**Assessing the low-frequency measurement procedure for the measurement of impact sound insulation using the rubber ball**

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**ABSTRACT**

*ISO 16283-2 includes a procedure for measuring field impact sound insulation at low frequencies using a tapping machine to improve the repeatability, reproducibility, and relevance of results in the 50, 63, and 80 Hz one-third octave bands in small receiving rooms (volumes less than 25m3). However, the low-frequency measurement procedure with excitation from a standardized rubber ball was not included because the link between measurements of Li,Fmax from the central region and corners had not been established at the time of writing. This paper assesses the use of the low-frequency measurement procedure with a rubber ball source through measurements of Li,Fmax in a vertical transmission suite at the Building Research Institute (Japan). It also provides analysis of the modal sound field in the receiving room due to rubber ball excitation of the concrete slab. The results indicated that the low-frequency measurement procedure was beneficial in this 60m3 room to estimate the room average sound pressure level below 80Hz. Future work could therefore evaluate the low-frequency procedure in the field with different room volumes and floor constructions.*

# 1. INTRODUCTION

The low-frequency measurement procedure (LFMP) for field measurements of impact sound insulation was introduced in ISO 16283-2:2010. This was based on research conducted by Hopkins and Turner [1] and Simmons [2] with airborne measurements to reduce the uncertainty in low-frequency measurements in the 50, 63 and 80 Hz one-third octave bands. It introduced additional sound pressure measurements in corners to improve the repeatability, reproducibility, and relevance with small room volumes [1,3]. This was only introduced for steady-state sources such as a loudspeaker for airborne sound insulation and the tapping machine for impact sound insulation. However, the use of the ISO rubber ball requires measurement of a Fast time-weighted maximum sound pressure level, *L*Fmax, and therefore additional work is needed to confirm its suitability for a transient source. For this reason, this paper experimentally investigates the use of LFMP for *L*Fmax measurements using the rubber ball source along with an assessment of the modal response of the receiving room.

# 2. Test facility and measurement procedures

Details of the test facilities are shown in Figure 1. It is a vertical transmission suite with two rooms on the ground floor and one room on the first floor. The ground floor rooms have dimensions of *L*x=5 m, *L*y=4 m and *L*z=3 m and are separated by a 200 mm thick concrete wall. Note that this gives a 60m3 receiving room which is too large for use with the LFMP described in ISO 16283-2 for the 50, 63 and 80 Hz one-third octave bands. However, by assessing measurements down to the 20 Hz one-third octave band it is still feasible to assess the LFMP. The first-floor room dimensions are *L*x=10 m, *L*y=4 m and *L*z=2.45 m and there are no walls that subdivide the space. The thickness of the floor slab is 200 mm on the left side and 150 mm on the right side. The concrete floor is rigidly connected to the side walls. Figure 2 shows the test setup in the receiving room. The timber frame on the floor slab was installed to comply with the requirement on JIS A 1440-2:2000 that requires the construction of an access floor to assess the change due to the floor finishing material.

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Figure 1 View of the chamber from Lx and Lz side (left) and Lx and Ly side (right)

木の板の上にジャンプしている男性

低い精度で自動的に生成された説明屋内, 小さい, 部屋, 座る が含まれている画像

自動的に生成された説明

Figure 2 Experimental setup in the source room (left) and receiving room (right).

The material properties of the concrete slab are given in Table 1.

Table 1 Material properties of the concrete slab

|  |  |  |  |
| --- | --- | --- | --- |
|  | Density (kg/m3) | Young’s modulus (N/m2) | Poisson’s ratio (-) |
| Concrete | 2200 | 3.05E10 | 0.2 |

Table 2 Excitation positions for the diagonal and the central position on the concrete slab.

|  |  |  |  |
| --- | --- | --- | --- |
| Excitation | *x* | *y* |  |
| Diagonal | 1.25 | 1 |  |
| Central | 2.5 | 2 |  |

In order to visualise the sound field in the receiving room a grid of 693 microphone positions is used with 0.5m spacing. Two excitation positions are used for these measurements corresponding to Table 2. Note that the central position is at the central point of the concrete floor area that is above the receiving room (not in the centre of the timber frame). The recordings were made using two data recorders (DA21, RION) and seven microphones. Figure 3 shows the positions of the seven microphones mounted on the tripod, with grid nodes marked on the base slab. The tripod was manually moved between positions. For the corner positions, three sets of tripods were used, with each tripod having two microphones located close to the ceiling and floor levels to measure each excitation position.

屋内, 床, 小さい, 座る が含まれている画像

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Figure 3 Microphone positions in the receiving room.

