Findings from the AkuLite project: Correlation between measured vibro-acoustic parameters and subjective perception in lightweight buildings

Fredrik Ljunggren\textsuperscript{1}, Christian Simmons\textsuperscript{2} and Klas Hagberg\textsuperscript{3}

\textsuperscript{1} Luleå University of Technology, Sweden
\textsuperscript{2} Simmons akustik och utveckling, Gothenburg, Sweden
\textsuperscript{3} WSP, Gothenburg, Sweden

ABSTRACT

Various research aspects on sound and vibrations in lightweight buildings are covered by the Swedish research programme AkuLite. One of the most important topics has been to find out to what extent objective measured parameters correlate with subjective opinions from people living in multifamily houses. Typical questions to be pointed out are: Do existing ratings like $R'\nu (+C_{50,1350})$ and $L'_{n,w} (+C_{L,50,2500})$ correlate well enough to the tenants’ perception? Can other measureable parameters be found that show better agreement? Are the often used frequency limits of 100Hz or 50Hz low enough? Can any significant differences be seen when comparing lightweight buildings with concrete buildings?

Extensive sound and vibration measurements have been performed in numerous buildings of varying construction including lightweight timber or steel based framing, cross laminated timber and concrete. In general frequencies from 20 Hz have been covered.

Questionnaires have been distributed to the tenants where they were asked to give their opinion on a number of adequate questions related to sound and/or vibration perception. The results from the measurements and from the questionnaires have then been compiled, followed by a comprehensive statistical analysis in order to see the degree of correlation between them.

Keywords: Sound insulation, Impact sound, Perception

1. INTRODUCTION

Lightweight buildings with wooden or thin steel gauge frame construction are nowadays often a competitive alternative to concrete constructions when multi-family houses are concerned. The popularity of lightweight constructions has increased in many countries during the last decades and the technique got a renaissance in Sweden when the authorities in 1994 gave permission for wooden houses higher than two stories.

As the total number of lightweight multi-family houses has increased ever since, it has been observed, with a continuously increased experience, that today’s legal framework regarding sound

\textsuperscript{1} fredrik.ljunggren@ltu.se
\textsuperscript{2} info@simmons.se
\textsuperscript{3} klas.hagberg@WSPGroup.se
insulation is not fully applicable to lightweight constructions [1]. The often used, and in Sweden mandatory, single number ratings $R'_{w} + C_{1,50-2500}$ and $L'_{n,w} + C_{1,50-2500}$ for airborne and impact sound insulation respectively, are not always consistent in their relation to residents’ perception. When two building objects of identical single number ratings are compared, one made of concrete and one of lightweight technique, the residents of the concrete building are prone to be more satisfied with the sound insulation performance compared to the lightweight building. Such a sound insulation evaluation procedure is for given reason unwanted and refined methods are therefore needed.

In the Swedish research project AkuLite, researchers worked together with the national building industry for more than three years. The project covered various aspects regarding lightweight building technique but a main issue was to study whether other measurable objective parameters than the ones that exist today could be found that show better correlation to subjective perception among tenants.

2. FIELD MEASUREMENTS

2.1 Objects

Ten building objects according to Table 1 were used in the study. Five of them are categorized as being traditional lightweight (four with timber and one with thin gauge steel), four are based upon cross laminated timber and one is made of concrete. The buildings were located all over Sweden and all of them represent “modern buildings”.

Table 1 – Building objects

<table>
<thead>
<tr>
<th>No</th>
<th>City</th>
<th>Construction</th>
<th>New building</th>
<th>Existing building</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Upplands Väsby</td>
<td>Wood</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Östervåla</td>
<td>CLT</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Umeå</td>
<td>Concrete</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>Växjö</td>
<td>CLT</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Växjö</td>
<td>CLT</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Falun</td>
<td>CLT</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Alingsås</td>
<td>Wood</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Lindesberg</td>
<td>Wood</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Örebro</td>
<td>Thin Steel</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Varberg</td>
<td>Wood</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Measurement procedure

A special measurement template was developed within AkuLite. It contains numerous sound- and vibration measurements where low frequencies are subject to extra attention. The essentials of the template are given below while a more comprehensive description can be found in [2]. General measurements were applied in all measured rooms, two to ten per object, while additional measurements were performed in one of these rooms.

General measurements:
- Impact sound insulation, tapping machine, 20-50 Hz
- Airborne sound insulation, 20-50 Hz
- Impulse sound, Japanese ball in sending room, measurements in receiving room, 20-500 Hz
- Impulse vibrations, Japanese ball and measurements in the same room

Additional measurements:
- Flanking vibrations over junctions, Japanese ball: 1-500 Hz, tapping machine: 10-3150 Hz
- Attenuation of floor vibrations, Japanese ball: 1-500 Hz, tapping machine: 10-3150 Hz
- Wall responses, impact hammer, 1-500 Hz
- Static deflection of the floor
2.3 Selected results

A lot of interesting data have been extracted from the extensive measurements [3]. A selection of results is presented here.

