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ACOUSTIC PERFORMANCE PREDICTION FOR WOOD FRAME BASED FLOORS

Catherine Guigou-Carter

CSTB, 24 Rue Joseph Fourier, 38400 Saint Martin d'Hères, France
email: catherine.guigou@cstb.fr

Corentin Coguenanff

CSTB, 24 Rue Joseph Fourier, 38400 Saint Martin d'Hères, France,

One of the major goals of the European project "Silent Timber Build" is to develop new prediction tools for timber based building components such as walls and floors. The complexity of these wood based systems (multi-cavities, stiffeners, connections, etc…) induces quite a challenge for acoustic performance modelling. In this paper, laboratory measurements and prediction results are compared for several types of wood frame based floors including suspended ceiling and sub-floors of different kinds. Different modelling techniques can be used and combined such as finite element, wave and SEA approaches. These prediction methods can be used to evaluate airborne sound insulation as well as impact noise level; however in this paper impact noise level is more specifically considered. Indeed, occupants dissatisfaction regarding acoustic comfort has been reported in wood frame based building especially due to walking noise and falling object on floors.
Keywords: wood frame floor, performance prediction

1. Introduction

During the last decade, a lot of work has been carried out to predict acoustic performances associated to lightweight building and lightweight elements. Models have been developed to predict the acoustic performance for heavyweight (mostly concrete based) buildings and building elements, with respect to air-borne and structure-borne excitation. Lightweight buildings and elements are more complex, more diverse and more complicated to model: they are multi-cavity stiffened systems with different types of possible connections.

Different projects throughout Europe [1-3] have demonstrated that one of the major needs was the acoustic performance prediction model from lightweight elements (walls and floors); in order to predict the acoustic performance of the building, the performances of the building walls and floors are necessary and a rather large number of these elements is not tested in the laboratory. These projects also established that impact noise is a major annoyance for the occupants of lightweight wood based buildings. On this basis and in order to ease and sustain wood usage, the European project "Silent Timber Build" was designed to develop new prediction tools for timber based building components such as walls and floors. It should be added that new versions of the standard series EN 12354 should be available in 2017 (indeed becoming ISO 12354); these new versions include an adaptation of the building acoustic performance prediction method to lightweight wood based buildings.

In this paper, the acoustic performance prediction is investigated using the combined wave-based transfer matrix and SEA approaches. Trends obtained from laboratory measurements and from prediction method are compared for several types of wood frame based floors including suspended ceiling and sub-floors of different kinds, including the reference floor C1 from ISO 10140-5. The acoustic performance of this reference floor C1 was already investigated [4]. Two companion papers present the step-by-step comparison between detailed measurements and prediction [5] and an integrated multi-criteria optimization approach in order to design floors with improved acoustic performance in order to avoid oversizing systems and lack of competitiveness [6].

The paper first briefly describes the approach taken to predict the acoustic performance of the wood frame based floors and then presents a comparison between predicted and measured impact sound level of different types of floors.

2. Prediction approach

It is usually much more appropriate to investigate the mid-high frequency range using wave and SEA approaches. Indeed, in the low frequency range, modal behaviour of the floor system is generally important and finite element modelling is mostly used. In this paper only wave-based transfer matrix and SEA approaches are considered for simplicity. Predicted results in terms of impact noise level could be refined in the low frequency range using finite element method.

2.1 Wave approach and transfer matrix method (TMM)

CSTB has been developing for quite long a computer program (today the commercially available Acousys software), based on wave approach and transfer matrix method [7] to predict sound transmission, sound absorption impact noise and rainfall noise of building elements.

Based on this wave-based TMM approach, it is also possible to evaluate propagation constants of a multi-layered system. From these obtained propagation constants, it is then possible to define an equivalent layer. This is used in the SEA model considered in this work since this model is limited to two point-connected plates (see Section 2.2).

The special case of orthotropic plate can also be taken into account with this prediction tool for multi-layered system. Therefore, a basic floor made of wood particle boards placed on wood joists, i.e. a rib stiffened plate structure, can be modelled as an orthotropic plate. However, this assumption is only valid in the low frequency range when the bending wave length is larger than the joists spacing. In the present paper, the rib stiffened plate structure is homogenized to an equivalent isotropic plate; this allows to have quick calculation time while acceptable in terms of precision for the floor cases considered.

