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Proc. Mtgs. Acoust. 51, 015005 (2023)
https://doi.org/10.1121/2.0001752

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Evaluating proposed low-frequency measurement guidelines for impact noise in buildings with ASTM ratings

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ASTM standards are used to calculate a single number performance rating for floor-ceiling assembly impact noise. A higher number represents better performance, and a lower number represents poor performance. This number is calculated by placing a standard tapping machine on the floor and measuring the radiated sound pressure level (SPL) in the receiving room below. In theory, the performance of an assembly can be represented by just this calculated number. In practice, however, the same assembly tested in the same configuration can lead to a range of single-number ratings, instead of just one number. The authors are working on developing a new measurement method with an improved standard deviation. A simulation model was used in previous works and the guidelines were developed. This research uses the previously proposed guidelines to test three structures and shows that the measurement standard deviation can be as low as approximately 1 dB as compared to the 4 - 10 dB variation observed with the current method. Additionally, the proposed method was able to rank-order the assemblies better than the existing method when compared to the subjective response in the receiving spaces.

Published by the Acoustical Society of America

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1. INTRODUCTION

Humans spend a significant amount of their time indoors[1] and the comfort of such spaces is important, especially in residential spaces. Footstep noise is reported as one of the biggest sources of annoyance in multistory residential buildings[2–4] and within the US, the building codes use ASTM standards[5–7] to evaluate the footstep impact performance of floor-ceiling assemblies.

For these ASTM tests, a standard tapping machine is placed on the floor above in four defined orientations and locations to generate the impact force. The radiated Sound Pressure Level (SPL) is measured in the room below by either averaging multiple discrete microphone locations or by scanning a single microphone through the measurement volume in the room. The measurement volume is defined as all the room volume that is at least 1 m away from all room boundaries. More details for the field tests and lab tests are available in ref. 5-6.[5,6] The averaged SPL in the 100 Hz to 3150 Hz one-third-octave (OTO) bands is compared with the reference spectra to calculate single number ratings such as the Impact Sound Rating (ISR).[7]

Research shows that the rank order of the assemblies using the ASTM ratings fails to correlate with the subjective response of the residents. Out of 75 structures studied by Mariner et al,[8] one floor that had the same single number rating as another floor was subjectively twice as loud and the standard test method failed to quantify this. Alternatively, the authors showed that two floors that had the same subjective loudness showed an 11.5-point difference in their standard ratings. Olynyk et al[9] found that two floors with the same subjective performance due to footstep impacts showed a difference of twenty points on the single number rating scale. Two other floors that had the same single number rating using the tapping machine showed a 15 dB difference in their subjective performance due to footstep noise. Other studies confirmed a similar behavior.[10,11]

Traditional single number ratings such as ISR do not consider frequencies below the 100 Hz OTO band, yet frequencies below 100 Hz are important for evaluating the footstep impacts on floors. Öqvist et al[12] showed that a concrete and a wood structure with the same rating had a significantly different subjective response, and the differences in their impact spectra were only apparent in frequencies below 100 Hz. Bodlund[2] made a similar observation in their work. Most of the footstep energy lies in frequencies below 100 Hz[13] and by including these frequencies in the analysis, down to 50 Hz or even 20 Hz OTO bands in some cases, the correlation between the subjective reaction and the objective standard ratings can be significantly improved.[14] ASTM recently introduced a Low-frequency Impact Rating (LIR),[15] based on the work done by LoVerde et al,[10] calculated from the SPL in the 50 to 80 Hz OTO bands.

However, measuring down to 50 Hz OTO bands increases the variability in SPL measurement. It has long been noted that SPL measurements at low frequencies suffer from high measurement variability. Hopkins et al[16] showed that the standard deviation for different microphone locations in the receiving room was 4 - 5 dB at low frequencies due to the presence of a non-diffuse sound field. This was studied by setting up a dense microphone grid in the receiving room for an airborne sound insulation test but similar conclusions could also be made for the impact test on floors for this receiving room. At higher frequencies, as the sound field becomes more diffuse, the authors observed a standard deviation of approximately 2 - 3 dB between different room microphone locations.

Oliva et al[17] used a simulation model to show that approximately 4 - 10 dB differences may exist in low-frequencies at different microphone locations from 40 - 160 Hz in a receiving room for an impact test. The authors concluded that this variation exists because there is a non-diffuse sound field in the room and different microphone locations can lead to different SPL measurements.

