Optimization of lightweight floors in the low frequency range with a FEM based prediction model

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Introduction

The impact noise transmission at low frequencies is a well known problem of lightweight floors, which is treated in many publications. A satisfying solution, considering the different construction principles of lightweight floors, could not be found so far. To overcome this problem a FEM based prediction model for the optimization of the floor construction and the improvement of the impact sound insulation has been developed and applied in a current research project at the TU München. The details of the prediction model were published in [1]-[3]. This contribution gives an overview of the prediction model and shows the results of the computations and the construction rules developed for optimized lightweight floors.

Survey of computation

The overview of the computational model, given in Figure 1, can be divided in the following steps:

Excitation of the impact-sound

In the tests of impact sound insulation of a floor the standard tapping machine [8] is most commonly used as the excitation source. For the computation model the excitation force has to be expressed with respect to the interaction between the hammer of the tapping machine and the floor surface at the driving point.

Modeling of the structure

The thin-walled lightweight floor, consisting of plates and beams is discretized with a fully three-dimensional approach, where anisotropic high-order solid finite elements are applied allowing different polynomial degrees for each direction of the element [4].

Modal analysis

In the modal analysis the eigenvectors of the problem are computed and used to decouple the system of differential equations. In the second step the differential equations are Fourier-transformed and solved in the frequency domain. Due to the fact that the impact sound level of lightweight floors is dominated by transmissions at very low frequencies, the computation can be restricted to a small number of eigenvalues.

Impact sound spectrum

The response of the structure to the excitation force spectrum with respect to the modal damping of the structure is computed in the frequency domain by summing up the result of each transformed differential equation. This computation is done for each excitation-position of the tapping machine and each considered radiation-point of the structure.

Radiation of the impact sound

For the assessment of the impact sound insulation of floors the normalized impact sound pressure level L_n is calculated from the sound pressure level in the receiving room. In the prediction model, this quantity is computed from the radiated impact sound spectrum in different ways.