The excitation force associated to the tapping machine has to be evaluated. When the impact between the hammer and the structure is assumed purely elastic (valid for impact on a rigid structure), the momentum of the hammer after impact is equal in magnitude to that prior to impact (the single pulse force low frequency asymptote is $2M_{hammer}\, v_{0hammer}$). The single pulse excitation force associated with the tapping machine is then [8]

$$F_{hammer}(x,y) = \frac{2M_{hammer}\, v_{0hammer}}{i\omega M_{hammer} Y_{input} + 1}\, \delta(x)\delta(y)\,, \tag{1}$$

where M_{hammer} and $v_{0hammer}$ are respectively the mass (0.5 kg) and the impact velocity (1 m/s) of the hammer, and Y_{input} the input mobility of the structure. In Equation (1), the position of structural excitation corresponding to the tapping machine has no effect on the results if the structure is infinite and has been homogenized. For a frequency bandwidth Δf, the force modulus associated to the tapping machine is then obtained from

$$\left|F_e\right|^2_{\Delta f} = 4 f_s\, \Delta f \left|\frac{2M_{hammer}\, v_{0hammer}}{i\omega M_{hammer} Y_{input} + 1}\right|^2, \tag{2}$$

where f_s is the impact frequency of the tapping machine (10 Hz).

In fact, the impact between the hammer and the lightweight multi-layered structure is not purely elastic. However, the use of Equation (2) allows predicting the impact noise performance well enough

[4]; therefore it is used in this paper. Furthermore, the force spectrum depends on the mobility of the walking surface of the floor; for simple floor made of board on joists it has been shown that in the mid-high frequency the input mobility of the infinite plate is a good assumption [9].

2.2 SEA Approach

For sound transmission, a SEA approach [10] has been previously used to model the structural transmission path through point connections (representing screws) associated to the structural elements linking double plate systems, such as double wall on a common set of studs or floors with ceiling. Assuming that the two plates (1 and 2) composing the structure have the same surface area, i.e. $S=S_1=S_2$, the vibrational level difference D_{v12} can then be expressed as

$$D_{v12} = 10 \log_{10}\left[m_{s2}\eta_2 \ \omega \frac{\left|Y_1 + Y_2 + Y_t\right|^2}{n \, \mathrm{Real}(Y_2)} \right], \tag{3}$$

where n is the number of connecting points per square meter, Y_1 and Y_2 are the structural input mobility of plate 1 and plate 2 respectively, m_{s2} is the density per unit area of plate 2, η_2 the damping of plate 2 and Y_t is the mobility of a point connecting tie, for a spring of stiffness K_t, $Y_t = i\omega / K_t$.

The approach presented in [10] can be extended to take into account a structural excitation (tapping machine) applied to the system, as long as the impact force spectrum is known (see Section 2.1). Therefore the power input to the structure in the SEA model is based on the impact force and the structure mobility evaluated from the wave-based transfer matrix approach (see Section 2.1).

The direct path through the double cavity is evaluated with the wave-based transfer matrix approach model (since it is known that SEA does not perform very well for such cavity path).

3. Comparison between prediction and measurements

For the prediction models, standard material properties are used for the different components. The measurements for the floors considered in this paper were selected from those presented in [11].

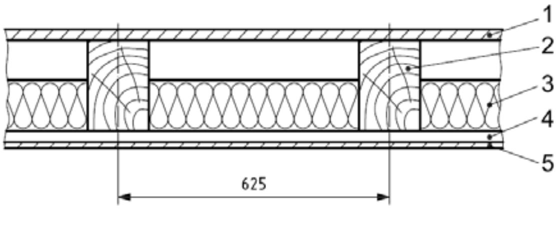
For floors system from the Lignum database [12], prediction was also available from Lignum using formula proposed by Kühn and Blickle [13]. These formula developed for the frequency range of 16 to 200 Hz are extended to cover the complete frequency range of interest.

