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The effect of suspension systems on the sound insulation of suspended ceilings: a finite element analysis

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It has been shown via laboratory measurements that the airborne and impact sound insulation of a concrete floor structure with a suspended plasterboard ceiling can be improved by using elastic ceiling suspension systems. The weighted airborne sound reduction index R_{w} was increased by 7 dB and the normalized impact sound pressure level $L_{\mathrm{n,w}}$ was decreased by 15 dB when using elastic ceiling hangers as opposed to fixed hangers. In order to study the effect of elastic ceiling hangers on sound insulation further and to make it easier to compare different suspension systems especially in the low frequency range, a calculation model applying the finite element method (FEM) and parametric calculation methods was created. The calculation model was validated using measured data. The calculation results were then used to predict the improve-ment of sound insulation achieved with the different suspended ceilings. Additionally, the calculation model was used to examine the phenomena around the performance of the different ceiling hangers. The calculation results confirm the observations made from the laboratory measurements; switching from fixed ceiling hangers to elastomer ceiling hangers improved the performance of the suspended ceiling by more than 10 dB, with significant improvements beginning from the low frequencies.

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1. INTRODUCTION

Suspended ceilings are often used to improve the sound insulation between spaces and in room-within-a-room applications. Typically a suspended ceiling system consists of three components: 1) one or more layers of building boards, 2) a ceiling frame for the installation of the building boards, and 3) a suspension system, i.e., ceiling hangers that attach the ceiling frame to the load bearing floor structure. Commonly used building boards in suspended ceilings are plasterboards or wood-based products (e.g. plywood), and the frame consists of steel or timber profiles. The ceiling hangers can be either elastic or rigid (i.e., very stiff compared to elastic hangers). The airspace between the suspended ceiling and the load bearing floor structure is usually attenuated using absorbing materials such as mineral wool or other porous media.

The acoustical behavior of a suspended ceiling structure can be simplified into a mass-spring-mass system, where the load bearing structure (a concrete or wooden slab) and the suspended ceiling boards act as the two coupled masses. Two different types of coupling can be identified from the system: the acoustical coupling between the load bearing structure and the ceiling boards through the (attenuated) airspace, and the mechanical coupling via the ceiling hangers and the ceiling frame [1]. If the airspace is sufficiently attenuated and large enough, the sound insulation of the structure will be mostly limited by the mechanical coupling rather than the acoustical coupling via the airspace [1].

A potential solution for improving the airborne and impact sound insulation performance of a suspended ceiling structure is to use an elastic suspension system. Using an elastic suspension system as opposed to a rigid one reduces the mechanical coupling between the load bearing structure and the ceiling boards, therefore improving the airborne and impact sound insulation of the structure. According to laboratory measurements on a concrete slab [2–3], the improvement of sound insulation achieved with the suspended ceiling increased when using elastic hangers instead of rigid hangers. The improvement was notable in the frequencies above 100 Hz.

The purpose of this study was to examine the behavior of different suspended ceiling systems and to make it easier to compare different ceiling hangers even in the low-frequency range below 100 Hz. Simulations were carried out where the aforementioned phenomena were investigated. Both the finite element method (FEM) and parametric calculation models were applied to predict both the airborne and impact sound insulation of a concrete slab with two differently suspended ceilings, one suspended with rigid hangers and the other suspended with elastomer hangers.

2. MATERIALS AND METHODS

A. SUSPENDED CEILINGS

I. EXAMINED FLOOR STRUCTURES

The sound insulation of two floor structures (F1 and F2) with suspended plasterboard ceilings installed under a laboratory concrete slab (Fig. 1) was investigated. Two 13 mm thick plasterboards were suspended from a 140 mm concrete slab with different suspension systems: rigid hangers (F1), and elastic elastomer hangers (AMC Mecanocaucho Akustik Rapid LC + Sylomer 20) (F2). The elastomer within the hanger had dimensions of 25 x 28 x 41.5 mm. The airspace between the concrete slab and the plasterboards was 130 mm thick including a 100 mm layer of mineral wool. In addition to F1 and F2, a bare reference concrete slab (F0) was examined to study the improvement of the sound insulation (both ΔR and ΔL) achieved with the ceilings. Structure F3 without any mechanical coupling between the concrete slab and the ceiling boards was also examined.

