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Cinema design to meet high acoustic demands without breaking the budget

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In the last three years two new Cinema complexes have been built in Stockholm. A new building system was developed to reach the high acoustic demands and on the same time decrease building cost and time. Predictions and measurement results are presented in this paper together with the chosen design concept.

1 Introduction

Modern cinemas have very high requirements of sound insulation, due to sound equipment that is capable of transmitting very high sound pressure levels at low frequencies. There are regulations of maximum allowed sound pressure levels in cinemas [1], but the criteria is only stated in dBA which leaves the low frequency sound practically without regulation. There are examples of cinemas where sound pressure levels reach up to 130 dB in 31.5 Hz band without exceeding the regulations. Without discussing risk for hearing damage, these levels set requirements for extremely high sound insulation between cinemas theatres.

In this paper two recent cinema complex projects will be presented. In both projects a new and innovative building concept has been used, which has proved to give high sound insulation, good acoustics and on the same time being cost effective and permitting a fast building process.

1.1 Filmstaden Täby

Filmstaden Täby is located in Täby, Stockholm and was finished in 2013. It contains 5 theatres, in total 516 seats.

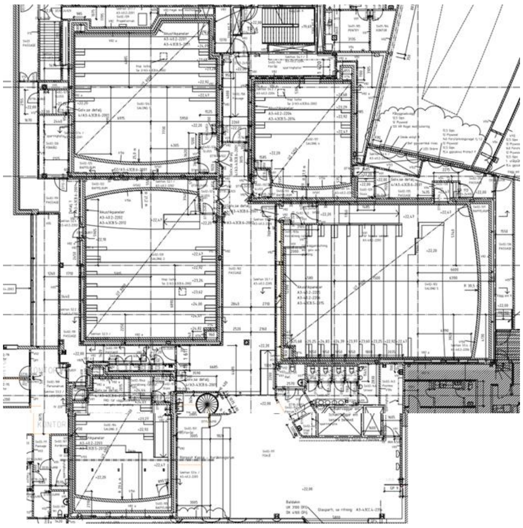

Figure 1: Filmstaden Täby has 5 theatres with steep risers. The largest theatre has 162 seats.

1.2 Filmstaden Scandinavia

Filmstaden Scandinavia is located in the Mall of Scandinavia, Solna, Stockholm and was finished in 2015. It contains 15 theatres, in total 1863 seats, restaurant, VIP area and the first commercial IMAX theatre in Scandinavia. The IMAX theatre has 421 seats. The three largest theatres are equipped with Dolby Atmos sound system.

