Prediction method adapted to lightweight constructions
and related laboratory characterizations

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When wood or steel frame lightweight constructions are considered, both the standardized methods for predicting building performances from the performances of building elements (EN 12354-1 and -2) and the related standardized laboratory measurement methods for characterizing building elements and their junctions have to be rethought. In this paper, a prediction method adapted to lightweight constructions is presented and applied to a two storey four room structure. The laboratory methods used to estimate the different input parameters (sound reduction index, impact sound level, radiation efficiency and loss factor of building elements as well as vibration reduction index of junctions between elements) have also been adapted to correctly characterize lightweight constructions. Comparisons between results expressed in terms of airborne and impact sound insulation between rooms, either directly measured or calculated using the prediction method are given in the three cases of vertical, horizontal and diagonal transmission; a rather satisfying agreement between calculated and measured results is obtained.

1 Introduction

When wood or steel frame lightweight constructions are considered, both the standardized methods, EN 12354-1 and -2, for predicting building performances from the performances of building elements and the related standardized laboratory measurement methods for characterizing building elements and their junctions have to be rethought. In this paper, a prediction method adapted to lightweight constructions is briefly presented (Section 2) and applied to a two storey four room building (Section 4) where the analysis of the different transmission paths were required in order to understand and improve the acoustic performances of the building. The laboratory methods, used to estimate the different input parameters of the prediction method (sound reduction index, impact sound level, radiation efficiency and loss factor of building elements as well as vibration reduction index of junctions between elements) differ also from the existing standards and are presented in Section 3.

The results presented in this paper are part of the Acousvibra European project (High Quality Acoustic and Vibration Performance of Lightweight Steel Constructions) launched at the end of 2003 [1].

2 Prediction method

European Standard EN 12354 is based on a first order Statistical Energy Analysis (SEA) but also differs from classical SEA since it only uses building acoustics quantities for which laboratory measurement standards (or draft standards) exist, such as the sound reduction index R or the loss factor of a building element, or the vibration reduction index \( K_{ij} \) of a junction between elements. When applied to lightweight constructions, the European model has to be modified [2] and a new quantity appears: the radiation efficiency, which value depends on the way the element is excited (airborne or mechanical excitation).

For airborne excitation, a flanking sound reduction index can then be estimated, using the following simple unidirectional equation:

\[
R_{ij} = R_i + D_{lij} + 10 \log \left( \frac{\sigma_{ai}}{\sigma_{rj}} \right) + 10 \log \left( \frac{S_j}{S_i} \right)
\]

where
- \( R_i \) is the sound reduction index of element i,
- \( D_{lij} \) is the vibration level difference between elements i and j when element i is mechanically excited,
- \( \sigma_{ai} \) is the radiation efficiency of element i with airborne excitation and \( \sigma_{rj} \) is the radiation efficiency of element j with mechanical excitation
- \( S_j \) is the surface area of the separating element

For mechanical excitation (tapping machine), a flanking impact sound level can also be estimated using the following simple unidirectional equation:

\[
L_{ij} = L_{nd} - D_{lij} + 10 \log \left( \frac{\sigma_{ai}}{\sigma_{rj}} \right) + 10 \log \left( \frac{S_j}{S_i} \right)
\]

where \( L_{nd} \) is the direct normalized impact sound level of the floor (element i), without suspended ceiling.

The presence of a suspended ceiling or a floating floor can be taken into account by considering their associated acoustic performance with respect to airborne or impact excitation in Equations (1) and (2).
The standardized airborne sound insulation $D_{nTij}$ corresponding to the flanking path in Equation (1) is then

$$D_{nTij} = R_{ij} + 10\log(0.32V/S_S)$$  \hspace{1cm} (3)

with $V$ representing the volume of the reception room; and the standardized impact sound insulation $L_{nTij}$ corresponding to the flanking path in Equation (2) is

$$L_{nTij} = L_{nj} - 10\log(0.032V)$$  \hspace{1cm} (4)

3 Laboratory and field characterization methods

There is no problem in applying existing standards for measuring the sound reduction index $R$ of lightweight elements since the airborne excitation is uniformly distributed over the element tested. In the case of localized mechanical excitation, lightweight elements being highly damped, the vibrational fields are no longer reverberant and existing standards become irrelevant. However, SEA can still be applied as long as the excitation is uniformly distributed [3], which is the case for floors excited by the ISO tapping machine on at least 6 positions (as described in draft standard pr ISO 140-11 on laboratory impact noise measurements of lightweight floors) or for walls uniformly excited by a hammer (“rain on the roof” excitation).