It should be mentioned that the stiffness associated to ceilings mounted on wood battens directly connected to the floor joists is quite high. Other ceiling mountings exists such as resilient metallic channels or spring hangers; the associated stiffness is then much lower.

The standardized measurement procedure for impact noise evaluation is defined in ISO 10140-3.

3.1 Reference floor C1 from ISO 10140-5

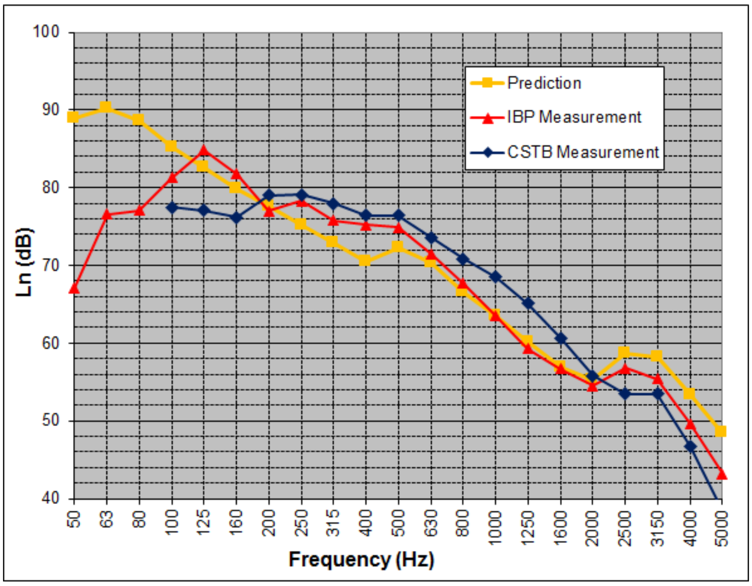
The lightweight floor C1 from ISO 10140-5 is described in Figure 1. Measurements results from IBP (starting at 50 Hz) as well from CSTB (starting only at 100 Hz) are used for comparison with predicted results. The connections between the walking surface (chipboard) and the ceiling (plasterboard) through the joists and the battens are quite stiff.



1: wooden chipboard, 22 mm in thickness
2: wooden joists with 180x120 mm² section, equally spaced (distance 625 mm)
3: 80 mm porous material layer
4: wood battens with 24x48 mm² section, equally spaced (distance 500 mm), perpendicularly oriented with respect to the joists
5: plasterboard, 12.5 mm in thickness
Screwing distance of board to joists or battens : 300 mm

Figure 1: Lightweight reference floor C1 from ISO 10140-5.

Figure 2 presents the comparison between predicted and measured impact sound levels, as well as the associated single number values. The prediction method provides fairly good results compared to measurement results (trends are relatively well predicted) except in the low frequency range where the impact sound level is largely over-estimated. The single number values $L_{n,w}$ and $L_{n,w}+C_I$ are in good agreement.



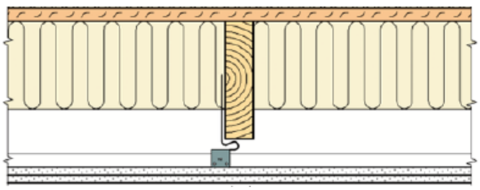
	$L_{n,w}$ (dB)	$L_{n,w} + C_I$ (dB)	$L_{n,w} + C_{I50\text{-}2500}$ (dB)
Prediction	73	74	80
IBP Measurement	74	74	75
CSTB Measurement	73	72	-

Figure 2: Impact sound level for lightweight reference floor C1 from ISO 10140-5.

3.2 Floor 2

A description of the lightweight Floor 2 is given in Figure 3. Measurements results from Norway (starting only at 100 Hz) are used for comparison with predicted results. The ceiling (2 layers of plasterboard) is mounted to the floor joists with steel spring hangers, i.e. leading to more resilient connections than wood battens directly connected to joists and ceiling boards.

