This paper compares and assesses field measurement procedures from Japan, South Korea and ISO 16283-2 for $L_{p,F_{\text{max}}}$ that are used to determine impact sound insulation with heavy impact sources. In Japan, the recommended microphone positions start from the 0.6m height central position with five positions chosen in a spiral pattern in the room by adding 0.3m height to each subsequent position. In South Korea, it is common to use five microphone positions; 0.75m from each wall (4 corner positions) and a central position at the height of 1.2m. In the ISO standard, random microphone positions are used with prescribed distances from room boundaries and a low-frequency procedure is proposed for tapping machine excitation. The three approaches also require different excitation positions. To assess the implications of these different approaches, numerical modelling is carried out using Finite Element Methods (FEM) to predict $L_{p,F_{\text{max}}}$ in the receiving room. The spatial variation of $L_{p,F_{\text{max}}}$ in the rooms was up to 28dB which is similar to that observed in airborne sound insulation measurements using steady-state signals with $L_{eq}$. The choice of measurement positions in the I-INCE-J and MOCT-K procedures seem difficult to justify because (a) the use of a central position (P1) in the room tends to cause the spatial-average $L_{p,F_{\text{max}}}$ to underestimate the room average $L_{p,F_{\text{max}}}$ and (b) the MOCT-K procedure uses a microphone height that tends to coincide with low values of $L_{p,F_{\text{max}}}$ in the room. An alternative approach to the I-INCE-J and MOCT-K procedures was investigated which was based on the low-frequency procedure in ISO 16283-2 that is currently used for the ISO tapping machine. It is shown that this could avoid the underestimation problems with the I-INCE-J and MOCT-K procedures.

**Keywords:** impact sound insulation, measurement procedures, FEM, rubber ball

### 1. Introduction

The assessment of impact sound insulation due to heavy impacts (e.g. ISO rubber ball) on floors in heavyweight buildings is described in International, Japanese and Korean standards [1,2,3]. These three approaches all require measurement of the Fast time-weighted maximum sound pressure level, $L_{p,F_{\text{max}}}$ in the room underneath the excited floor. However, the three approaches differ in their requirements for the excitation and measurement positions.

With heavy impact sources it tends to be the low-frequency range that is of particular interest. For field measurements in typical residential rooms the diffuse field condition assumption used in laboratory measurements is not valid in the low frequency where individual room modes tend to dominate the response. This issue has been addressed for field measurements of airborne sound insulation and
impact sound insulation using the ISO tapping machine by using corner measurements to give an estimate of the room average level and improve the repeatability and reproducibility [4,5]. There have also been studies on the spatial variation in the sound pressure level with the impact ball and bang machine [6,7,8]. In Japan and Korea, field measurements are conducted according to JIS 1418-2 or KS 2810-2 respectively although there are additional national guidelines for excitation and measurement positions. In Japan, the sub-committee of the floor impact sound research group of I-INCE-JAPAN (I-INCE-J) have produced recommendations for excitation and measurement positions [9]. In South Korea, the Ministry of Construction Transportation (MOCT-K) issued a notice for the excitation and measurement positions [10]. Both I-INCE-J and MOCT-K procedures use corner measurements to give better estimates of the room average level.

For field measurements, this paper investigates the difference in the spatial average \( L_{p,F_{\text{max}}} \) from the three different measurement procedures using Finite Element Methods (FEM). The FEM model was validated in an accompanying paper [11]. In the current paper, numerical experiments with FEM are used to assess the rubber ball impacting a 140mm concrete floor in four box-shape rooms with different volumes (50, 37.5, 25 and 15 m\(^3\)) and a frequency-independent reverberation time of 1.5s.

The room responses are considered as follows. Firstly, the sound field in terms of \( L_{p,F_{\text{max}}} \) is visualised in order to give insights into the room response with different room dimensions. Secondly, a grid with finer detail is used to assess the variation of \( L_{p,F_{\text{max}}} \) in the vertical direction at the measurement positions according to Japanese and Korean guidelines. Thirdly, the spatial average \( L_{p,F_{\text{max}}} \) obtained from three measurement procedures is compared against the room average \( L_{p,F_{\text{max}}} \) for four different rooms.

2. Theory and models

All the modelling in this paper concerns a receiving room underneath a concrete floor which is excited by a rubber ball drop (1m height).