The configuration of structures F1–F2 was the same except for the type of hanger used. The hangers were attached to the concrete slab by threaded steel rods with a diameter of 6 mm. The spacing of the hangers was 1200 mm along the ceiling frames and 600 mm in the perpendicular direction according to the ceiling frame spacing. The height of the ceiling frame profiles was 18 mm and width 45 mm. The plasterboards ($m' = 9$ kg/m^2) were attached to the ceiling frame with screws.

The rigid hangers were relatively stiff when compared to the elastomer hangers. The natural frequency f_0 (of a mass-spring system) of the elastomer hanger was 11.5 Hz, when the mass per hanger was 8.5 kg, which corresponds the total mass of the plasterboards divided between the 32 hangers in the ceiling. The spring constant for the elastomer hanger was 44 400 N/m.

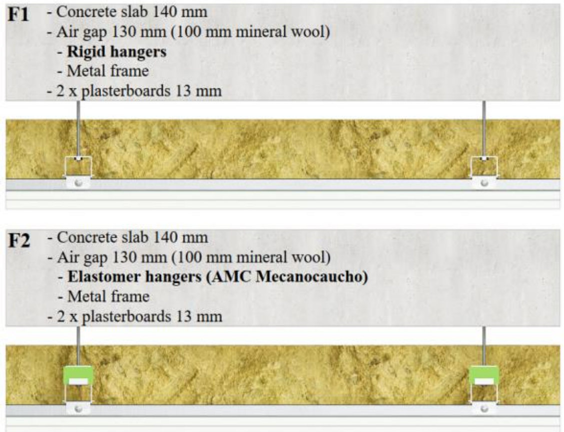

Figure 1. Floor structures F1 and F2.

II. IMPROVEMENT OF SOUND INSULATION WITH SUSPENDED CEILINGS

Prior to the simulations, the airborne and impact sound insulation of structures similar to the floors F0–F2 have been measured in a building acoustics laboratory [2–3]. To distinguish between the measured structures and the ones examined in this study, the measured floor structures were denoted as F0 lab., F1 lab. and F2 lab. The floor F1 lab. was different from the structures in this study since the air gap between the concrete slab and the plasterboards was only 100 mm as opposed to 130 mm, and the hanger spacing was 600 mm in both directions [2]. For structure F1 lab., the measurements were carried out in the frequency range 100–5000 Hz [2] and for structures F0 lab. and F2 lab., the measured frequency range was 50–5000 Hz [3].

From the laboratory measurement results [2–3], improvements of the sound insulation achieved with the suspended ceilings were determined for structures F1 lab. and F2 lab. Measurement results for the improvement of the sound reduction index (ΔR) and the reduction of the impact sound pressure level (ΔL) are shown in Fig. 2. The single-number quantities (SNQs) ΔR_w and ΔL_w determined according to standards ISO 717-1 [4] and 717-2 [5] are also presented in Fig. 2. The weighted sound reduction index R_w of the laboratory slab F0 lab. was 56 dB and the weighted normalized impact sound pressure level $L_{n,w}$ was 77 dB.

According to Fig. 2, ΔR and ΔL of the suspended ceiling are strongly dependent on the ceiling hangers. The improvements of the SNQs ΔR_w and ΔL_w were 7 and 15 dB higher for the elastically suspended ceiling F2 lab. compared to the rigidly suspended ceiling F1 lab. As discussed above, there were differences in the ceiling configurations between F1 lab. and F2 lab., and therefore the improvement of ΔR_w and ΔL_w cannot reliably be attributed to the ceiling hangers alone.