Measurements in a non-diffuse sound field can result in large uncertainties in the test method. In extreme cases, the single number rating of an assembly may depend on the receiving room as much as the assembly. In previous work,[18] the authors compared vibration levels on the ceiling of the assembly under study to the SPL in the receiving room. The SPL showed a peak in the 100 Hz OTO band that was attributed to an acoustic room mode; this peak controlled the single number rating of the assembly. If the same assembly

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had been tested in another room with a different modal structure, the rating would have been different. This suggests that it may be useful to develop a measurement method based on the vibro-acoustic response of the assembly that does not require measuring the SPL or is at least less affected by sound field variability. Similar methods have been supported by other authors.[19–21] A vibro-acoustic method may also address some other issues with the current method, such as the nonlinear response of some flooring to the tapping machine, and the difference between the source impedance of the tapper compared to footsteps.[4,13,22,23]

The authors have previously investigated a method based on Frequency Response Functions (FRF) between an input force on the floor and the sound pressure level in the room.[24] In previous work, the authors investigated using a reciprocity method as an easier measurement to achieve the same result.[25] The source (input force: F) and the receiver (radiated SPL: P) are swapped for the reciprocal measurement method where a Q source speaker is placed in the room below (volume acceleration from an acoustic source: $\dot{Q}$) and the acceleration is measured on the floor above (acceleration: A). The principle of reciprocity states that

$$\frac{P}{F} = \frac{A}{\dot{Q}} \tag{1}$$

where, P/F is the direct FRF and the $A/\dot{Q}$ is the reciprocal FRF. Note that the term $\dot{Q}$ is the volume acceleration of the source, given by the product of the area of the speaker cone and its acceleration.[26] The reciprocal measurement method finds applications in the automotive industry[27–31] and previous work by the authors showed that it can also be used to measure footstep performance of floor-ceiling assemblies in buildings.[25]

The non-diffuse sound field can still lead to problems with the reciprocal method. Since the direct and the reciprocal FRFs are the same, the 4 - 10 dB low-frequency measurement variability observed with different microphone locations would still be observed for the reciprocal measurement method with different Q source locations. Previous research[32] used a simulation model to develop measurement guidelines using the reciprocity method. The simulation model used a concrete and a wood-joist assembly in three shapes that are generally observed in the field to develop the following measurement guidelines:

1. Identify the common floor area between the upstairs and the downstairs room for a floor-ceiling assembly under test
2. Ignore the coupled spaces (if any). See the dashed black line in Fig. 1
3. Identify the two longest room diagonals and place the Q source at one of the corners along the diagonals (red cross marks in Fig. 1)
4. Identify the measurement locations along the length of the diagonal at 17%, 50%, and 83% (black cross marks in Fig. 1)
5. Measure the $A/\dot{Q}$ FRFs for the three diagonal locations
6. Use the following formula to get the final diagonal averaged FRF

$$Avg\ FRF \ = \ \frac{2 \times FRF_{17\%} + FRF_{50\%} + 2 \times FRF_{83\%}}{5} \tag{2}$$

7. Repeat for the other room diagonal with the other Q source corner location
8. Take an average of the two diagonal FRFs to get the final performance

The final LIRR rating (Low-frequency Impact Response Rating) as proposed in[32] is calculated using the following formula:

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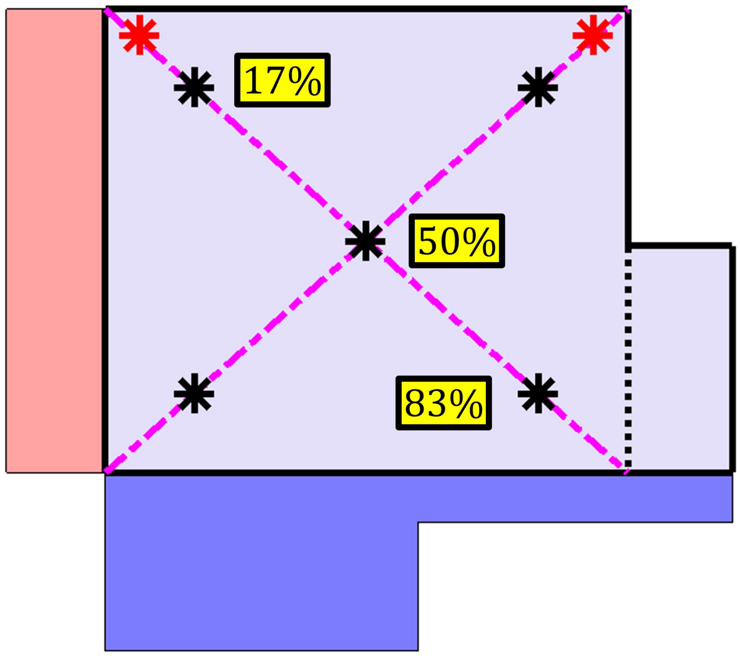

Figure 1: The measurement guidelines developed by these authors previously in[32] shows the Q source locations (red cross marks) and the diagonal measurement locations (black cross marks)

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$$LIRR = 130 - 2 \times 10\, log_{10} \left(\sum_{f=50}^{f=80} 10^{FRF(f)/10} \right) \tag{3}$$

where $FRF(f)$ is the measured FRF using the two corner locations of the Q sources in OTO bands. Note that because of the reciprocity principle, the same guidelines can be followed for the direct FRF (using a force input) or the reciprocal FRF (using a Q source acoustic input).