2.1 Measurement procedures

Figure 1. I-INCE-J and MOCK-K procedures: (Left) excitation positions on the concrete slab and (Right) measurement positions in the room.

For field measurements, the default measurement procedure in the International standard ISO 16283-2 requires a minimum of four random excitation positions, and a minimum of four microphone positions that are uniformly distributed within the maximum permitted space throughout the room. There should be at least 0.7m between (a) microphone positions, (b) at least 0.5m between any microphone position and room boundaries, and (c) 1m between any microphone position and the floor being excited by the impact source. The low-frequency procedure for the 50, 63 and 80Hz one-third octave bands also measures the sound pressure level in corner positions and uses a weighted energy average to give an estimate of the room average sound pressure level.
Figure 1 summarises the excitation and measurement positions used in I-INCE-J and MOCT-K. The I-INCE-J and MOCT-K procedures implement the requirements of JIS 1418-2 and KS F 2810-2 with at least 0.7m between microphone positions, and 0.5m from any room boundaries.

I-INCE-J requires five excitation positions: one central and four corner positions located one-quarter of the way along both room diagonals from the corner; these are referred to as JP ExP1 to ExP5 – see Fig. 1. The five microphone positions are directly underneath the excitation positions, JP P1 to P5, where the central position (P1) is at 0.6m height and the four corner positions (P2 to P5) increase in height in a spiral pattern around the room by adding 0.3m height to each subsequent position.

MOCT-K requires five excitation positions: one central and four corner positions that are 0.75m from each wall; these are referred to as KR ExP1 to ExP5 – see Fig. 1. The five microphone positions (P1 to P5) are directly underneath the excitation position at a height of 1.2m from the ground.

### 2.2 Numerical experiments

Four models are created that consider the ISO rubber ball impacting a 140mm concrete base floor with four box-shape rooms with different volumes (50, 37.5, 25 and 15m³) and different reverberation time of 1.5s. The model parameters are summarised in Tables 1, 2 and 3.

#### Table 1: Material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus (N/m²)</th>
<th>Poisson’s Ratio</th>
<th>Density (kg/m³)</th>
<th>Rayleigh Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber (Ball)</td>
<td>3.4×10⁶</td>
<td>0.48</td>
<td>1188</td>
<td>N/A</td>
</tr>
<tr>
<td>Concrete (Floor)</td>
<td>31×10⁹</td>
<td>0.16</td>
<td>2200</td>
<td>α=14.5489 β=3.55×10⁻⁶</td>
</tr>
<tr>
<td>Air (Room)</td>
<td></td>
<td></td>
<td>1.21</td>
<td>142355</td>
</tr>
</tbody>
</table>

#### Table 2. Dimensions of the concrete base slab and the room, critical and fundamental frequencies.

<table>
<thead>
<tr>
<th>Model</th>
<th>Lₓ(m)</th>
<th>Lᵧ(m)</th>
<th>Lₜ(m)</th>
<th>h(m)</th>
<th>Plate critical frequency (Hz)</th>
<th>Fundamental plate mode, f₁₁ (Hz)</th>
<th>Vertical axial room mode, f₀₀₁ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>4</td>
<td>2.5</td>
<td>0.14</td>
<td>121.8</td>
<td>24.7</td>
<td>68.6</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>3</td>
<td>2.5</td>
<td>0.14</td>
<td></td>
<td>36.5</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>2</td>
<td>2.5</td>
<td>0.14</td>
<td></td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>2</td>
<td>2.5</td>
<td>0.14</td>
<td></td>
<td>87.18</td>
<td></td>
</tr>
</tbody>
</table>

#### Table 3: Acoustic impedances used for all room surfaces to simulate different reverberation times.

<table>
<thead>
<tr>
<th>Sabine RT (s)</th>
<th>Acoustic impedance (Ns/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>Model A 52550 Model B 57703 Model C 68006.5 Model D 76249.7</td>
</tr>
</tbody>
</table>

### 2.3 Finite element method – Modelling detail

FEM analysis is used to obtain the time-domain contact force at the contact point and sound pressure in the room below excitation. The time domain response is then used to calculate and \( L_{p,F_{\text{max}}} \) [12].