Figure 4 presents the comparison between predicted and measured impact sound levels as well as the associated single number values. The prediction method provides acceptable results compared to measurement results; trends are relatively well respected. The prediction in the low frequency range shows large increase in impact sound level which is probably over-estimated. The evaluated single number values ($L_{n,w}$ and $L_{n,w}+C_I$) are also in good agreement.



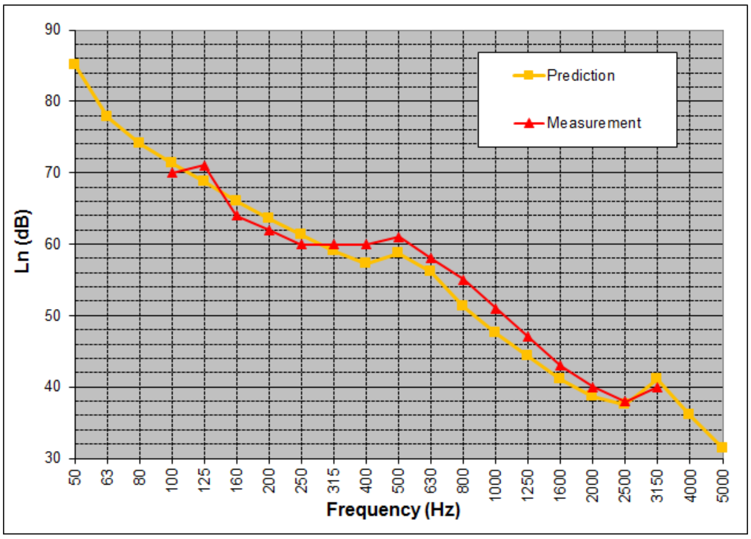
1: wooden chipboard, 22 mm in thickness
2: wooden joists with 48x198 mm² section
3: 150 mm mineral wool layer
4: steel spring hangers
5: 2 layers of 12.5 mm in thickness plasterboard

Figure 3: Lightweight Floor 2.

3.3 Floor 4

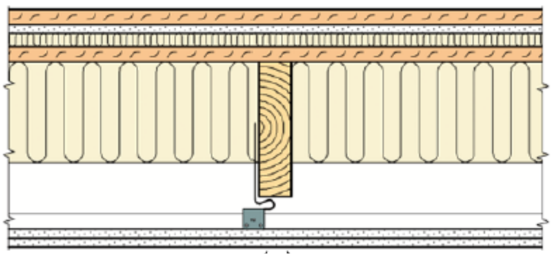
A schematic description of the lightweight Floor 4 is given in Figure 5. Measurements results from Norway (starting only at 50 Hz) are used for comparison with predicted results. The ceiling (one plasterboard and one chipboard) is mounted to the floor joists with steel spring hooks and 30x48 mm² laths, i.e. leading to quite resilient connections. It should be noted that the perforated 22 mm thick chipboard mounted on the joists has not been considered perforated in the model for simplicity and since the effect of these perforations should be limited on the impact sound level.

Figure 6 presents the comparison between predicted and measured impact sound levels as well as the associated single number values. The prediction method is in good agreement with measurement results except in the low frequency range. However some behaviours are more pronounced in the predicted results (around 250 Hz, 1600 Hz and 3150 Hz). The single number values shows some differences between 2 and 5 dB (the largest being for $L_{n,w}$+C_I).



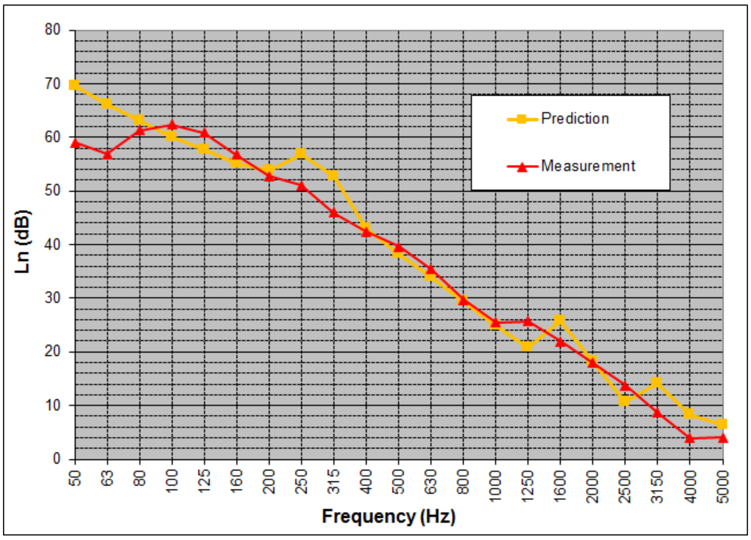
	$L_{n,w}$ (dB)	$L_{n,w} + C_I$ (dB)	$L_{n,w} + C_{I50\text{-}2500}$ (dB)
Prediction	59	60	71
Measurement	59	60	-