The recording time for each impact was ten seconds with a sampling frequency of 12.8k Hz (frequency resolution was 0.1 Hz). The post-processing included FFT and one-third octave band filtering, time-weighting filtering, and plotting, was carried out using the Python libraries SciPy, NumPy, pandas, matplotlib, and plotly. The variable of primary interest was *L*Fmax in one-third octave bands but in order to check that the Fast time-weighting did not significantly change the sound pressure levels in the corners of the room, *L*eq,10s was calculated as well.

# 3. Modal response of the plate and room

Using the floor parameters given in Table 1 the bending mode frequencies for an isotropic rectangular thin plate with simply supported boundaries were calculated using [4]

|  |  |
| --- | --- |
|  | (1) |

where *c*L can be calculated from

|  |  |
| --- | --- |
|  | (2) |

The eigenfrequencies of the room were calculated using

|  |  |
| --- | --- |
|  | (3) |

Table 3 and Table 4 show the show the predicted plate and room mode frequencies respectively*.*

Table 3 First six eigenfrequencies predicted for the 5m×4m×0.2m concrete slab.

|  |  |  |
| --- | --- | --- |
| *m* | *n* | Frequency (Hz) |
| 1 | 1 | 35.32 |
| 2 | 1 | 76.68 |
| 1 | 2 | 99.94 |
| 2 | 2 | 141.29 |
| 3 | 1 | 145.60 |
| 1 | 3 | 207.63 |

Table 4 First ten eigenfrequencies predicted for the 5m×4m×3m receiving room.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *p* | *q* | *r* | Frequency (Hz) | Mode shapes |
| 1 | 0 | 0 | 34.3 | Axial |
| 0 | 1 | 0 | 42.88 | Axial |
| 1 | 1 | 0 | 54.91 | Tangential |
| 0 | 0 | 1 | 57.17 | Axial |
| 1 | 0 | 1 | 66.67 | Tangential |
| 2 | 0 | 0 | 68.6 | Axial |
| 0 | 1 | 1 | 71.46 | Tangential |
| 1 | 1 | 1 | 79.26 | Oblique |
| 2 | 1 | 0 | 80.90 | Tangential |
| 0 | 2 | 0 | 85.75 | Axial |

# 3. Results

# 3.1. Sound pressure levels in the room in narrow bands

Figure 4 shows the narrow band sound pressure levels measured at each of the 693 microphone positions in the receiving room along with the arithmetic average of all 693 grid positions. The room mode frequencies are estimated from these measurements, with the white horizontal line drown n the plot representing the peak detection threshold. The predicted mode frequencies are shown on the upper boundary of the graph. The measurements indicate that the eigenfrequencies obtained from the analytical prediction are close estimates of those indicated experimentally. By considering a normal mode model for the coupling between a plate and a room [5, 6, 7, 8] it should be possible to explain why some room modes are not excited by specific plate modes. However, in this experimental situation where some flanking transmission is expected to occur and the mode shapes on the concrete floor are unlikely to correspond closely to those for a simply supported plate it appears that this model is of limited use in explaining which modes are excited. For example, a central excitation position would be expected to only excite the lowest vertical axial mode but not the other two axial modes below 100Hz. However, it appears that all three of the lowest axial modes are excited, potentially due to the reasons indicated above.

グラフ, ヒストグラム

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自動的に生成された説明

Figure 4 Narrow band sound pressure level in the receiving room due to rubber ball excitation at the central (left) and diagonal (right) positions on the floor.

Figure 5 visualises the room sound field in narrow bands at the experimentally identified eigenfrequencies in Table 5. It is normalised to the maximum sound pressure level in the narrow band and a colour bar ranging from the highest level 0 dB (blue) to the lowest level 40 dB (red); hence clear nodal planes or nodal lines are typically red. Clear mode shapes can be observed for all axial modes at 34.8 Hz (*f*100), 43.3 Hz (*f*010), 58.1 Hz (*f*001), 69.6 Hz (*f*200) and 86.6 Hz (*f*020). The tangential mode at 55.3 Hz (*f*110) was not clear for either the central or diagonal excitation position. However, a clear tangential mode was observed for the diagonal excitation position at 66.7 Hz (*f*101) and for both excitation positions at 72.5 Hz (*f*011). However, the oblique mode at 80.3 Hz (*f*011) and tangential mode at 81.9 Hz (*f*011) are too close together to be able to identify them.