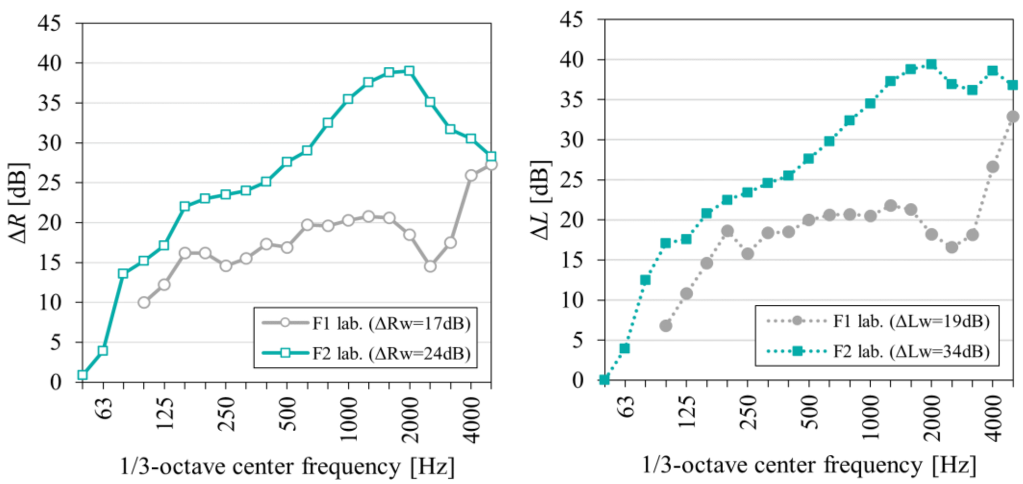

Figure 2. The measured improvement of the sound reduction index ΔR and the reduction of the impact sound pressure level ΔL for structures F1 and F2.

B. SIMULATION PROCEDURES AND MODEL DESCRIPTIONS

The airborne and impact sound insulation of floor structures F0–F3 were examined using simulations. The simulations were used to study the phenomena around the performance of the different ceiling suspension systems. The simulations were done by applying the finite element method using COMSOL Multiphysics 6.1. The FEM simulations were carried out in the 1/3-octave bands 50–200 Hz and supplemented with parametric calculation models for airborne and impact sound insulation in the 1/3-octave bands 250–5000 Hz. The parametric calculations models were developed by AINS Group.

I. FEM-SIMULATIONS

The FEM simulations were performed in the frequency domain by applying a fully coupled multiphysics problem with a two-way interaction between the structural and acoustical domains. The governing partial differential equation of motion (without the volume force part) in the structural parts of the model (i.e. the concrete, plasterboard and steel components of the floor structure) was:

$$\nabla \cdot \boldsymbol{S} = -\rho\omega^2\boldsymbol{u} \tag{1}$$

where $\boldsymbol{S}$ is the second Piola-Kirchoff stress tensor, ρ is material density, $\omega = 2\pi f$ is the angular frequency, f is frequency, and $\boldsymbol{u}$ is the displacement [6].

The governing equation in the acoustical domains (airspaces) was the Helmholtz equation:

$$\nabla \cdot \left(-\frac{1}{\rho_0}\nabla p\right) - \frac{\omega^2 p}{\rho_0 c_0^2} = 0 \tag{2}$$

where p is the time-harmonic sound pressure, and ρ_0 and c_0 are the density of air (1.21 kg/m^3) and the speed of sound in air (343 m/s), respectively [7]. The poroacoustical domains (i.e. the mineral wool absorber within the air gap between the concrete slab and the ceiling boards) were modelled as an equivalent fluid using the modified Allard and Champoux model [7–8]. Thus the governing equation in the poroacoustical domains was also the Helmholtz equation, but Eqn. (2) was solved with modified complex values for the density and speed of sound in the material.

In addition to the floor structures, a half-infinite airspace was modeled below the structures to determine the sound power radiated by the structure. The fully absorptive boundary conditions for the receiving airspace were achieved with perfectly matched layers (PML).

First, the models were used to determine the sound reduction index R of each floor structure. The upper surface of the concrete slab was excited with a diffuse sound field as a boundary load by generating a sum of N plane waves with random phases and an even distribution over a half sphere over the surface [9] with total sound power P_{dif}. The model was used to solve the sound power radiated by the structure into the receiving air domain $P_{\mathrm{rad,air}}$. The sound reduction index R was then determined from:

$$R = 10\,log\left(\frac{P_{dif}}{P_{rad,air}}\right) \tag{3}$$

Second, the FEM models were used to determine the normalized impact sound pressure level L_{n} of each floor structure. The floors were excited by a set of point forces representing the force excitation of the ISO tapping machine [10]. The sound power radiated by the structure into the receiving air domain $P_{\mathrm{rad,imp}}$ was solved, and the normalized impact sound pressure level was determined from:

$$L_n = 10\,log\left(\frac{P_{rad,imp}}{P_0}\right) + 10\,log\left(\frac{A_{ref}}{A_0}\right) \tag{4}$$

where $P_0 = 10^{-12}$ W is the reference sound power, and A_{ref} and A_0 are reference sound absorption areas of 4 m^2 and 10 m^2, respectively. It was assumed that the sound field in the receiving room was perfectly diffuse.

