wayland Dong, John LoVerde, Ben Shafer, and Sunit Girdhar. Investigation of vibration-based measurements of impact and airborne noise insulation. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 265(2):5436–5442, 2023-02-01T00:00:00///.

[25] ISO 16283-2:2018. 16283-2: Acoustics — Field measurement of sound insulation in buildings and of building elements — Part 2: Impact sound insulation, 2018.

[26] ASTM_E3222-20. Standard Classification for Determination of High-frequency Impact Sound Ratings, 2020.

[27] PCB Piezotronics. Impact Hammer | 086D50. https://www.pcb.com/products?model=086D50.

[28] Ward Heylen, Stefan Lammens, and Paul Sas. *Modal Analysis Theory and Testing*. Katholieke Universiteit Leuven, Faculty of Engineering, Dept. of Mechanical Engineering, Division of Production Engineering, Machine Design and Automation Belgium, Belgium, [2nd ed.] edition, 1998.

[29] Peter Avitabile. *Modal Testing: A Practitioner's Guide*. John Wiley & Sons, 2017.

27 May 2025 23:14:45