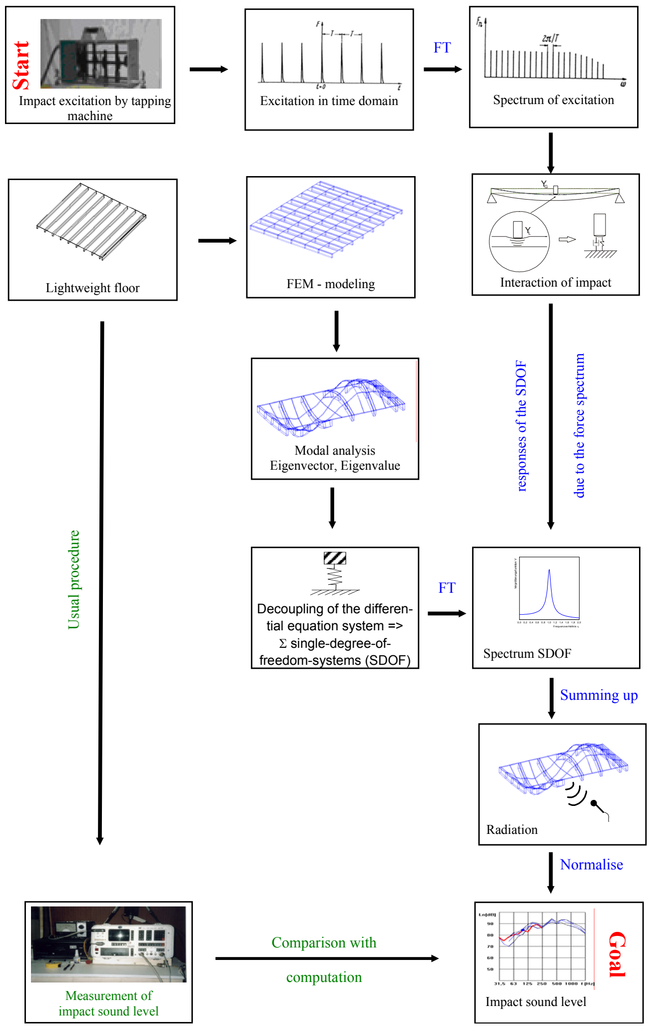

Fig. 1: Workflow of computation

Validation of the prediction model

As a validation of the prediction model the computed normalized impact sound pressure level L_n of 25 different floor constructions were compared with measured data. The FEM calculations, with the modal and spectral analysis as a post-processing step, were carried out in *AdhoC* [5] a FEM code developed at the Chair for Computation in Engineering, TU München. The measurement data applied in this study were taken from the database of the ift Rosenheim. These measurements were made in a test facility according to EN ISO 140-06 [8]. The dimensions of the tested floors (L x W = 5.00 m x 5.25 m) and the boundary conditions (simple supported at two sides) were adapted for the FEM calculations. As an example of the validation Fig. 2 shows the comparison between measurement and prediction for a vertically laminated timber floor with a floating floor screed on mineral wool and a ballasting by crushed stones.

For the validation, the differences between the computed and the measured L_n were evaluated frequency-dependent and also as a single value. If more than one measurement result of a floor construction was available, the average of the measured data was applied.

The computation of the L_n was carried out in a frequency range from 10 to 250 Hz. Therefore it was not possible to evaluate the single value $L_{n,w}$, which is defined in a frequency range from 100 to 3150 Hz. To overcome this problem the definition of the spectrum adaptation term C_I according to EN ISO 717-2 [6] was used:

$$C_{I,50-2500} = 10\log(\sum 10^{0,1L_{n,i}}) - L_{n,w} - 15dB \quad (1)$$

Which gives for $L_{n,w} + C_{I,50\text{-}2500}$:

$$L_{n,w} + C_{I,50-2500} = 10\log(\sum 10^{0,1L_{n,i}}) - 15dB \quad (2)$$

As shown in (2) the evaluation of $L_{n,w} + C_{I,50\text{-}2500}$ is possible without the prior evaluation of $L_{n,w}$. So this form of evaluation is also possible for the computed data (50-250 Hz), if the impact sound transmission below 250 Hz is dominant. To ensure this statement the evaluation in (2) was done for the measurements of the 25 floor constructions in both frequency ranges (50-2500 Hz and 50-250 Hz). The discrepancies between the results were in all cases between 0 and 1.0 dB.

Fig. 3 shows the Difference between prediction and measurement for this single value. The standard deviation between prediction and measurement is σ = 1.5 dB, the mean deviation 0 dB. The differences are inside the confidence interval R according to ISO 140-02 [7] which is defined for measurements of the same floor in different test facilities.

Fig. 4 shows the frequency-dependent differences between prediction and measurement for the investigated floor constructions. The differences are compared with frequency-dependent confidence interval of ISO 140-02 for measurements of lightweight floors in test facilities.

Additionally the confidence interval for the extended frequency range down to 50 Hz is shown, calculated from measurements at the ift Rosenheim in different test facilities

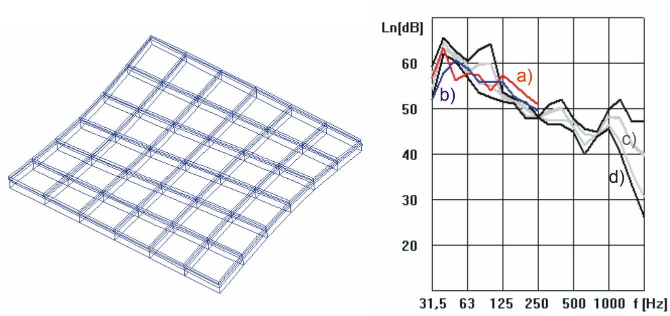

Fig. 2: Comparison measurement – computation for a vertically laminated timber floor with a floating floor screed on mineral wool and a ballasting by crushed stones. a)-b) computation using different radiation methods c) measured data of similar floors in different test facilities d) mean value of measured data ± 2σ