In Figure 1 the outcome of the airborne sound insulation measurements are shown in terms of R’w, R’w+C50-3150, R’w+C20-3150 and the summed low frequency reduction from 20 to 100 Hz, R’20-100. All values represent the mean value from each object respectively. It is noticed that when C50-3150 is added to R’w there is a significant drop in sound reduction for practically all the objects. When the frequency range is further extended down to 20 Hz, the sound reduction remains the same indicating that these low frequencies do not contribute to the weighted single number rating. When the frequencies 20-100 Hz are studied separately, it can be seen that the concrete object (No 3) has the highest insulation.

Figure 1 – Airborne sound insulation of 10 building objects, a) R’w, b) R’w+C50-3150, c) R’w+C20-3150 and d) R’20-100. The sound classes according to the Swedish standard are indicated in b).

In Figure 2 the corresponding impact sound pressure values are presented, i.e. L’n,w, L’n,w+C50-2500, L’n,w+C1,20-2500 and the summed low frequency level from 20 to 100 Hz, L’20-100. Note that the values are evaluated according to Swedish standard [4] meaning that the volume of the receiving room is restricted to 31 m³. Is it seen that the impact sound level increases for most of the object as C50-2500 is added to L’n,w but the increase is even more significant as lower frequencies are included, L’n,w+C1,20-2500. This indicates that frequencies below 50 Hz are of importance concerning impact sound in lightweight buildings. When the frequencies 20-100 Hz are studied separately, the concrete object (No 3) again obtains the best result, i.e. the lowest impact sound level.
3. QUESTIONNAIRE

3.1 Objects

The questionnaires involve the same objects as described above. The questionnaire was distributed to all households within each object. The answering rate was 33-80%.

3.2 Questionnaire

The used questionnaire “Are you disturbed by noise in your house” according to Figure 3 was originally developed within the European network COST TU 0901. The work has previously been described [5] and the questionnaire has also been used within a related project [6]. The document contains 15 questions formulated in a way to easily be understood by non-acousticians. The questions deal with airborne sound through walls and floors, music of low frequencies, footstep noise, sound from staircases and balconies, traffic noise, sound from installations, etc. The tenants are instructed to judge to what extent they are bothered, disturbed or annoyed on an 11-point scale ranging from 0 to 10, where “0” means not at all and “10” means extremely.

3.3 Selected results

One of the questions asked was about the overall sound annoyance from various sources. This rating should be relatively high since it, in a way, acts as a summation of annoyance from individual sources. The mean overall annoyance varied among the objects from 0.6 to 4.0, see Figure 4. The individual source that led to the highest annoyance was, by margin, the impact sound where several objects obtained annoyance around 4 or higher. The question that gave the second highest annoyance was the one about low frequent sound. Annoyance from airborne sound was rated relatively low with mean value from 0.1 to 3.0.
**Instructions:**

Choose an answer on the 0-to-10 scale for how much noise bothers, disturbs or annoys you when you are in your house.

<table>
<thead>
<tr>
<th>if you hear a small amount of noise AND you are not at all disturbed by it, choose 0</th>
<th>if you are extremely bothered, disturbed or annoyed by it, choose 10</th>
<th>if you are somewhere in between, choose a number from 1 to 9</th>
<th>if you do not hear anything at all, the source does not exist or if you cannot answer, choose “Don’t know”</th>
</tr>
</thead>
</table>

**Thinking about the last 12 months in your house, how much are you bothered, disturbed or annoyed by noise in general e.g. from neighbours, technical installations**

1. Noise in general e.g. from neighbours, technical installations

**Thinking about the last 12 months in your house, how much are you bothered, disturbed or annoyed by these sources of noise?**

2. Neighbours; daily living, e.g. people talking, audio, TV through the walls (what is heard)

3. Neighbours; daily living, e.g. people talking, audio, TV through the floors / ceilings

4. Neighbours; Music with bass and drums

5. Neighbours; footstep noise, i.e. you hear when they walk on the floor

6. Neighbours; rattling or tinkling noise from your own furniture when the neighbours move on the floor above you

7. Staircases; access balconies etc; people talking, doors being closed

8. Staircases; access balconies etc; footsteps or other impact sounds

9. Water installations; plumbing, using or flushing WC, shower

10. Climate installations; heaters, air condition, air terminal devices

11. Service installations; elevators, laundry machinery, ventilation machinery

12. Premises; garages, shops, offices, pubs, restaurants, laundry rooms or other, heard indoors with windows closed

13. Traffic (cars, buses, trucks, trains or aircraft), heard indoors with windows closed

14. Own family; heard within your dwelling with doors closed

**Before moving to the apartment, how important was the sound insulation to you, with respect to noise in general e.g. from neighbours, technical installations**

**Are you tolerant or sensitive with respect to noise in general e.g. from neighbours, technical installations**

**Comments (describe important sources of noise, type of premises, neighbour activities etcetera):**

---

Figure 3 – Questionnaire
4. CORRELATIONS

4.1 Results

The next step is to correlate the field measurements with the questionnaire results. In Table 2, the degree of explanation, R², is shown for several linear regression analysis related to perceived vs. measured airborne and impact sound insulation.