Gravity was assigned as the initial condition on the rubber ball to simulate the free fall of the rubber ball from 1m height onto the concrete floor. The general ‘Hard’ contact relationship was used for the rubber ball and the concrete floor. The concrete floor has pinned boundaries around its perimeter. The constraint between the concrete floor and the room below excitation was created using ABAQUS ‘tie’ constraints. The acoustic impedance associated with the Sabine reverberation time shown in Table 3 was assigned as the boundary condition for all six room surfaces. The total loss factor of the floor was modelled with Rayleigh damping.

The acoustic medium uses the element AC3D8R. The rubber ball and concrete slab are created using the thin shell triangular mesh element S3R [13]. Suitable element sizes are usually between
\( \lambda_B/3 \) and \( \lambda_B/6 \) [14]. Therefore, the mesh element size is 0.1m for the room and the concrete floor, and 0.01m for the rubber ball which corresponds to \( \lambda_B/12, \lambda/5, \) and \( \lambda_B/8 \) for the concrete floor, the room and rubber ball at 708Hz (this corresponds to the upper band edge of the 500Hz octave band).

3. Results

3.1 Room response

Figure 2 shows the sound pressure field in terms of \( L_{p,F_{\text{max}}} \) with rubber ball excitation at the central position of the concrete slab for four different models.

For Models A, B and C which all have the longest room dimension being 5m, the lowest room mode is \( f_{100} \) (34.3Hz) but this is not excited by the fundamental plate mode; hence in the 31.5Hz octave band the sound field appears to be determined by the direct field radiated by the fundamental plate mode. In the 63Hz octave band, the \( f_{001} \) vertical axial mode (68.6Hz) and the \( f_{200} \) horizontal axial mode (68.6Hz) occur at the same frequency in the 63Hz band and are both excited by the fundamental plate mode. For Model A, the response appears to be a combination of \( f_{001} \) and \( f_{200} \). For Models B and C, the \( f_{001} \) mode is evident. For Model D, \( f_{001} \) (68.6Hz) occurs in the 63Hz band and \( f_{200} \) (114.3Hz), \( f_{201} \) (133.3Hz) and \( f_{002} \) (137.2Hz) occur in the 125Hz band; this results in the spatial variation in the 63Hz band being clearly attributed to the \( f_{001} \) mode. In the 125Hz band, there is evidence of the \( f_{201} \) tangential room mode (97Hz) in Model A. For Models B, C and D it is difficult to identify this mode.

The highest spatial variation of \( L_{p,F_{\text{max}}} \) is between 6 and 30dB; the former occurs with the Model D room at 31.5Hz and the latter occurs with the Model C room at 63Hz. Measurements in a 62m\(^3\) room by Yoo et al indicate a maximum difference of \( \approx 16\)dB at 31.5Hz and 63Hz [8]. Note that for airborne sound insulation measurements with broadband noise sources using \( L_{\text{eq}} \), measured data suggest this difference will be between 17 and 28 dB for typical rooms in the low-frequency range [14].

3.2 I-INCE-J and MOCT-K microphone positions

Figure 3 shows the average \( L_{p,F_{\text{max}}} \) from five excitation positions in the vertical lines for the I-INCE-J and MOCT-K microphone positions which are directly underneath the excitation positions. This average \( L_{p,F_{\text{max}}} \) value is normalised to the highest value in the vertical line. Because of the symmetry that exists for the box-shaped room in these numerical experiments, Figure 3 only shows the results for the 31.5 to 125Hz octave bands from microphone positions KR P1, JP P1, KR P2 and JP P2. Note that the values on Figure 3 are not directly comparable with those in Figure 2 because the latter only considers one excitation position.

In general, the largest variations tend to occur for JP P1 and KR P1 but they occur in different frequency bands and at different heights. For Model A, the lowest value was -15dB which occurred at 125Hz at a height of 1.2m. For Model B, the lowest value was -15dB which occurred at 31.5Hz at a height of 0.6m. For Model C, the lowest value of -28dB occurred at 63Hz at a height of 1.1m and 1.5m. For Model D, the lowest value of -22dB occurred at 63Hz at a height of 1.2m.