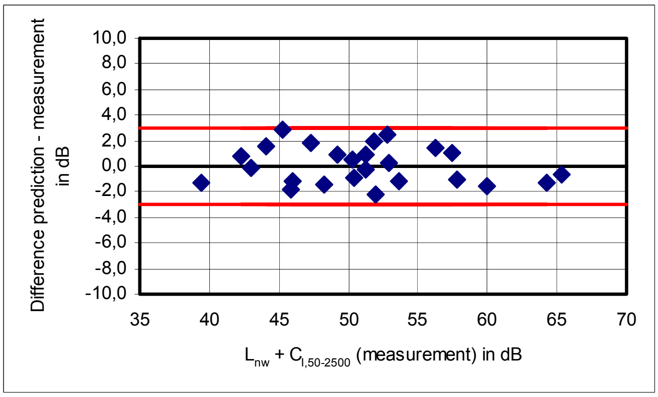

Fig. 3: Differences between measurement and calculation for the single value. Rhomboids: Difference for 25 floor constructions. Red line: confidence interval according to ISO 140-2 for measurements under laboratory conditions (1-3 dB)

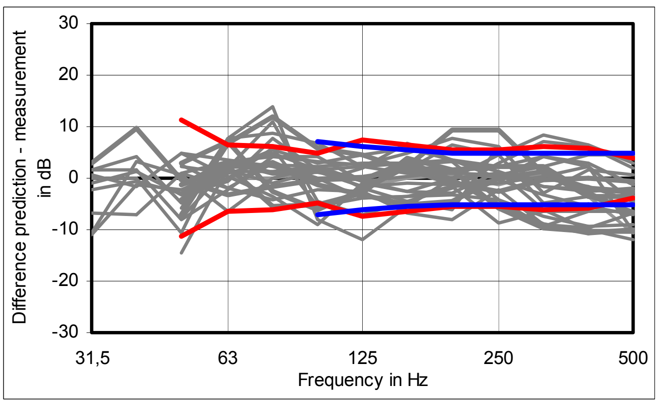

Fig. 4: Frequency-dependent difference between prediction and measurement. Grey lines: Differences for 25 floor constructions. Blue line: Confidence interval according to ISO 140-2 for lightweight floors. Red line: Confidence interval for the extended frequency range down to 50 Hz, calculated from measurements of the ift Rosenheim

Optimization

After the validation of the prediction model numerical studies were carried out to find optimized lightweight floor constructions with reduced impact noise transmissions at low frequencies. The target values of the optimization were $L_{n,w} + C_{I,50\text{-}2500} \leq 53$ dB for standard solutions and $L_{n,w} + C_{I,50\text{-}2500} \leq 46$ dB for advanced solutions. The target values basing on subjective ratings of occupants [9],[10] and measurements in the ift Rosenheim.

The numerical studies were done for typical lightweight floors (timber beams) and for laminated timber floors. The following construction parameters were investigated:

- Mass / thickness of floating floor screed
- Dynamic stiffness of mineral fibre boards as resilient layers
- Additional mass as topping of the floor
- Thickness / stiffness of laminated timber floor

The optimized floor constructions were finally measured in the test facility at the ift Rosenheim. Fig. 5 shows the measured impact sound pressure level of two optimized floor constructions in comparison with a common concrete floor. The optimized floor constructions fulfil the target values for advanced solutions ($L_{n,w} + C_{I,50\text{-}2500} \leq 46$ dB) and their impact sound level is also at low frequency nearly as good as a much heavier concrete floor.

Construction rules for optimized lightweight floors are given in the appendix.