II. PARAMETRIC CALCULATION MODELS

Parametric calculation models developed by AINS Group were used to calculate both the airborne and impact sound insulation of the structures in the mid- and high frequencies (250–5000 Hz). The parametric model for the airborne sound insulation is based on refs. [1,11-15]. The parametric calculation model for airborne sound insulation combines different models found in literature, and is based mostly on statistical energy analysis, lumped mechanical models and/or forced transmission approaches. The model takes into account, e.g., the mass and stiffness of structural layers, absorption materials inside a structure and the stiffness of studs and frames.

The parametric calculation model for calculating the impact sound insulation is based on refs. [16-20]. In addition to the previously mentioned features of the parametric airborne sound insulation model, the impact sound insulation model considers the force interaction between the ISO tapping machine and the floor structure.

C. SIMULATIONS

The calculation models were validated by comparing the simulation and measurement results (presented in ref. [3]) of the bare concrete floor (F0 and F0 lab.) and the floor with an elastic ceiling suspension system (F2 and F2 lab.). The validated models were then used to simulate the sound insulation of floors F1 (rigid ceiling hangers) and F3 (only acoustical coupling). Elastic material properties for all parts of the floor structures were not available. The material parameter values (density ρ, elastic modulus E, Poisson's ratio ν, structural loss factor η_s) presented in Table 1 were used in the simulations. The structural parts of the structures were modeled as isotropic elastic materials. Additionally, it was assumed that the static airflow resistivity of the mineral wool absorber was 15 000 Pa·s/m^2. Most materials in the FEM simulations were modelled as solid domains, except for the ceiling frames which were modelled using shell elements. The computed displacements of the floor structures F0 and F2 have been illustrated in Fig. 3.

Table 1. Elastic material properties used in the calculations.

Material	ρ [kg/m^3]	E [MPa]	ν [-]	η_s [-]
Concrete	2 320	30 000	0.2	0.006*
Plasterboard	720	2 600	0.3	0.01
Steel**	7 850	210 000	0.3	0.005

*) Total loss factor was fit in validation to match airborne sound insulation measurement.

**) Metal frames and steel hangers.

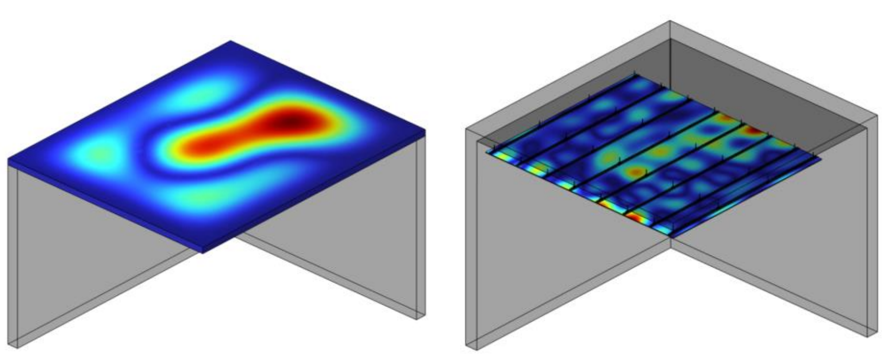

Figure 3. Simulated displacements of the bare floor structure F0 (left) and structure F2 with the suspended ceiling (right) at 100 Hz. The concrete slab was excited with a diffuse sound field.

The mesh of the FE-model was built using hexahedral and tetrahedral quadratic elements. A frequency dependent mesh was used, with the element size being at most a fifth of the wavelength of sound in air according to [7]. For the smaller geometries in the model, such as the hangers and ceiling frames, smaller element sizes were used to precisely account for their deformation behavior.

The concrete wall structures connected to the concrete floor structure were modelled according to the measurement reports [2–3]. However, all details of the measurement setup were not available. The walls were rigidly connected to the concrete floor structure. The steel studs of the ceiling frame were connected to the plasterboard by a bonded line contact along the centerline of the stud. The individual plasterboard layers were connected to one another by a no separation contact between the board surfaces.