The simulation model presented in[32] showed that if different corners are selected for the Q source placement, the standard deviation of measurement is less than 1 dB for all the construction types and shapes studied, a significant improvement from the 4 - 10 dB variation observed with the current method.[17] This research, in part, verifies this measurement variability and compares the rank order of three floors tested using the proposed LIRR method and the existing ASTM ISR and LIR ratings. The next section provides the details of the assemblies under test and the measurement procedure.

2. METHODOLOGY

For this work, three assemblies were studied - O1 (heavy concrete assembly), O2 (lightweight joist-frame floor with a hardwood finish), and O3 (lightweight joist-framed floor with a carpet finish). For the standard ASTM E1007 field test,[6] a tapping machine (Scantek 211A SN29653) was used in the four pre-defined orientations, and the radiated SPL was measured in the room below using a sound level meter (B&K

2250 SN2551401). The standard ISR and LIR ratings were calculated according to ASTM E989[7] and compared with the proposed LIRR ratings.

For all the LIRR guidelines presented in the previous section, the Ratio of Powers Function (RPFs) was measured for all the assemblies, given as

$$RPF = \frac{\sqrt{G_{aa}}}{\sqrt{G_{qq}}} \tag{4}$$

where G_{aa} is the acceleration autopower spectrum measured on the floor and G_{qq} is the volume acceleration autopower spectrum measured for the Q source. To avoid running a long cable between the two floors, simultaneous measurements were avoided and the phase information was ignored. The two autopower spectra were measured separately and these RPFs were used to calculate the LIRR ratings of the structures.

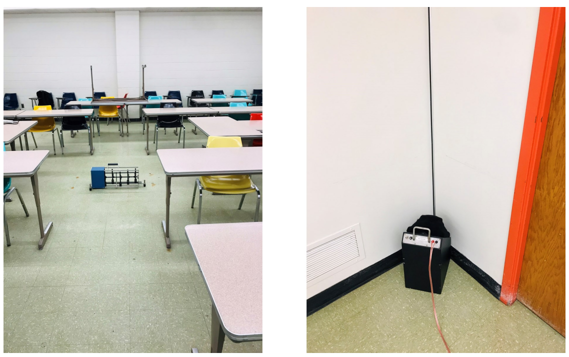

Figure 2: For the assembly O1, the ASTM tapping machine is shown on the left, and the Q source placed near one of the corners is shown on the right

Assembly O1 was a 6-in reinforced concrete structure with a $1/2$" thick metal sheet. The upstairs and downstairs rooms had the same shape and size and they both had general classroom furnishings. Figure 2 shows the standard ASTM tapping machine (left) and the Q source (Siemens SN13379) placed near one of the four room corners studied for this work (right). The test was conducted after hours to reduce the effects of background noise on the measurement but no special provisions were made to avoid this effect on the measured data.

Assembly O2 was a residential building with a lightweight joist-framed assembly and a hardwood floor finish. The rest of the assembly details are unknown. The upstairs space is a dining room that is open to the kitchen on one side and the living room on the other (red lines in Fig. 3 top) and the downstairs space is a slightly larger home office (compared to the dining room above - blue lines in Fig. 3 bottom). The Q source locations and the acceleration measurement locations are shown using the black cross marks and the magenta cross marks (respectively) in Fig. 3 top and the bottom figure shows the standard tapping machine for the ASTM tests (left) and the Q source placed near one of the four room corners (right).

The assembly O3 is a residential structure with a high pile carpet finish, oriented strand board sheathing, 12" manufactured joists (16" on center), and a gypsum ceiling. The rest of the assembly details are unknown. Because it was not possible to mount an accelerometer on the carpet in a non-destructive manner - the reciprocal RPFs could not be measured. Instead, the direct FRFs were measured using a modal hammer (PCB 086D50[33]) and the radiated SPL was measured using PCB 130D21 array microphones.

The upstairs and downstairs spaces have different dimensions (red and blue lines, respectively, in Fig. 4 - top), and the Q source locations and acceleration measurement locations are presented with black cross marks and magenta cross marks, respectively. The standard ASTM tapping machine is shown in Fig. 4 bottom - left along with the high-pile carpet on the floor, and the figure on the right shows the Q source placed near one of the four corners. The residential house was occupied during the test but the residents were in the other part of the building and they made an effort to reduce their effect on the measured data.

The next section discusses the LIRR measured for all three assemblies, addresses the measurement error by selecting different corner locations for Q source placements, and compares the rank order of the LIRR ratings with the standard ASTM ISR and LIR ratings.