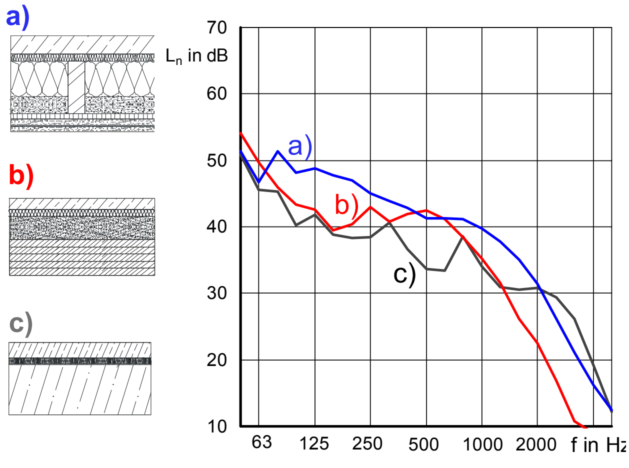

Fig. 5 : Comparison of optimized floors with a common concrete floor (measured data).
a) lightweight floor with floating floor screed on mineral- and wood fibre boards ballasted by 80 mm grit as additional mass between the timber beams: $L_{n,w} + C_{I,50\text{-}2500} = 44$ dB
b) Laminated timber floor with floating floor screed on mineral wool and ballasted by 100 mm grit as additional mass: $L_{n,w} + C_{I,50\text{-}2500} = 42$ dB
c) concrete floor with floating floor screed on mineral wool: $L_{n,w} + C_{I,50\text{-}2500} = 40$ dB

Acknowledgments

The authors acknowledge the helpful discussions, in particular with Ulrich Schanda (FH Rosenheim). The financial support provided by the AiF and the coordination of the project by the DGfH is also gratefully acknowledged.

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[7] EN 20140-2, Acoustics -- Measurement of sound insulation in buildings and of building elements -- Part 2: Determination, verification and application of precision data (ISO 140-2:1991)

[8] EN ISO 140-06, Acoustics -- Measurement of sound insulation in buildings and of building elements -- Part 6: Laboratory measurements of impact sound insulation of floors (ISO 140-2:1991)

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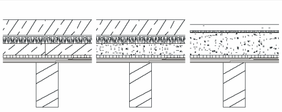
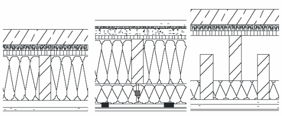
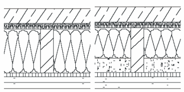
Appendix

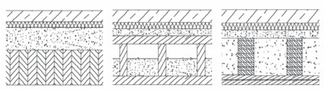
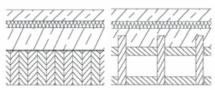
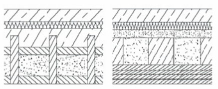
Construction rules for optimized lightweight floors with reduced impact noise transmissions at low frequencies. The tables shows the construction principles for the different floor types depending on the target values ($L_{n,w}$ + $C_{I,50\text{-}2500}$ ≤ 53 dB for standard solutions and $L_{n,w}$ + $C_{I,50\text{-}2500}$ ≤ 46 dB for advanced solutions) and the life load.