To take the ceiling hangers into account in the FEM models, spring-damper (SD) components were used to connect the ceiling frame to the concrete slab, as previously done by Kohrmann et al. [21–22]. The validity of using the spring-dampers was assessed by comparing the acceleration amplitudes of mass-spring systems for the fully modelled elastomer hangers and then replacing the full models with the spring-damper components (Fig. 4). According to Fig. 4., the agreement between the full and simple models was reasonable. The peak in Fig. 4 represents the natural frequency f_0 of the modelled systems (rigid mass of 8.5 kg at the end of the hanger) for the elastomer hanger. The respective natural frequency f_0 of the rigid hanger was 322,5 Hz.

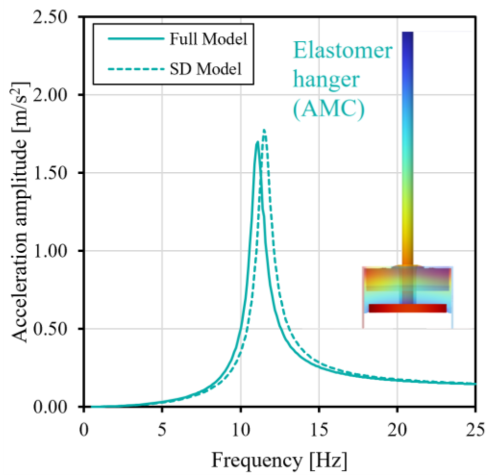

Figure 4. Acceleration amplitude comparison between the fully modeled ceiling hanger and the spring-damper model together with the simulated displacement of the fully modeled hanger.

3. RESULTS

A. VALIDATION RESULTS

Comparisons between the simulated and measured sound reduction indices R and the normalized impact sound pressure levels L_n of floor structures F0 and F2 are shown in Fig. 5. The difference between measured and simulated R_w was 1 dB and 4 dB for floors F0 and F2, respectively. In the case of R, the differences between measurement and simulation were at their highest in the mid- and high frequencies. The differences between measured and calculated $L_{n,w}$ were 0 dB and 2 dB for structures F0 and F2, respectively. For L_n there were differences between the measured and calculated values in the low- and mid-frequencies, with larger deviations at 50–63 Hz 1/3-octave bands. The comparisons in Fig 5. show that the calculation models can accurately evaluate the sound insulation of the bare concrete floor F0. Due to the good agreement between the measured and simulated results, the models for R and L_n were considered to be valid. However, the discrepancies between measured and calculated L_n indicate that the calculation result may not be accurate in frequency bands 50 Hz–63 Hz, 200 Hz and 2500–5000 Hz.

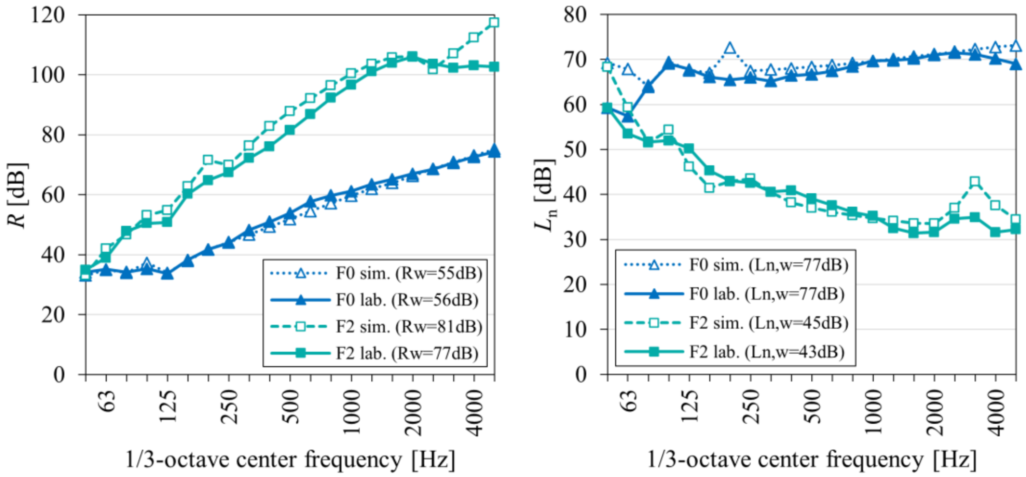

Figure 5. Validation results for the sound reduction index R and R_w (left) and the normalized impact sound pressure level L_n and $L_{n,w}$ (right).