Table 5 Comparison of predicted and measured room eigenfrequencies.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| *p* | *q* | *r* | Predicted (Hz) | Measured - Central (Hz) | Measured - Diagonal (Hz) | Mode shapes |
| 1 | 0 | 0 | 34.3 | 34.8 | 34.8 | Axial |
| 0 | 1 | 0 | 42.9 | 43.3 | 43.3 | Axial |
| 1 | 1 | 0 | 54.9 | 55.3 | 55.3 | Tangential |
| 0 | 0 | 1 | 57.2 | 58.1 | 58.1 | Axial |
| 1 | 0 | 1 | 66.7 | 67.7 | 67.7 | Tangential |
| 2 | 0 | 0 | 68.6 | 69.6 | 69.5 | Axial |
| 0 | 1 | 1 | 71.5 | 72.5 | 72.5 | Tangential |
| 1 | 1 | 1 | 79.3 |  | 80.3 | Oblique |
| 2 | 1 | 0 | 80.9 |  | 81.9 | Tangential |
| 0 | 2 | 0 | 85.8 | 86.7 | 86.6 | Axial |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | ***f100*** | ***f010*** | ***f110*** | ***f001*** | ***f101*** |
| Central | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, レーダー チャート, 等高線グラフ  自動的に生成された説明 | グラフ, レーダー チャート, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 |
| Diagonal | グラフ, レーダー チャート, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, レーダー チャート, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 |
|  | ***f200*** | ***f011*** | ***f111*** | ***f210*** | ***f020*** |
| Central | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 |
| Diagonal | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 |

Figure 5 Visualised modal response of the room due to rubber ball excitation (narrow band FFT) at the predicted eigenfrequencies.

# 3.2. Measured room sound pressure levels in one-third octave bands with *L*eq and *L*i,Fmax

One-third octave band data from 25 Hz to 200 Hz are shown for *L*eq,10s in Figure 6 and for *L*i,Fmax in Figure 7. The values shown in the figures are normalised to the maximum sound pressure level in each band; the colour bar is set to a maximum of 20 dB (red) and a minimum of 0 dB (blue).

For *L*eq,10s and *L*i,Fmax in the 25 Hz band (i.e. below the lowest room mode), the levels near the ceiling were lower than near the floor as observed in other grid measurements for floor impact sound measurements [9]. For bands from 25 Hz to 63 Hz the sound field is similar for *L*eq,10s and *L*i,Fmax but the nodal planes in the central zone of the room are more defined for *L*eq,10s than *L*i,Fmax. Whilst this indicates that the Fast time-weighting might influence the range of sound pressure levels in the central zone of the room, it is unlikely to affect the use of corner positions, and this is assessed in the next stage of the analysis.

For *L*eq,10s the mode shapes in the 31.5 Hz and 40 Hz bands correspond to the axial modes. At 50 Hz expected mode shapes at 55.3 Hz (*f*110) and/or 58.1 Hz (*f*001) were not observed. At 63 Hz, there were three possible modal responses 58.1 Hz (*f*001), 66.7 Hz (*f*101) and 69.6 Hz (*f*200), but the figure shows a response corresponding to the combination of *f*001 and *f*200 which only occurs around the halfway point between the ceiling and the base floor. At 80 Hz, the 69.6 Hz (*f*200)mode shape was clearly observed, but the modes at 72.5 Hz (*f*011), 80.3 Hz (*f*111), 81.9 Hz (*f*210) and 86.6 Hz (*f*020) were not evident. Above 80 Hz, the modal responses obtained from central and diagonal excitation differ.

For *L*i,Fmax the expected mode shape at 34.8 Hz (*f*100) was not observed in 31.5Hz band. At 40 Hz the expected mode shape at 43.3 Hz (*f*010) was clear. At 50 Hz mode shapes at 55.3 Hz (*f*110) and 58.1 Hz (*f*001) were not evident. At 63 Hz there are potentially modes at 58.1 Hz (*f*001), 66.7 Hz (*f*101) and 69.6 Hz (*f*200), but the figure shows a combination of *f*001 and *f*200 which only occurs at around the halfway between ceiling and floor. At 80 Hz the expected mode shape at 69.6 Hz (*f*200)was clear but mode shapes at 72.5 Hz (*f*011), 80.3 Hz (*f*011), 81.9 Hz (*f*011) and 86.6 Hz (*f*020) were not evident. In general, the differences in the sound field for *L*Fmax and *L*eq were not significant such that the Fast time-weighting and the use of a maximum level should not affect the use of corner measurements with the LFMP.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | 25 Hz | 31.5 Hz | 40 Hz | 50 Hz | 63 Hz |
| Central | グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, レーダー チャート, 等高線グラフ  自動的に生成された説明 | グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 |
| Diagonal | グラフ  自動的に生成された説明 | グラフ, レーダー チャート, 等高線グラフ  自動的に生成された説明 | グラフ, レーダー チャート  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 |
|  | 80 Hz | 100 Hz | 125 Hz | 160 Hz | 200 Hz |
| Central | グラフ  自動的に生成された説明 | グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ  自動的に生成された説明 | グラフ, レーダー チャート  自動的に生成された説明 |
| Diagonal | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, レーダー チャート  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, レーダー チャート  自動的に生成された説明 |