Tab 1: construction rules for timber joist floors

construction rules	target value: $L_{nw} + C_{I,50\text{-}2500}$ ≤ 53 dB, life load p, p < 2,5 kN/m²		$L_{nw} + C_{I,50\text{-}2500}$ ≤ 53 dB, p < 5 kN/m²	$L_{nw} + C_{I,50\text{-}2500}$ ≤ 46 dB, life load p, p < 2,5 kN/m²	
	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 60 mm Splitt, m' ≥ 90 oder ≥ 40 mm Betonpl., m' ≥ 100 ≥ 13 mm V20, m' ≥ 7 ≥ 24 mm Dielen, m' ≥ 11 ≥ 200 mm Balken	≥ 25 mm TE, m' ≥ 25 ≥ 12 mm TSD, s' ≤ 40 ≥ 120 mm Splitt, m' ≥ 180 ≥ 13 mm V20, m' ≥ 7 ≥ 24 mm Dielen, m' ≥ 11 ≥ 200 mm Balken	≥ 80 mm ZE, m' ≥ 190 ≥ 20 mm TSD, s' ≤ 20 ≥ 100 mm Splitt, m' ≥ 150 ≥ 13 mm V20, m' ≥ 7 ≥ 24 mm Dielen, m' ≥ 11 ≥ 200 mm Balken	≥ 80 mm ZE, m' ≥ 190 ≥ 40 mm TSD, s' ≤ 7 ≥ 100 mm Splitt, m' ≥ 150 ≥ 13 mm V20, m' ≥ 7 ≥ 24 mm Dielen, m' ≥ 11 ≥ 200 mm Balken	-
	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 60 mm Splitt, m' ≥ 90 oder ≥ 50 mm Betonpl., m' ≥ 120 ≥ 22 mm V20, m' ≥ 14 ≥ 220 mm Balken + Däm. ≥ 24 mm Lattung ≥12,5 mm GKB, m' ≥ 10 ≥12,5 mm GKB, m' ≥ 10	≥ 25 mm TE, m' ≥ 25 ≥ 12 mm TSD, s' ≤ 40 ≥ 30 mm Splitt, m' ≥ 45 oder ≥ 40 mm Betonpl., m' ≥ 100 ≥ 22 mm V20, m' ≥ 14 ≥ 220 mm Balken + Däm. ≥ 27 mm Federschiene ≥12,5 mm GF o GKB, m' ≥ 10 ≥12,5 mm GF o GKB, m' ≥ 10	≥ 50 mm ZE, m' ≥ 120 ≥ 20 mm TSD, s' ≤ 20 ≥ 30 mm Splitt, m' ≥ 45 ≥ 22 mm V20, m' ≥ 14 ≥ 220 mm Balken + Däm. ≥ 27 mm Federschiene ≥12,5 mm GF o GKB, m' ≥ 10 ≥12,5 mm GF o GKB, m' ≥ 10	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 30 mm Splitt, m' ≥ 45 ≥ 22 mm V20, m' ≥ 14 ≥ 220 mm Balken + Däm. ≥ 100 mm Abh. + Däm. ≥12,5 mm GF, m' ≥ 13 ≥12,5 mm GF, m' ≥ 13	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 22 mm V20, m' ≥ 14 ≥ 200 mm Balken ≥ 200 mm Balken,versetzt ≥ 25 mm GKB, m' ≥ 20 ≥ 25 mm GKB, m' ≥ 20
	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 220 mm Balken mit ≥ 220 mm HWF, druckfest ≥ 22 mm V20, m' ≥ 14 ≥ 25 mm GKB, m' ≥ 20 ≥ 25 mm GKB, m' ≥ 20		-	≥ 80 mm ZE, m' ≥ 190 ≥ 40 mm TSD, s' ≤ 7 ≥ 220 mm Balken mit ≥ 140 mm HWF, druckfest ≥ 80 mm Splitt, geb. ≥ 22 mm V20, m' ≥ 14 ≥ 25 mm GKB, m' ≥ 20 ≥ 25 mm GKB, m' ≥ 20	

ZE: floating floor screed (cement, or anhydrite) with mass m' in kg/m²
TE: gypsum board as floor element with mass m' in kg/m²
V20, Dielen: chipboard or boarded floor with mass m' in kg/m²
TSD: mineral - or wood fibre boards with dynamic stiffness s' in MN/m³
Splitt: (lime) grit or gravel with mass m' in kg/m²
Betonpl.: concrete paving flag, glued on the floor, max dimension ≤ 0,30 m, with mass m' in kg/m²
Balken, Däm: timber beam with mineral wool, d ≥ 100 mm
HWF: wood fibre mat, ρ ≈ 140 kg/m³
Lattung: timber batten, 24 x 48 mm, spacing 417 mm
Abh.: suspension rod with elastomer (Sylomer), fibre mat, d ≥ 100 mm
Federschiene resilient metal channel, spacing 417 mm
GF, GKB: gypsum board with mass m' in kg/m²