B. IMPROVEMENT OF SOUND INSULATION

The validated models for F0 were used to simulate the behavior of the different suspended ceilings. The calculated improvement of the sound reduction index Δ*R* and the reduction of the impact sound pressure level Δ*L* for structures F1–F3 are shown in Fig. 6. The single-number quantities ΔR_w and $\Delta L_{n,w}$ presented in Fig. 6 were calculated according to the standards ISO 717-1 [4] and 717-2 [5]. The suspended ceiling hangers were modelled as spring-damper components as discussed in Section 2.C.

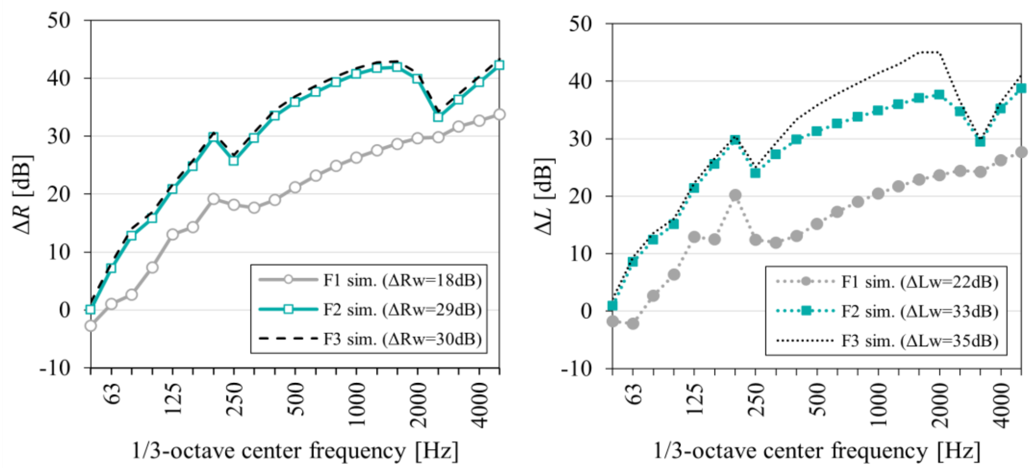

Figure 6. Simulated improvement of the sound reduction index ΔR and ΔR_w (left) and the simulated reduction of the impact sound pressure level ΔL and ΔL_w (right) for structures F1–F3.

The results presented in Fig. 6 show major differences between the performance of the rigid (F1) and elastic (F2) ceiling suspension systems. An improvement of over 10 dB to the performance of the suspended ceiling was achieved by using the elastomer hangers instead of the rigid hangers. The differences between F1 and F2 are prominent across the entire 50–5000 Hz frequency range. It is also notable that the simulated Δ*R* and Δ*L* values for the elastomer hanger ceiling (F2) were close to the performance of the mechanically uncoupled ceiling (F3).

A full 3D model of the elastomer hanger was also examined in the FEM simulation of the sound reduction index *R* to examine the low-frequency behavior of the 3D-hangers in comparison to the spring-damper components. In the low frequencies between 50–200 Hz, the differences between the Δ*R* and Δ*L* of the elastically suspended and the fully uncoupled ceilings were approximately 1 dB (Figs. 7 and 8). It is apparent that the rigid hangers decrease the Δ*R* values above 50 Hz. It is also notable that there is no significant difference in Δ*R* between the 3D and spring-damper models of the elastomer hanger between 50–200 Hz (Fig. 7).

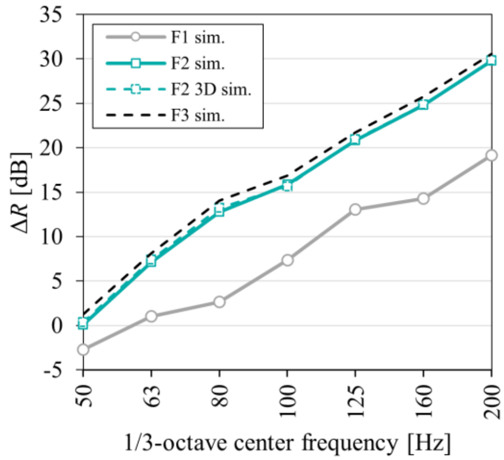

Figure 7. Simulated improvement of the sound reduction index ΔR in the low frequencies (50–200 Hz) for structures F1–F3. A version of F2 with fully 3D-modeled elastomer ceiling hangers is included in the comparison.