Figure 4: Impact sound level for lightweight Floor 2.



1: 22 mm thick chipboard
2: 2 mm thick foam underlayer
3: 12 mm thick plasterboard
4: 20 mm thick stone wool resilient layer
5: 22 mm thick chipboard perforated
6: wooden joists with 48x198 mm² section
7: 150 mm mineral wool layer
8: steel spring hooks and 30x48 mm² laths
9: 12.5 mm thick plasterboard
10: 12 mm thick chipboard

Figure 5: Lightweight Floor 4.



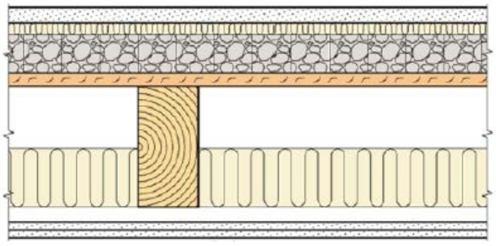
	$L_{n,w}$ (dB)	$L_{n,w} + C_I$ (dB)	$L_{n,w} + C_{I50\text{-}2500}$ (dB)
Prediction	49	50	58
Measurement	47	45	55

Figure 6: Impact sound level for lightweight Floor 4.

3.4 Floor 5

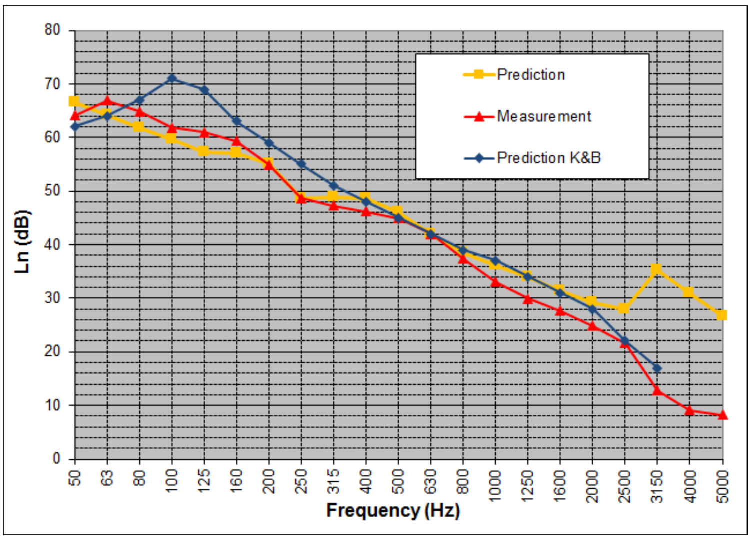
A schematic description of the lightweight Floor 5 is given in Figure 7. Measurements results from Germany (starting only at 50 Hz) are used for comparison with predicted results. This floor is part of the Lignum database with provided simulation results following Kühn and Blickle formula [13]. The ceiling is mounted on wood battens, i.e. leading to relatively stiff connections.

Figure 8 presents the comparison between predicted and measured impact sound levels as well as the associated single number values. The prediction method is in good agreement with measurement results; however the simulation using Kühn and Blickle formula (prediction K&B provided by Lignum) shows a resonant behaviour in the low frequency range that is over-evaluated compared to measurements and not correctly placed in frequency.