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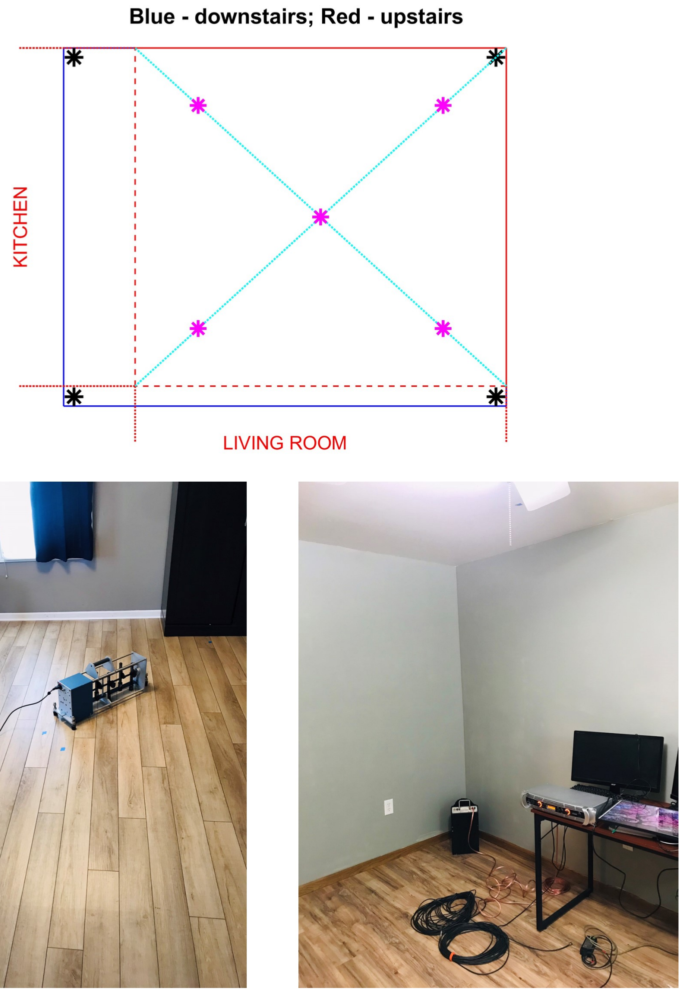

Figure 3: For the assembly O2, the top figure shows the upstairs (blue) and the downstairs (red) space, the Q source locations (black cross marks), and the acceleration measurement locations (magenta cross marks). The bottom figure shows the standard tapping machine (left) and the Q source placed near one of the four room corners (right)

3. RESULTS

According to the proposed LIRR guidelines, the Q source should be placed near two room corners that can be randomly selected. The simulation model studied previously by these authors[32] showed that the standard deviation of measurement due to this random selection was less than 1 dB. For all three structures, the Q source was placed near all four room corners, and in each case, the standard deviation between all possible combinations for two room corners was studied. The results for assembly O1 are shown in Fig. 5 where different colored lines represent different room corner combinations. The corner numbers on the top right side of the plot are inconsequential since all corner combinations were evaluated. The standard deviation of measurement (right axis) is approximately 1 dB and this matches the conclusions of the simulation model.

For assemblies O2 and O3, the measurement variability due to random room corner selection is presented in Fig. 6 (left) and (right), respectively. The standard deviation of measurement due to different Q source placement near corners is approximately 1 dB, as concluded from the simulation model. Note that for

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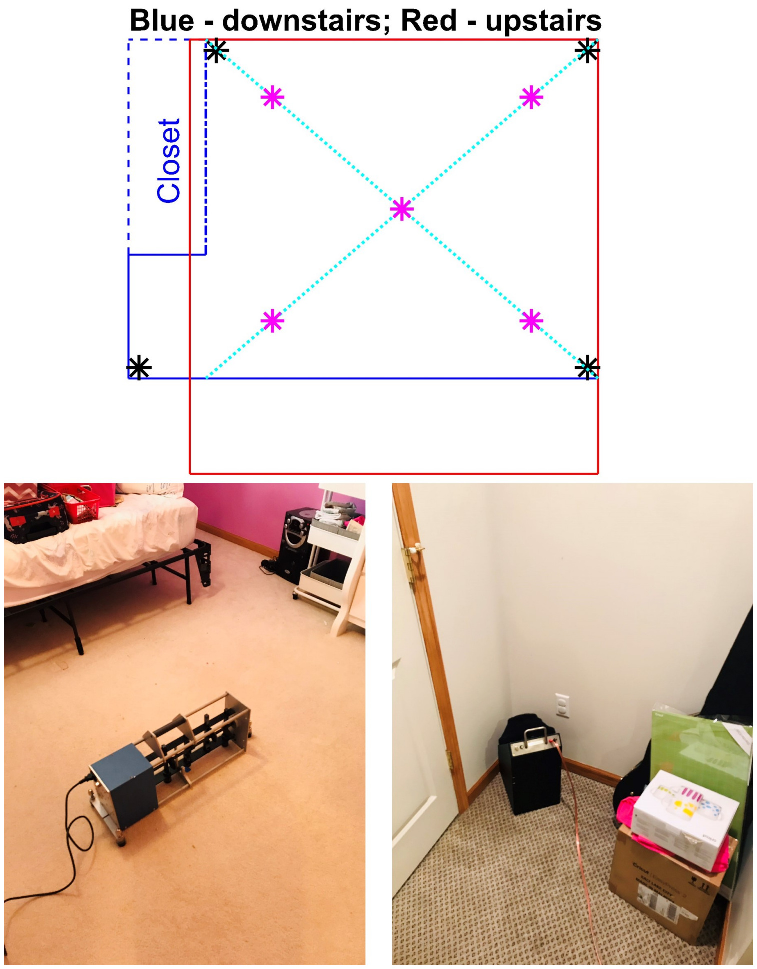