It is not clear why the inclusion of P1 in the I-INCE-J and MOCT-K procedures is chosen because it is not representative of the central zone and it tends to give lower values than P2, P3, P4 and P5 (i.e. corner positions). In addition, it is unusual to have an excitation position at the centre of the floor with the receiver position at the centre point in the room. For this reason the next section assesses whether the spatial average \( L_{p,F_{\text{max}}} \) which is determined from INCE-J and MOCT-K microphone positions gives a reasonable estimate of the room average \( L_{p,F_{\text{max}}} \).
<table>
<thead>
<tr>
<th></th>
<th>31.5Hz</th>
<th>63Hz</th>
<th>125Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A (50m³)</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Model B (37.5m³)</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>Model C (25m³)</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>Model D (15m³)</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 2. Sound pressure field in terms of $L_{p,F_{\text{max}}}$ (dB re the highest level in the room) for four different room models in the 31.5, 63 and 125Hz octave bands.

### 3.3 Comparison of I-INCE J, MOCT-K and ISO measurement procedures with the room average

The spatial-average $L_{p,F_{\text{max}}}$ in Figure 4 has been calculated using the following approaches:

1. Room average: calculated from all points except those points on the boundaries,
2. Central region: energy average of all points in the central region that are ≥0.5m from the boundaries (ISO 16283-2 default procedure),
3. I-INCE-J procedure,
4. MOCT-K procedure,
5. Weighted energy average using highest corner level: the weighted energy average of the central region that is ≥0.5m from the boundaries and the highest of the eight corner positions that are 0.3m from each surface forming the corner (similar to the ISO 16283-2 low-frequency procedure),
(6) Weighted energy average using all eight corner levels: the weighted energy average of the central region that is ≥0.5m from the boundaries and the energy average of the eight corner positions that are 0.3m from each surface forming the corner (similar to the ISO 16283-2 low-frequency procedure).

Figure 3. Spatial variation of normalised $L_{P,F_{\text{max}}}$ in the vertical direction. The black vertical line indicates the 1.2m height for MOCT-K and the green vertical lines indicate the heights for I-INCE-J.
Figure 4. Spatial-average $L_{p,Fmax}$ from the room average and different measurement procedures.

Ideally, an appropriate averaging procedure should represent the room average. For Models A, B, C and D, the central region always underestimates the room average, and this was the reason that the I-INCE-J, MOCT-K and ISO 16283-2 procedures were developed.

For Models C and D, I-INCE-J gives closer agreement with the room average than MOCT-K. For Models A, B, C and D, the MOCT-K procedure tends to underestimate the room average because of the use of 1.2m height that coincides with nodal regions of room modes (see section 3.1 and 3.2). Measurements in a 62m³ room from Yoo et al [8] indicated that I-INCE-J and MOCT-K procedures produce underestimates, but that these were most significant with the MOCT-K procedure at 63Hz which is consistent with the findings in the current paper.

Use of procedure (5) which is closest (but not identical) to the low-frequency procedure in ISO 16283-2 tends to overestimate the room average in the 31.5, 63 and 125Hz bands for Models A, B, C and D.

Use of procedure (6) which is close (but not identical) to the low-frequency procedure in ISO 16283-2 tends to give the closest agreement with the room average. This indicates the potential for a method that is similar to the ISO 16283-2 low-frequency procedure to avoid the underestimation problems with I-INCE-J and MOCT-K.

4. Conclusions

This paper has investigated the measurement positions that are used to determine the spatial-average $L_{p,Fmax}$. Numerical experiments using FEM have been carried out with the ISO rubber ball impacting a 140mm concrete floor with room volumes of 50, 37.5, 25 and 15 m³.
The spatial variation of $L_{p,F_{\text{max}}}$ in the rooms was up to 28dB which is similar to that observed in airborne sound insulation measurements using steady-state signals with $L_{eq}$.

The choice of measurement positions in the I-INCE-J and MOCT-K procedures seem difficult to justify because (a) the use of a central position (P1) in the room tends to cause the spatial-average $L_{p,F_{\text{max}}}$ to underestimate the room average $L_{p,F_{\text{max}}}$ and (b) the MOCT-K procedure uses a microphone height that tends to coincide with low values of $L_{p,F_{\text{max}}}$ in the room.

An alternative approach to the I-INCE-J and MOCT-K procedures was investigated that was based on the low-frequency procedure in ISO 16283-2 that is currently used for the ISO tapping machine. It was shown that this could avoid the underestimation problems with I-INCE-J and MOCT-K.

ACKNOWLEDGEMENT

This research was supported by a grant (16RERP-B082204-05) from the Residential Environment Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

REFERENCES