Figure 6 Visualised modal response of the room due to rubber ball excitation (*L*eq,10s).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | 25 Hz | 31.5 Hz | 40 Hz | 50 Hz | 63 Hz |
| Central | グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 |  | グラフ, 等高線グラフ  自動的に生成された説明 |  |
| Diagonal | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 |
|  | 80 Hz | 100 Hz | 125 Hz | 160 Hz | 200 Hz |
| Central |  | グラフ  自動的に生成された説明 | グラフ  自動的に生成された説明 | グラフ  自動的に生成された説明 |  |
| Diagonal | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 | グラフ, 等高線グラフ  自動的に生成された説明 |  |

Figure 7 Visualised modal response of the room due to rubber ball excitation (*L*i,Fmax).

# 3.1 Low-frequency measurement procedure

Although the LFMP is not intended for a large room volume such as this receiving room of 60 m3, it is still possible to assess its use because the experimental work here went down below the 50 Hz band. With the LFMP described in ISO 16283, a fixed microphone shall be positioned in room corners at a distance of 0.3 m to 0.4 m from each room boundary that forms the corner. Using the measurement grid, it is possible to assess different distances *d* = 0.1, 0.2, 0.3, 0.4 and 0.5 m – see Figure 8 (left). Using the measurement grid, the inner part and outer part of the room are defined as shown in Figure 8 (right). The red circles indicate the inner section and black circles the outer section.

ダイアグラム, 概略図

自動的に生成された説明ダイアグラム が含まれている画像

自動的に生成された説明

Figure 8. Corner microphone positions according to ISO 16283 (left) and grid points used to calculate the spatial average sound pressure level in the central zone in red (right).

The calculation of low-frequency energy-average impact sound pressure levels were calculated using Eq.4 and Eq. 5 according to ISO 16283-2

|  |  |
| --- | --- |
|  | (4) |
|  | (5) |

where indicates the highest mean-square sound pressure from corner measurements for excitation position *N* at 50, 63 and 80 Hz and *p*0 is the reference sound pressure (2E-5Pa).

Table 6 shows the mean, standard deviation, minimum and maximum of the total of 40 corner positions by considering five corner distances, *d* = 0.1, 0.2, 0.3, 0.4 and 0.5 m from the eight tetrahedral corners in the room. For the central excitation position, the standard deviation of the corner measurement was <1.9 dB from 25 Hz to 100 Hz. For the diagonal excitation position, the maximum difference was obtained at 25 Hz as 3.31dB. From 31.5Hz to 125Hz the difference was <3 dB. When assessing different distances, *d*, for façade sound insulation, Liu et al [10] concluded that a maximum distance *d*=0.3m was appropriate. However, in this experiment, the choice of distance from 0.1m to 0.5m is not critical.

Table 6. Statistical description of the corner positions (upper: centre, lower: diagonal excitations).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Freq | 25 Hz | 31.5 Hz | 40 Hz | 50 Hz | 63 Hz | 80 Hz | 100 Hz | 125 Hz |
| *µ* | 56.9 | 66.0 | 85.7 | 75.5 | 75.1 | 65.9 | 65.8 | 73.2 |
| *σ* | 1.9 | 1.6 | 0.5 | 1.7 | 0.9 | 1.3 | 1.5 | 3.0 |
| min | 54.0 | 63.5 | 84.6 | 72.8 | 73.2 | 62.6 | 63.1 | 66.7 |
| max | 59.5 | 69.0 | 86.8 | 78.4 | 76.7 | 68.6 | 68.2 | 76.8 |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Freq | 25 Hz | 31.5 Hz | 40 Hz | 50 Hz | 63 Hz | 80 Hz | 100 Hz | 125 Hz |
| *µ* | 53.5 | 68.4 | 83.7 | 73.1 | 75.0 | 71.1 | 78.6 | 72.4 |
| *σ* | 3.3 | 0.9 | 0.5 | 1.3 | 1.0 | 2.3 | 1.6 | 2.9 |
| min | 46.5 | 67.0 | 82.5 | 71.2 | 72.2 | 66.6 | 74.3 | 65.1 |
| max | 57.8 | 70.2 | 84.6 | 75.6 | 77.0 | 74.5 | 81.1 | 77.5 |