For the vibration measurements presented in this paper, the number of accelerometer positions has been the following:

- for field measurements of the vibration level difference, at least 12 accelerometer positions uniformly distributed have been used per wall or floor,
- radiation efficiencies have been estimated in laboratory according to

$$10\log(\sigma) = L_p - 6 - L_v + 10\log(A/S)$$  \hspace{1cm} (5)

where $L_p$ is the spatially averaged sound level radiated in the receiving room, $L_v$ is the spatially averaged vibration level (16 accelerometer positions) of the element tested (of surface area $S$), and $A$ is the equivalent absorption area of the receiving room
- for loss factor measurements, standard pr EN 10848, only valid if the vibration attenuation across the element is less than 6 dB, could only be applied on lightweight elements for frequencies below 500 Hz; for higher frequencies, attenuation with distance has been used to estimate the loss factors (see Section 4.2).

4 Experimental results

4.1 Building structure tested

The two storey four room building tested is a lightweight structure with a separate primary beam / column metal frame. Figures 1 and 2 show vertical sections of the building corresponding to the junction between floor and separating wall and the junction between floor and façade wall respectively. It should be noted that the building was also tested without floating floor.

Figure 1: Steel frame two storey four room lightweight building tested – Junction between floor and separating wall.

Figure 2: Steel frame two storey four room lightweight building tested – Junction between floor and façade wall.

4.2 Laboratory and field measurements

The vertical, horizontal and diagonal sound insulations and impact sound insulations between the rooms of the building were measured according to the methods given in Section 3. Moreover and in order to be able to rank the different transmission paths, the vibration...
level difference $D_{ij}$ of the junctions between building elements were also measured. It should be noted that the building elements involved in flanking transmissions (elements $i$ or $j$ in Equations (1) and (2)) are the single leaf elements (bare floor without suspended ceiling or half separating walls or façade walls) facing either the emission room or the receiving room. For the building structure considered here, the half separating wall is composed of two layers of gypsum boards (each of thickness 13 mm) mounted on C shaped studs (70 mm in height) spaced every 60 cm; and the bare floor is composed of a single layer of wood board (CTBH22, 22 mm in thickness) mounted on doubled Ω shaped joists (150 mm in height) spaced every 60 cm. Examples of measured $D_{ij}$ spectra are given in Figure 3, showing that their values are much higher than in heavy concrete buildings and that the floor to floor attenuation is much lower than the floor to wall paths.

The attenuation of the floor vibration level as a function of the distance from the excitation is shown in the direction perpendicular to the joists and in the direction parallel to the joist in Figure 4(a) and (b) respectively. The higher values obtained in the direction perpendicular to the joist come from the discontinuity associated to the joists. Standards for heavyweight constructions specify that vibration attenuation with distance should not exceed 6 dB across a building element (around 2 dB/m); in this case, vibrational fields can be considered as reverberant and diffuse. The results for the lightweight steel frame constructions presented here show that this condition is never fulfilled in the direction perpendicular to the joists and only fulfilled below 500 Hz in the direction parallel to the joist.

The acoustic performances (index $R_i$, impact sound level $L_{n}$ and radiation efficiencies $\sigma_a$ and $\sigma_r$) of the single leaf elements mentioned above were measured separately in laboratory according to the methods given in Section 3. Figure 5 shows the frequency behavior of the radiation efficiencies $\sigma_a$ (for acoustic excitation) and $\sigma_r$ (for structural excitation); below the critical frequency of the element considered (in this example the bare floor structure), differences up to 10 dB can be observed.