Figure 4: For the assembly O3, the top figure shows the upstairs (blue) and the downstairs (red) floor area as seen from the top, the Q source locations (black cross marks), and the acceleration measurement locations (magenta). The bottom figure shows the standard tapping machine (left) and the Q source placed near one of the four room corners (right)

assembly O3 (Fig. 6 right), the $A/\dot{Q}$ RPF could not be measured due to equipment restrictions and P/F FRFs were compared.

The three performance RPFs are compared in Fig. 7 using the blue, red, and yellow solid lines for assemblies O1, O2, and O3, respectively. The concrete assembly (O1) significantly outperforms the lightweight structures. Assembly O3 (carpet) performs very similar to assembly O2 (hardwood), generally, but slightly worse from the 40 to 100 Hz OTO bands. The LIRR ratings calculated using Eq. 3 for the three assemblies are 57, 37, and 35, respectively. The higher numbers reflect better performance and as expected from Fig. 7, the concrete assembly (O1) scores significantly higher number than the other assemblies, and assembly O3 scored two points lower than O2.

Standard tapping tests were also conducted for all three assemblies and the measured radiated SPL spectra from 12.5 to 3150 Hz OTO bands are shown in Fig. 8. The hardwood floor (O2) is loudest below approximately 800 Hz and the carpet floor (O3) is louder than concrete (O1) below approximately 100 Hz but quieter above that frequency.

The ISR and LIR ratings are tabulated in Table 1. The rank order of the floors in decreasing performance

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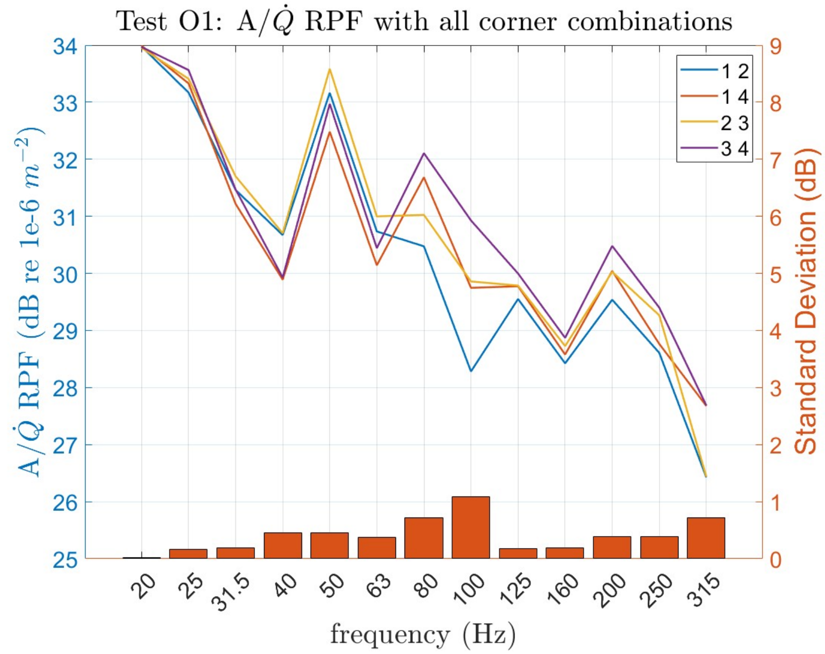
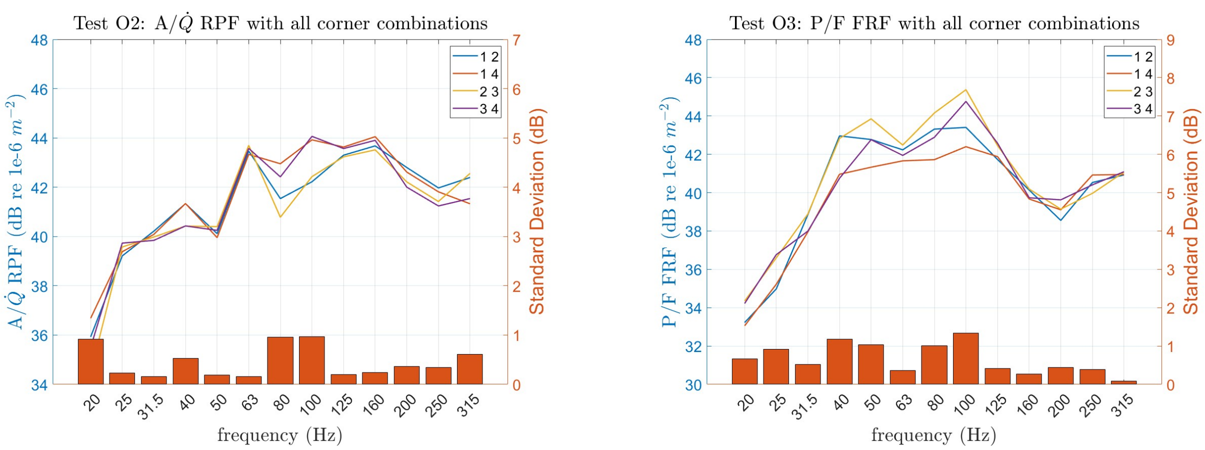