1: 25 mm thick fiber reinforced ciment board
2: 20 mm thick mineral wool resilient layer
3: 13 mm thick thermal layer
4: 63 mm thick granulate layer
5: 22 mm thick woodboard
6: wooden joists with 100x220 mm² section, spaced by 572 mm
7: 200 mm mineral wool layer
8: 24x48 m² battens, spaced by 400 mm
9: 2 layers of 12.5 mm thick plasterboard

Figure 7: Lightweight Floor 5.

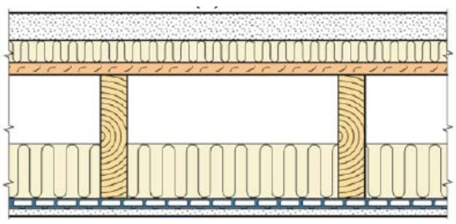


	$L_{n,w}$ (dB)	$L_{n,w} + C_I$ (dB)	$L_{n,w} + C_{I50\text{-}2500}$ (dB)
Prediction	49	49	55
Measurement	50	51	57
Prediction K&B	56	57	60

Figure 8: Impact sound level for lightweight Floor 5.

3.5 Floor 6

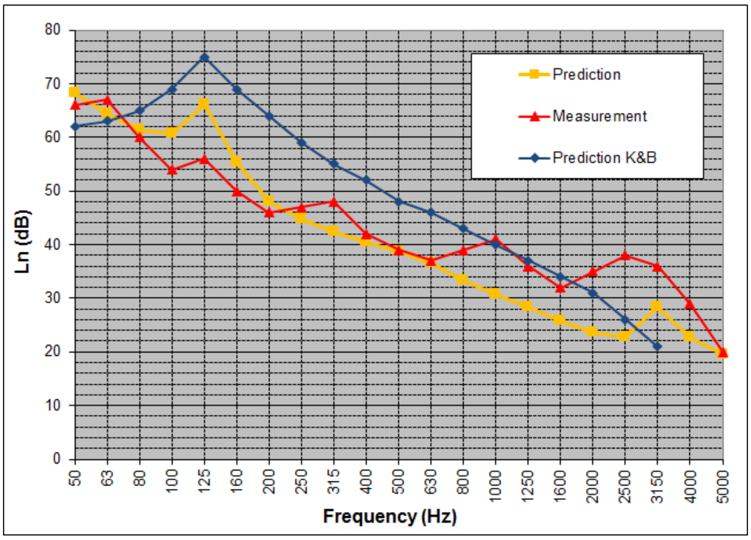
A schematic description of the lightweight Floor 6 is given in Figure 9. Measurements results from Germany (starting only at 50 Hz) are used for comparison with predicted results. This floor is part of the Lignum database. The ceiling is attached with steel resilient channels; the connection is then not as stiff as wood battens but stiffer than resilient hangers.



1: 50 mm thick concrete layer
2: 40 mm thick mineral wool resilient layer
3: 22 mm thick woodboard
4: wooden joists with 80x220 mm² section, spaced by 625 mm
5: 100 mm mineral wool layer
6: steel resilient battens, spaced by 400 mm
7: 12.5 mm thick plasterboard

Figure 9: Lightweight Floor 6.

Figure 10 presents the comparison between predicted and measured impact sound levels and the associated single number values. The prediction results compare fairly well with measurement results; the resonant behaviour around 125 Hz is however overestimated. Furthermore, some peaks observed in the measurements (315, 1000 and 2500 Hz) are not quite well predicted. Above 630 Hz, the prediction results under-estimate the measured results.On the other hand, the simulation using Kühn and Blickle formula (prediction K&B provided by Lignum) shows a resonant behaviour that is quite over-evaluated compared to measurements leading to single number values much higher than those obtained from measurements. A large difference between measurement and prediction is obtained for the single number value $L_{n,w}$+C_I; the other single number values are in relative good agreement.