Table 2 – Correlation for airborne and impact sound

<table>
<thead>
<tr>
<th>Airborne sound</th>
<th>R² (%)</th>
<th>Impact sound</th>
<th>R² (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R'₢ₜ</td>
<td>4</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>R'₢ₜ+C₅₀-₃₁₅₀</td>
<td>9</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>R'₢ₜ+C₂₀-₃₁₅₀</td>
<td>9</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>Jap. Ball corner</td>
<td>19</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Jap. Ball corner A</td>
<td>18</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>*) Two outliers removed</td>
<td></td>
<td></td>
<td>43</td>
</tr>
</tbody>
</table>

Concerning the airborne sound insulation, there are two outliers that strongly affect the result. Both objects (No 2 and 9) are not regarded as being representative for ordinary family activities and therefore parallel analyses were performed with and without them. The degree of explanation when the judged annoyance was correlated to the measured R'₢ₜ is 58% with the two outliers omitted. When the spectrum adaptation term C₅₀-₃₁₅₀ is added, R² increases to 73% and when C₂₀-₃₁₅₀ is added, R²
becomes 75%. When using the Japanese ball as the source, using a single microphone position in an arbitrarily chosen corner of the receiving room, \( R^2 \) becomes 11% and 47% using linear and A-weighted sound level respectively.

When the annoyance from perceived impact sound is correlated with the measured normalized impact sound level, \( L'_{n,w} \), the degree of explanation is only 26% which increases to 32% when the spectrum adaptation term \( C_{I,50-2500} \) is added. When considering frequencies down to 20 Hz, i.e. \( L'_{n,w} + C_{I,20-2500} \), \( R^2 \) improves significantly to 74%. In an attempt to further increase the degree of explanation, an alternative spectrum adaptation term with strengthened impact to the lowest frequencies (see sec. 4.2) was evaluated. Using this new spectrum term, \( C_{I,AkuLite,20-2500} \), 85% \( R^2 \) is achieved, see Figure 5.

\[ C_{I,50-2500} = \sum_{i} 10^{L'_ni} - 15 - L'_{n,w} \]  

4.2 New suggested spectrum adaptation term

The present spectrum term \( C_{I,50-2500} \) of ISO 717-2 is calculated according to Eq. 1 [7]. In practice it means that a uniform weighting of 15 dB is applied to all frequencies. The extended term \( C_{I,20-2500} \) is handled in exactly the same way besides that the frequency rage now begins at 20 Hz.

\[ C_{I,AkuLite,20-2500} = \sum_{i} 10^{(L'_ni-FWC_i)} - L'_{n,w} \]  

<table>
<thead>
<tr>
<th>( f ) (Hz)</th>
<th>20</th>
<th>25</th>
<th>31.5</th>
<th>40</th>
<th>50-400</th>
<th>500</th>
<th>630</th>
<th>800</th>
<th>1000</th>
<th>1250</th>
<th>1600</th>
<th>2000</th>
<th>2500</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWC (dB)</td>
<td>-7</td>
<td>-9</td>
<td>-11</td>
<td>-13</td>
<td>-15</td>
<td>-14</td>
<td>-13</td>
<td>-12</td>
<td>-11</td>
<td>-10</td>
<td>-9</td>
<td>-8</td>
<td>-7</td>
</tr>
</tbody>
</table>

Figure 5 – Regression line, including 95% confidence intervals.
5. DISCUSSION AND CONCLUSIONS

R’w+C50-3150 showed good correlation when subjectively rating of annoyance from airborne sound was compared to various objective measurements. The correlation was higher than for R’w alone but practically unaffected of a further extended frequency range, i.e. R’w+C20-3150. Thus, the present method seems to work well given that frequencies down to 50 Hz are considered. The study does not support any further extension towards even lower frequencies.

Considering the impact sound, both L’n,w and L’n,w+C1,50-2500 indicated poor correlation to subjective perception of impact sound. When frequencies down to 20 Hz was included, a significant improvement was achieved using L’n,w+C1,20-2500. The highest correlation was obtained by a modified CI-term with even more emphasis to the lowest frequencies, L’n,w+C1,AkuLite,20-2500.

However, it must be stressed that the results are based upon ten buildings objects which is too few in order to get any statistically significant differences among the evaluated measurement parameters’ correlation to subjective annoyance. In addition, the measurements were taken only between strictly limited numbers of rooms for some objects, mainly due to practical difficulties when entering inhabited buildings. The findings about the impact sound though, is in accordance with an independent listening test [9] and further research about the lowest frequencies significance in this context is needed.

ACKNOWLEDGEMENTS

The reported work is a result of the Swedish research project AkuLite funded by Vinnova, Formas and the national building industry.

REFERENCES