Figure 5: For assembly O1, the measurement standard deviation due to different corner selections for the Q source placement is approximately 1 dB, as predicted by the simulation model discussed in[32]



(a) Assembly O2 ***(b) Assembly O3***

Figure 6: For assembly O2 (left) and O3 (right), the measurement standard deviation due to different corner selections for the Q source placement is approximately 1 dB, as predicted by the simulation model discussed in.[32] Note that for the assembly O3, $A/\dot{Q}$ RPF could not be measured due to equipment restrictions and P/F FRF was used for comparison

according to the ISR rating is floor O3 followed by O1 and O2, while the order based on the LIR rating is floor O1, followed by O3 and O2. Recall that the LIR rating considers the performance from 50 - 80 Hz OTO bands, while the ISR rating evaluates the performance from the 100 - 3150 Hz OTO bands. The rank order of floors O3 and O1 is switched based on the ISR and the LIR rating because of the higher low-frequency radiated SPL levels with the floor O3 that are not accounted for by the ISR ratings.

Note that the LIR rating for assemblies O2 and O3 are 36 and 52, respectively. A 16-point difference

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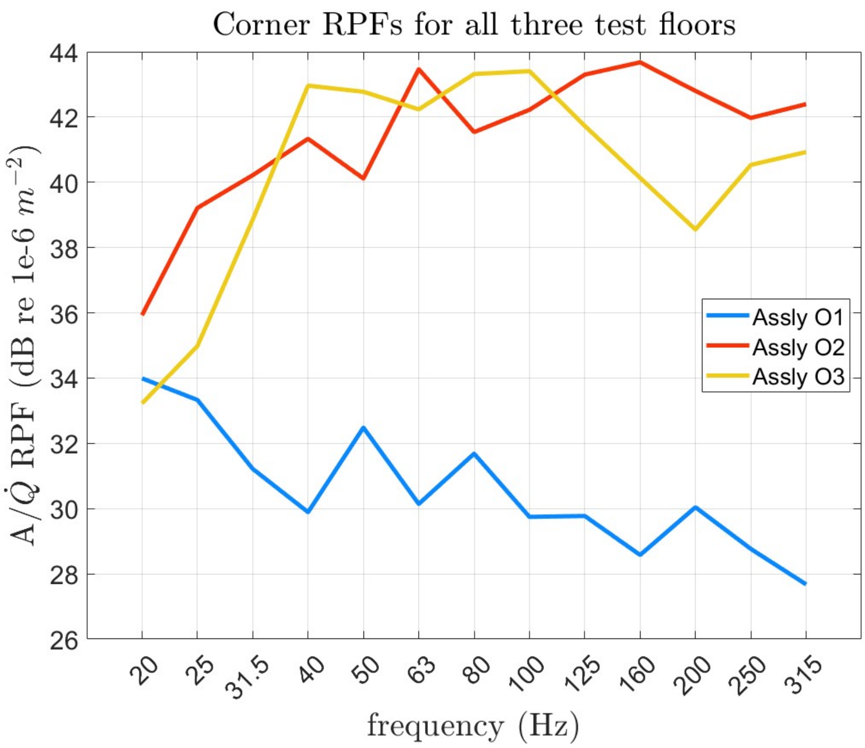

Figure 7: The performance RPFs measured for assemblies O1, O2, and O3 compared using blue, red, and yellow solid lines show that assembly O1 significantly outperforms the two lightweight floors and assembly O3 slightly underperforms as compared to assembly O2 from 40 to 100 Hz OTO bands

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Table 1: ISR and LIR ratings

Assembly	ISR	LIR
Assly O1: Concrete	52	66
Assly O2: Hardwood	35	36
Assly O3: Carpet	69	52

corresponds to the difference between an assembly that just meets building code and a luxury assembly. This large difference does not correspond to the subjective response of the authors in the space. The difference between the two floors may be inflated because the force due to the tapping machine is very different on different structures.[24] Note that the input force from the standard tapping machine could not be measured since there is no provision to directly measure this force during a standard test, but the force has been previously measured on other floors with a similar construction (see Appendix and see[24]) from a single tapping hammer impact.