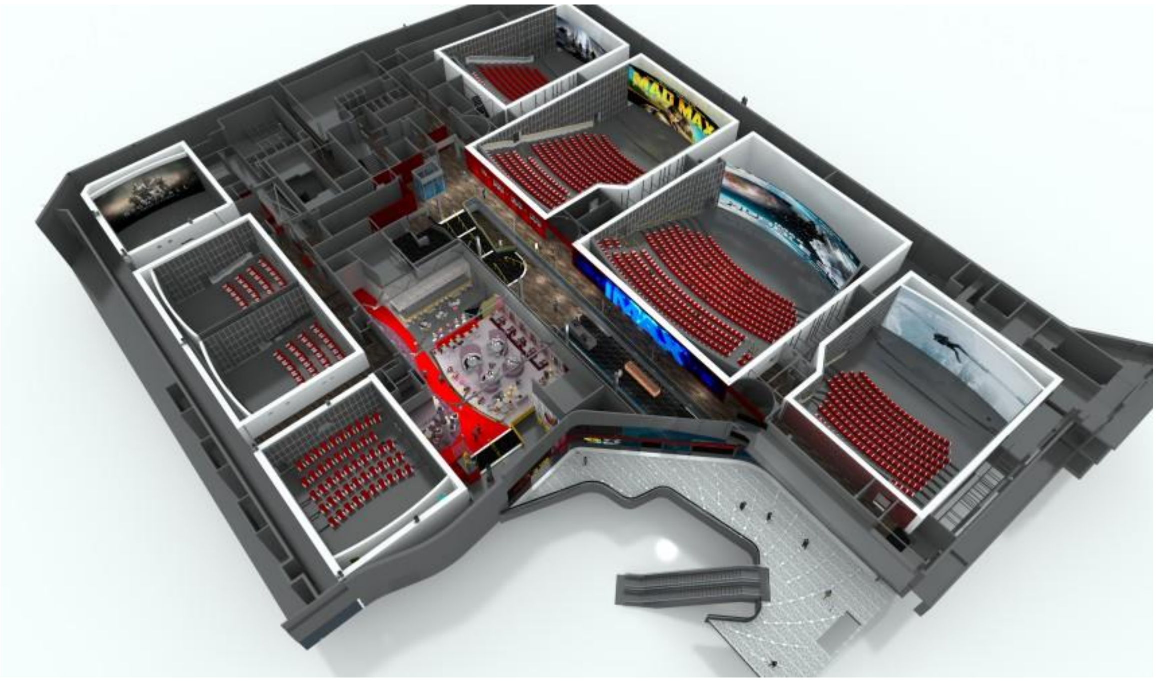

Figure 2: The lower floor of Filmstaden Scandinavia has 8 theatres, with seven additional theaters situated on the upper floor. (Picture by Scheiwiller Svensson Arkitektkontor AB)

2 The building design concept

2.1 Basic design

It is important to plan the cinema complex in a way that corridors and dead space are placed between the theatres. This strategy will increase the sound insulation without adding cost. If the theatres are placed next to each other with a common wall, it will be very difficult and expansive to get the needed sound insulation.

2.2 Floating floors

Normally the flanking transmission in the concrete slabs is limiting the sound reduction between the rooms. To reduce this flanking transmission the slab has to be covered with a floating floor. Predicting the sound insulation of floating floors in an accurate way is a very difficult task. To the author's knowledge there is no accurate prediction model available. However, you can look at some approached and do a parameter study.

The first and most famous work was presented by Cremer in 1952 [2]. He did studies on a locally reacting floating floor on a load bearing continous elastic layer.

$$\Delta L = 40\log\left[\frac{f}{f_0}\right] \tag{1}$$

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{s'}{\rho_s}} \tag{2}$$

Where s' is the dynamic stiffness per unit area and ρ_s is the mass per unit area of the walking surface. Equation (2) is only valid if the main slab is much heavier than the floating floor and the mobility of the main floor is low.

In real buildings this expression is more valid, due to finite size slabs etc:

$$\mathit{\Delta} L = 30\log\left[\frac{f}{f_0}\right] \tag{3}$$

Ver did a study in 1971 on impact noise on resonantly reacting floating floors placed on discrete resilient mounts [3]. His work is derived from statistical energy analysis, SEA.

$$\mathit{\Delta} L = 10\log\left[\frac{2.3\,{\rho_{s1}}^2\,c_{L1}\,h_1\,\eta_1\,\omega^3}{n'\,k^2}\right] \tag{4}$$

Where: ρ_{s1} is the mass per unit area of the floating floor.
c_{L1} is the longitudinal wave speed floating floor
h_1 is the thickness of the floating floor
η_1 is the loss factor of the floating floor
n' is the number of mounts per unit area
k is the spring constant of the mount [N/m]
$\omega = 2\pi f$

From the above expressions you may conclude the following parameter study for high sound insulation

n'	low (few mounts)
k	small with power 2 (weak mounts)
ρ_{s1}	high with power 2 (heavy floor)
c_{L1}	high (fast longitudinal wave velocity)
h_1	high (thick floor)
η_1	high (high loss factor)

Above the mass-spring-mass resonance frequency the frequency dependency is 30 dB per octave above.

Gudmundsson solved the problem using spatial Fourier transforms for point excitation [4]

$$\mathit{\Delta} L = 10\log\left[\frac{\int_0^1\left[|N_3 + N_0|^2\sqrt{1-\xi^2}\right]^{-1}\xi\,d\xi}{\int_0^1\left[|\cos(k_s h_2)\,[N_1 + N_3\,] + j\sin(k_s h_2)\,[N_2 + N_3 N_1\,/N_2\,]\,|^2\sqrt{1-\xi^2}\right]^{-1}\xi\,d\xi}\right] \tag{5}$$

$$N_0 = \frac{j\omega\rho c}{\sqrt{1-\xi^2}} \tag{6}$$

$$N_1 = \left[B_1(k\xi)^4 - \omega^2 m_1\right] + j\left[\frac{\omega\rho c}{\sqrt{1-\xi^2}} + B_1\eta_1(k\xi)^4\right] \tag{7}$$

$$N_2 = j\omega^2\rho_s c_s \tag{8}$$

$$N_3 = \left[B_3(k\xi)^4 - \omega^2 m_3\right] + j\left[\frac{\omega\rho c}{\sqrt{1-\xi^2}} + B_3\eta_3(k\xi)^4\right] \tag{9}$$