Tab 2: construction rules for laminated timber floors and box-type constructions

construction rules	target value: $L_{nw} + C_{I,50\text{-}2500}$ ≤ 53 dB, life load, p < 2,5 kN/m²		$L_{nw} + C_{I,50\text{-}2500}$ ≤ 53 dB, p < 5 kN/m²	$L_{nw} + C_{I,50\text{-}2500}$ ≤ 46 dB, life load, p < 2,5 kN/m²	$L_{nw} + C_{I,50\text{-}2500}$ ≤ 46 dB, p < 5 kN/m²
	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 60 mm Splitt, m' ≥ 90 ≥ 150 mm MHD, m' ≥ 50	≥ 25 mm TE, m' ≥ 25 ≥ 12 mm TSD, s' ≤ 40 ≥ 120 mm Splitt, m' ≥ 180 ≥ 150 mm MHD, m' ≥ 50	≥ 80 mm ZE, m' ≥ 190 ≥ 20 mm TSD, s' ≤ 20 ≥ 120 mm Splitt, m' ≥ 180 ≥ 150 mm MHD, m' ≥ 50	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 120 mm Splitt, m' ≥ 180 ≥ 150 mm MHD, m' ≥ 50	-
 -	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 70 mm Beton, m' ≥ 170 ≥ 150 mm MHD, m' ≥ 50	≥ 12 mm TE, m' ≥ 13 ≥ 28 mm V20, m' ≥ 16 ≥ 30 mm TSD, s' ≤ 15 ≥ 120 mm Beton, m' ≥ 290 ≥ 150 mm MHD, m' ≥ 50	≥ 80 mm ZE, m' ≥ 190 ≥ 30 mm TSD, s' ≤ 15 ≥ 120 mm Beton, m' ≥ 290 ≥ 150 mm MHD, m' ≥ 50	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 120 mm Beton, m' ≥ 290 ≥ 150 mm MHD, m' ≥ 50	-
- 	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 70 mm Beton, m' ≥ 170 ≥ 100 mm Splitt, m' ≥ 150 ≥ 150 mm MHD, m' ≥ 50	≥ 25 mm TE, m' ≥ 25 ≥ 12 mm TSD, s' ≤ 40 ≥ 70 mm Beton, m' ≥ 170 ≥ 100 mm Splitt, m' ≥ 150 ≥ 150 mm MHD, m' ≥ 50	≥ 50 mm ZE, m' ≥ 120 ≥ 20 mm TSD, s' ≤ 20 ≥ 70 mm Beton, m' ≥ 170 ≥ 100 mm Splitt, m' ≥ 150 ≥ 150 mm MHD, m' ≥ 50	≥ 50 mm ZE, m' ≥ 120 ≥ 40 mm TSD, s' ≤ 7 ≥ 70 mm Beton, m' ≥ 170 ≥ 100 mm Splitt, m' ≥ 150 ≥ 150 mm MHD, m' ≥ 50	≥ 80 mm ZE, m' ≥ 190 ≥ 30 mm TSD, s' ≤ 15 ≥ 70 mm Beton, m' ≥ 170 ≥ 100 mm Splitt, m' ≥ 150 ≥ 150 mm MHD, m' ≥ 50

ZE: floating floor screed (cement, or anhydrite) with mass m' in kg/m²
TE: gypsum board as floor element with mass m' in kg/m²
V20 chipboard with mass m' in kg/m²
TSD: mineral- or wood fibre board with dynamic stiffness s' in MN/m³
Splitt: (lime) grit or gravel with mass m' in kg/m²
Beton: timber/concrete compound, with mass m' in kg/m²
MHD: vertical- or horizontal (glued) laminated timber floor, timber box-type construction, with mass m' in kg/m²