The performance RPFs can be calculated by dividing the measured SPL with the previously measured force on similar assemblies and the results are shown in Fig. 9 using the same color scheme. The concrete floor (O1) significantly outperforms the other two and the carpet floor (O3) slightly underperforms the hardwood floor (O2) from 40 to 100 Hz OTO bands. These results match very closely with the RPFs

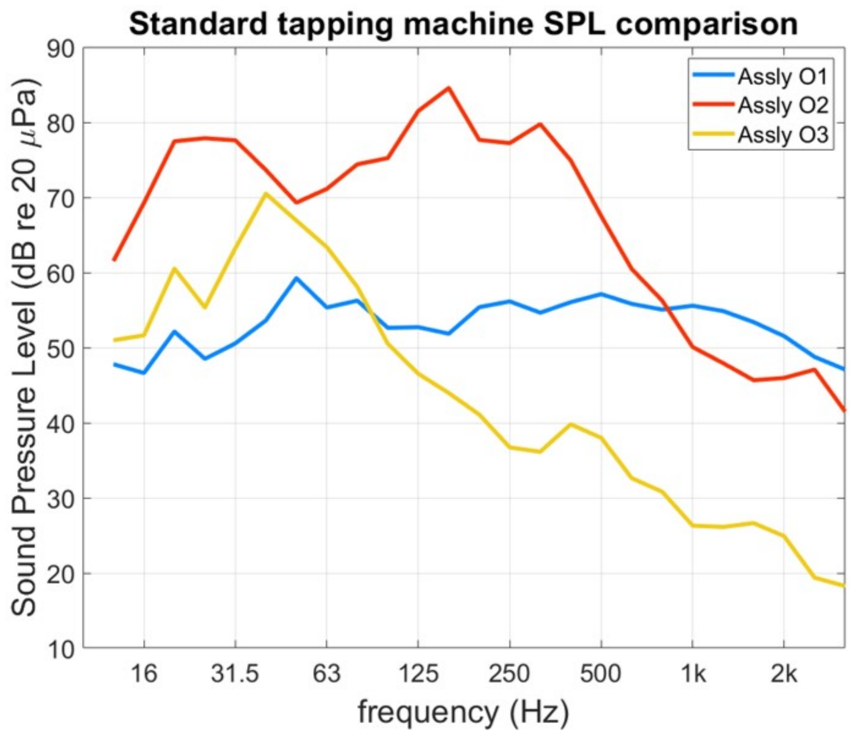

Figure 8: The radiated SPL measured with the standard tapping machine impacts for assemblies O1, O2, and O3 compared using blue, red, and yellow solid lines show that assembly O3 is significantly louder than the other two below approximately 800 Hz and assembly O3 is louder than O1 below 100 Hz but quieter above 100 Hz. ASTM ISR and LIR ratings were calculated using these data

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measured using the proposed LIRR guidelines (Fig. 7).

The next section discusses lessons from this work and proposes a way forward to evaluate footstep noise insulation for floor-ceiling assemblies.

4. DISCUSSION

For the three structures tested, the ISR and LIR rank order was swapped for two assemblies, primarily because of different floor performances in different frequency regions, but a 16-point difference in the LIR ratings was observed between the two lightweight floors. This was not the subjective response of the authors and the footstep noise in both the floors sounded very similar. This may be due to differences in the input force from the tapping machine, which can vary widely depending on the floor characteristics[24] and is unaccounted for in the standard methods.

The rank order of the floors can be improved by using the proposed LIRR test method, where the two lightweight floors (O2 and O3) only showed a two-point difference. This study is limited in scope with only three assemblies but the results are promising that the proposed FRF-based test method can improve the subjective rank order of assemblies.

Additionally, two people testing the same room and following the same measurement guidelines can select different corners for the Q source placement and the standard deviation of measurement would be less than 1 dB. This was confirmed using the three assemblies studied for this work and with the simulation model studied previously.[32] This is a significant improvement over the existing variation of approximately 4 - 10 dB.[17] The guidelines developed previously in[32] and evaluated in this work can be an alternative test