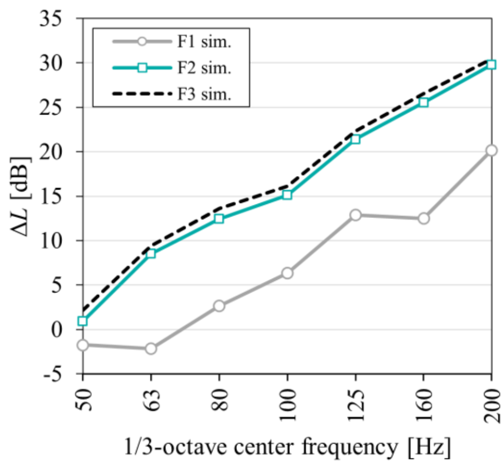

Figure 8. Simulated reduction of the impact sound pressure level ΔL in the low frequencies (50–200 Hz) for structures F1–F3.

4. DISCUSSION

The measured sound reduction indices R of the floor structure F2 were high and close to the maximum values that can be measured at the laboratory facility above 400 Hz [3]. This could mean that flanking sound transmission may have an effect on the measured performance of the floor structure, thus lowering the sound insulation values achieved in the laboratory setting. Moreover, measuring such high sound reduction indices demands great sound power levels in the sending room. Based on the measurement results it is evident that ΔR and ΔL were close to each other. The presented measurements for the floor structure F1 lab. [2] are not fully comparable with the more recent measurement for structure F2 lab. since the cavity thickness and the hanger configuration were different.

The simulated sound insulation improvements ΔR and ΔL (Fig. 6) were comparable with the measurement results (Fig. 2) for the floor F2 even though exact material parameters and dimensions of the floor structure were not known in all respects. More significant discrepancies between calculation and measurement were observed in the case of L_n (Fig. 5), which suggests that the calculation results may not be accurate at certain frequency bands (see Section 3A). However, from the measurement results (Fig. 2) it appears that ΔR and ΔL are roughly equivalent, which also appears to be the case for the simulation results (Fig. 6).

An idealized point-point connection with spring-damper components proved to be accurate in describing the behavior of the ceiling hangers in the low frequencies (Fig. 7). The inclusion of an accurate elastomer hanger geometry (F2 3D) did not have an effect on ΔR below 200 Hz. Thus, simplifying the hanger geometry (and probably the material parameters) into an ideal spring-damper seemed justified in the low-frequency range. The stiff hanger system F1 differs from other configurations starting at 50 Hz, but more prominently at 63 Hz.

Using the parametric models requires simplifications to the real geometries of floor structures F1 and F2. The parametric model cannot accurately describe a connection between plates (concrete slab – plasterboards) where the connecting force is not symmetric, and the ceiling frames are not accounted for. Therefore a moderate estimation is most likely achieved. The uncertainties caused by the simplifications can be seen from ΔR and ΔL results (Fig. 6) around the coincidence frequency of the plasterboards (1/3-octave bands 2500–3150 Hz). Additionally, calculation uncertainty is assumed to involve the possibly frequency-dependent material characteristics.

5. CONCLUSIONS

In this paper the sound insulation behavior of two differently suspended ceilings was examined and compared to the performance of a fully uncoupled ceiling. According to the results, it is beneficial to use elastic ceiling hangers, which improves the ceiling performance with more than 10 dB. The improvement is prominent even at low frequencies. Thus, the results confirm the benefits of the elastic hangers compared to the rigid hangers.

By using different modelling techniques (spring-damper components and fully 3D-modelled hangers) it was noted that at least the lowest natural frequency of the ceiling hangers should be known when designing a suspended ceiling. Differences in geometry and elastic material properties between hanger models may become a more important factor when particularly high sound insulation values are required. In the case of the elastomer hangers (F2), the addition of accurate 3D geometry had no effect on the ΔR and ΔL results when compared to the results obtained using the spring-damper components below 200 Hz.

6. ACKNOWLEDGEMENTS

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