The performance of the floating floor, composed of a cement board (23 mm in thickness) and a dense mineral wool (10 mm in thickness), was also measured separately in laboratory and expressed as a sound reduction index improvement $\Delta R$ and an impact sound pressure level reduction $\Delta L_i$; in the presence of a floating floor, these two quantities have to be
considered in Equations (1) and (2), with the assumption that the floating floor does not modify the vibrational behavior of the supporting floor. The laboratory results are shown in Figure 6, as well as the reduction $\Delta L$ measured with the same floating floor on a 14 cm thick concrete support for comparison; indeed, the performance of the floating floor is quite different when it is placed on a lightweight or heavy support.

In Equations (1) and (2) however, a reduction $\Delta L_2$ of the floating floor obtained when the supporting floor is mechanically excited and the sound pressure level measured on the floating floor side has also to be determined; for lightweight supporting elements, this reduction $\Delta L_2$ is different from the improvement $\Delta R$ and also different from the reduction $\Delta L$ if supporting floor and floating floor are not similar. In the results presented in Section 4.3, $\Delta L_2$ was estimated by calculation (see result in Figure 6).

4.3 Analysis of the transmission path

The different transmission paths were estimated according to the prediction method given in Section 2 and combined to calculate the different sound insulations and impact sound insulations between rooms in the building studied. The calculated insulations were then compared to the measured ones; in general, a rather satisfying agreement between calculated and measured results for horizontal, vertical and diagonal transmission was obtained.

Results are presented for the vertical transmission in the presence or not of a floating floor. The different paths considered for the estimation of the sound insulation are shown in Figure 7.

![Figure 5: Radiation efficiencies measured for the bare floor with airborne and mechanical excitation (radiation on board side).](image)

![Figure 6: Sound insulation and impact noise performance of the considered floating floor.](image)

![Figure 7: Paths for vertical transmission – (a) Airborne sound insulation and (b) impact sound insulation.](image)

The case without a floating floor is first considered. Figure 8 presents the predicted sound insulation for the different paths considered, the predicted total sound insulation and the measured sound insulation. For the whole frequency range, the dominant path is the direct path (through the floor and the suspended ceiling). Figure 9 presents the same results in the case of impact noise. Up to the third octave band 400 Hz, the dominant path is the direct path; above 400 Hz, all paths are shown to contribute to the impact noise level. Both results show that the prediction model is in very good agreement with the measurements except for the first two third octave bands 100 and 125 Hz where the direct path estimation is wrong. Two reasons can be given: (i) the system floor - floating floor - suspended ceiling has not been measured and the suspended ceiling, found in the CSTB data base, might not be exactly the same; (ii) the supporting floor might not
have the same behavior at low frequencies in laboratory and in the field because of different boundary conditions.

The case with a floating floor is now considered. Figures 10 and 11 present the results obtained in terms of airborne sound insulation and impact sound level respectively. When implementing the considered floating floor, the direct path (through the floor and the suspended ceiling) remains dominant in the low frequency range (below 500 Hz). Above 500 Hz, all paths are shown to contribute to the airborne and impact sound insulation level. The prediction model is again in good agreement with the measurements.

Tables 1 and 2 present the global indexes (DnTw and Lntw) for the different vertical transmission cases presented in Figures 8 to 17.
5 Discussion

A few comments can be made:

- the modified prediction method presented requires a new parameter (the radiation efficiency) which is added to the already substantial number of parameters required; could it be simply estimated by calculation?
- the use of sound reduction index improvements $\Delta R$ and of impact sound level reductions $\Delta L$ becomes tricky with lightweight supporting elements
- a simple unidirectional formulation of the flanking sound reduction index or impact sound level is proposed in this paper; a bidirectional formulation (like in EN 123544-1 -2) would have some advantages (but might be difficult to derive in the case of impact noise).
- most of the existing laboratory measurement standards are made for heavy constructions and assume reverberant vibrational field; there is a need for standards adapted to lightweight constructions where the former assumption is not verified.

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References