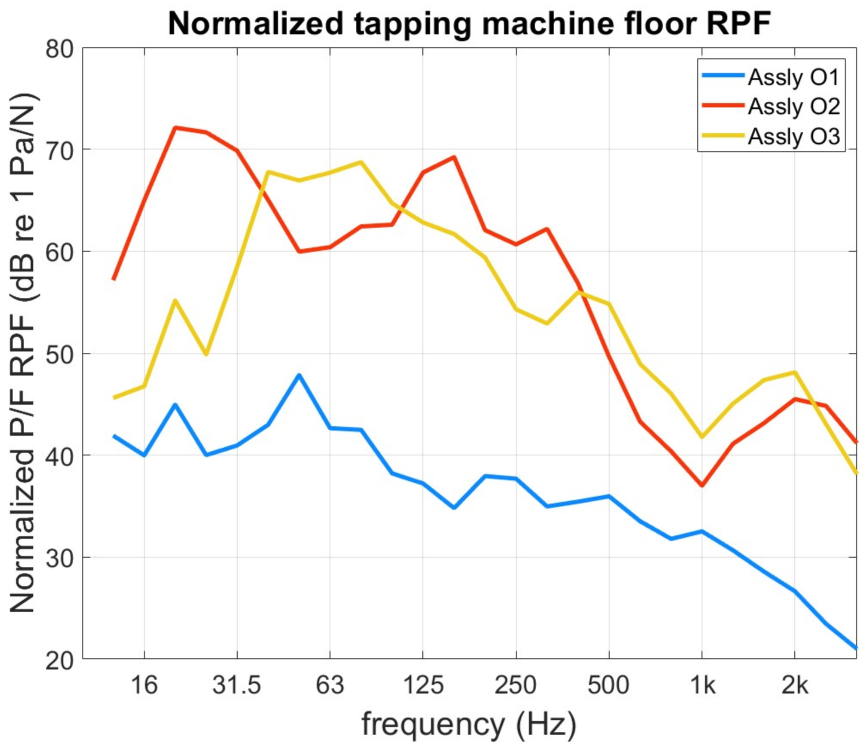

Figure 9: The SPL from the standard tapping test divided by the tapper force on similar constructions (see Appendix) is shown using blue, red, and yellow solid lines for assemblies O1, O2, and O3, respectively. Assembly O1 significantly outperforms the two lightweight floors and assembly O3 slightly underperforms as compared to assembly O2 from 40 to 100 Hz OTO bands

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method to evaluate footstep noise in buildings with improved reproducibility. For this work, this variability was only studied for frequencies below 400 Hz due to the restrictions of the Q source which is only rated from 25 - 400 Hz OTO bands.

5. CONCLUSIONS AND FUTURE SCOPE

The proposed LIRR test method improves the rank order of the assemblies based on subjective evaluation. Two assemblies with similar LIRR ratings had a similar subjective performance according to the authors but showed an approximately 16-point difference for LIR ratings and a 34-point difference for ISR ratings. Additionally, the measurement variability with the proposed guidelines is approximately 1 dB below 400 Hz OTO bands.

In the future, the authors plan to collect data on more structures and perform a jury study with multiple participants to evaluate the rank order of floor performance with the existing and proposed method. The authors are also working on using any off-the-shelf speaker instead of a specialized Q source speaker by measuring the acoustic power in an anechoic chamber and assuming monopole radiation in low-frequencies.

ACKNOWLEDGMENTS

The authors would like to thank the Paul S Veneklasen Research Foundation (PSVRF) and INCE-USA for their financial support. The authors would also like to thank their colleagues and friends at the Dynamic

Systems Laboratory at Michigan Technological University and the Graduate Program in Acoustics at Penn State University for their support.

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APPENDIX

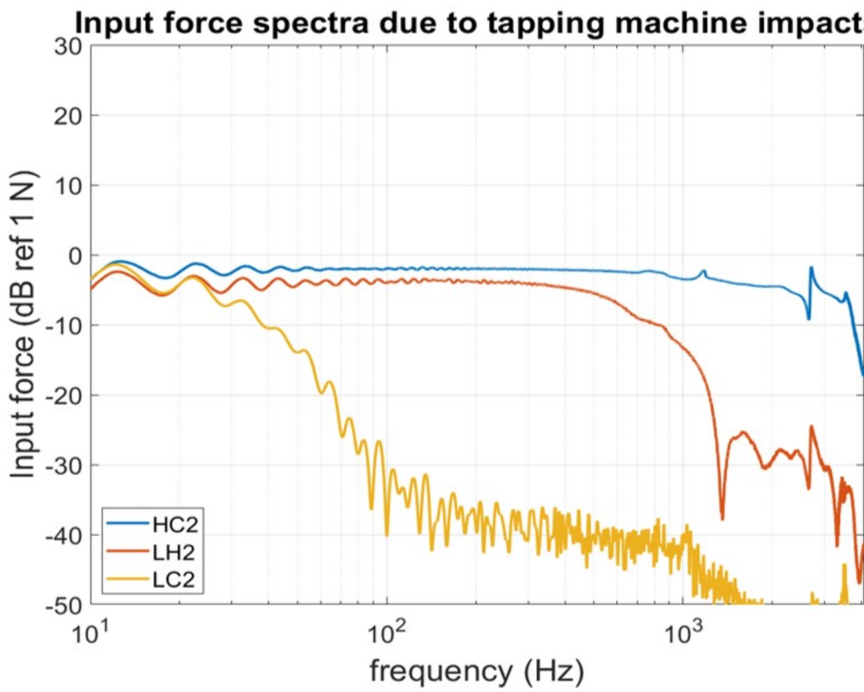

Figure 10: The force measured due to a single tapping machine impact on a heavy concrete floor (blue), a lightweight joist-framed floor with hardwood finish (red), and a lightweight joist-framed floor with a carpet finish (yellow) collected from previous work.[24] This force was used to 'normalize' the measured SPL with the tapping machine impacts for assemblies O1, O2, and O3, respectively, to get an FRF-like quantity

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