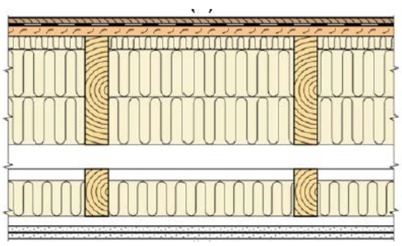


	$L_{n,w}$ (dB)	$L_{n,w}$ + C_I (dB)	$L_{n,w}$ + $C_{I50\text{-}2500}$ (dB)
Prediction	49	53	57
Measurement	47	45	55
Prediction K&B	60	62	63

Figure 10: Impact sound level for lightweight Floor 6.

3.6 Floor 3

A schematic description of the lightweight Floor 3 is given in Figure 11. Measurements results from Finland (starting only at 50 Hz) are used for comparison with predicted results. This system uses an independent set of joists for the supporting floor and for the ceiling. There is no point connection between floor and ceiling; therefore the wave-based TMM approach only is used for predicting the impact noise level.



1: 22 mm thick fiber reinforced gypsum board
2: 30 mm thick mineral wool resilient layer
3: 12 mm thick plywood board
4: wooden joists with 73x223 mm² section, spaced by 400 mm
5: 100 mm mineral wool layer
6: wooden joists with 45x120 mm² section, spaced by 400 mm
6: 20x97 mm² battens, spaced by 400 mm
7: 2 layers of 12.5 mm thick plasterboard

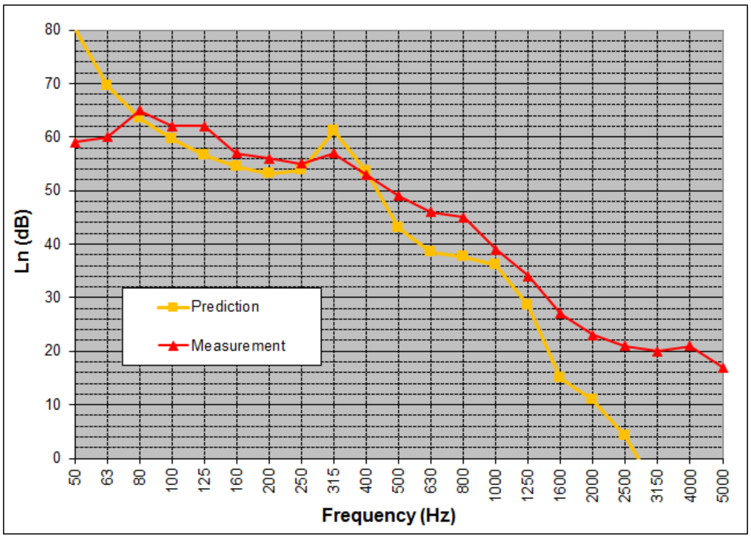
Figure 11: Lightweight Floor 3.

Figure 12 presents the comparison between predicted and measured impact sound levels and the associated single number values. The prediction method compares fairly well with measurement results except in the low frequency range. In the high frequency range, it is expected that vibrational short-cut through the laboratory frame and the background noise could limit the measured performance of this floor system. The single number values $L_{n,w}$ and $L_{n,w}$+C_I are in relative good agreement (2 dB difference); a difference of more than 10 dB is observed for $L_{n,w}$+$C_{I50\text{-}2500}$ since discrepancy in impact sound level between measurement and prediction is important in the low frequency range.

4. Conclusions

In this paper, acoustic performance prediction results in terms of impact sound level for different types of lightweight wood floors have been compared to measurements. A simple combination of wave-based TTM and SEA approaches has been used. Comparisons show that prediction refining is necessary for some floors in the low frequency range using FEM technique for example. The fixing of the ceiling on the joists plays an important role in the floor system performance.

In order to improve the impact noise level of wood frame floor, it is important to use a floating screed and a ceiling mounted on resilient elements. In order to achieve good performance in the low frequency range ($L_{n,w}$+$C_{I50\text{-}2500}$ below 50 dB) it is usually necessary to add mass to these wood frame floor system [13].



	$L_{n,w}$ (dB)	$L_{n,w} + C_I$ (dB)	$L_{n,w} + C_{I50\text{-}2500}$ (dB)
Prediction	50	51	66
Measurement	52	52	55

Figure 12: Impact sound level for lightweight Floor 3.

5. Acknowledgements

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