Figure 9 shows the measurement results grid measurement results due to the central excitation (left) and diagonal excitation position (right). ‘All’ indicates the energetic average of 693 grid microphone positions, and central is the energetic average of 108 microphone positions in the central region away from the room boundaries. There is a peak in the 40 Hz band where *f*010 is expected at 43.3 Hz. For the central excitation position in Figure 9 (left) the use of the central region measurement with LFMP reduced the difference in *L*i,Fmax from all microphone positions to 0.1dB and 0.8dB but at 50 and 63 Hz respectively but increased it to 2.5 dB at 80 Hz. For the diagonal excitation position in Figure 9 (right) the use of the central region measurement with LFMP reduced the difference in *L*i,Fmax from all microphone positions to 0.9 dB and 1.7 dB at 50 and 63 Hz respectively but it was not reduced at 80 Hz and was 3.3 dB.

Figure 10 shows the energetic average of both central and diagonal excitations. At the 50 Hz, 63 Hz and 80 Hz band, the use of the central region measurement with LFMP reduced the difference in *L*i,Fmax from all microphone positions to 0.3 dB and 1.2 dB at 50 and 63 Hz respectively but at 80 Hz the difference was 3.2 dB. Although only two excitation positions were used and the room volume was 60 m3 the results indicate that the LFMP could also be used for field measurements of heavyweight floor impact sound insulation.

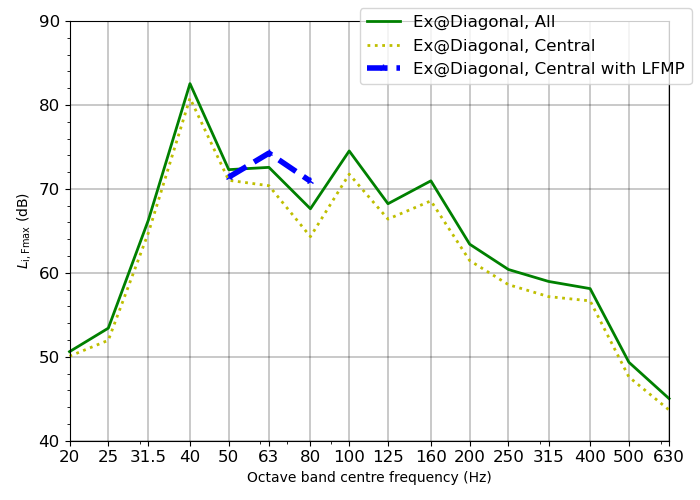
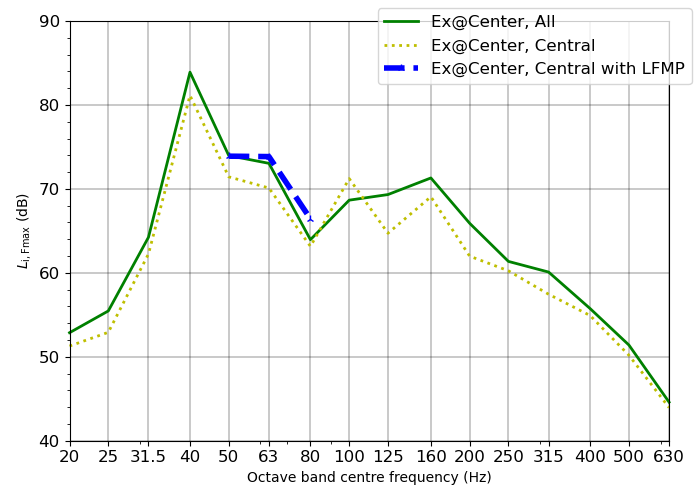


Figure 9 Grid measurement result due to the central excitation position (left) and the diagonal excitation position (right).

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Figure 10 Grid measurement result in combination of central and diagonal excitation positions.

# 4. Conclusions

This paper assessed the use of the LFMP with a rubber ball source through measurements of *L*i,Fmax and *L*eq. Grid measurements were used to visualise the sound field in the room using two different excitation positions for the rubber ball. In general, there were no significant differences in the modal sound field for *L*Fmax and *L*eq which indicates the potential to use the LFMP. In this particular experimental set-up the receiving room volume was 60 m3 but when the LFMP approach was used with *L*i,Fmax, the results showed closer agreement with the room average sound pressure level at 50 Hz and 63 Hz. Future work should evaluate the low-frequency procedure with different room volumes, floor constructions and more excitation positions.

# 5. Acknowledgement

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