Where: ρ is the density of air.
ρ_s is the density of the interlayer.
c is the speed of sound
c_s is the speed of sound in the interlayer
k is the wavenumber
B_1 is the bending stiffness of the main slab
η_1 is the loss factor of the main slab
m_1 is the mass per unit area of the main slab
B_3 is the bending stiffness of the main slab
η_3 is the loss factor of the main slab
m_3 is the mass per unit area of the main slab
$\omega = 2\pi f$

From this expression N$_3$ should be small to get high sound insulation. This means high mass and low bending stifness. The rest of the parameters are hard to see through.

B_3	low (low bending stiffness of the floating floor)
m_3	high (high mass of floating floor)

In 1973 Nilsson derived this expression for a floating floor on continous elastic interlayer [5].

$$\Delta L = 10\log\left[\frac{f^{\frac{5}{2}}\,\eta_2\,2\pi\left({f_{c3}}^2 - {f_{c1}}^2\right)^2 6\,ab}{c{f_0}^2{f_{c3}}^3{f_{c1}}^{\frac{1}{2}}(a+b)}\right] + 10log\left[\frac{\sigma_3}{\sigma_1}\right] \tag{10}$$

It says that the critical frequency of the floating floor should be high, much higher than the critical frequency of the slab. Another way to put it is that the bending stiffnesses of the floating slab should be low, much lower than the bending stiffness of the slab. Also the resonance frequency should be low and the floating floor should have high loss factor.

So, even if we don’t have a reliable expression for the sound insulation of a floating floor we know what parameters to work with.

- The resilient mounts should have low dynamic stiffness
- The density of the floor should be high
- The longitudinal velocity of the floor material should be high
- The thickness of the floor should be high
- The loss factor of the floor should be high
- The bending stiffness of the floor should be low
- The difference in critical frequency of the slab and the floor should be high

Table 1: Importance of different parameters has been ranked compared to each other. Parameters with rank 1 has the highest importance for the sound insulation.

Parameter	**Rank**
The resilient mounts should have low dynamic stiffness	1
The density of the floor should be high	1
The main slab should have much higher mass than the floating floor	1
The main slab should have low mobility	1
The bending stiffness of the floor should be low	2
The longitudinal velocity of the floor material should be high	2
The number of mounts should be low	2
The thickness of the floor should be high	2
The loss factor of the floor should be high	2

To conclude we have the following slab that fulfills all criterias above:

The chosen design consists of a prefabricated subfloor system with the elastic vibration isolation included in the system or on top. The upper slab consists of 22 mm chipboard, concrete tiles (400x400x50 mm) and an upper 22 mm chipboard. In the cavity below a layer of 70 mm glass wool is placed. The walls can be either placed on top of the floating slab or on the main slab. The loss factor of the floor is very high due to internal friction between the tiles and the chipboards. No bending waves can be carried by the concrete tiles, only by the chipboards so the critical frequency is high compared to the main slab.

Figure 3: Picture of the floating slab. In cinemas the upper board was chipboard and a layer of glass wool was placed in the cavity below the floor.

In 1982 Widén presented measurements where he compared concrete tiles with a continous corcrete plate [6]. By this subdivision the sound insulation of the floor was increased by approximately 6-10 dB. Gudmundsson also investigated this concept with good result. However, they used a continous loadbearing elastic layer of mineral wool. The now presented concept with discrete resilient studs combined with concrete tiles has never been used before to the authurs knowledge.

2.2.1 Pros and Cons of the chosen type of floating floor.

Pros: 👍

+ High sound insulation due to:
    High internal damping
    Locally reacting
    Low bending stiffness
+ Low cost
+ Fast building process
+ No casting of concrete means no concrete pumps
+ No time is needed for drying out the concrete.
+ Relatively low weight
+ Can be mounted by carpenters. No concrete casting craftsmen is needed which saves money and time.
+ No need for screed on the main slab

Cons 👎

- The floor has low bending stiffness and cannot be used for carrying high load over large distance. Load has to be supported at the spot where it is acting, using extra vibration isolation where high load occur, under walls etc. This is normally no problem if you know the load and location in advance.
- Running heavy lifts on the floor during the building process is not allowed. High scaffolding with high point loads has to be distributed with beams on top of the floor. If walls are placed beside the floor, the floor can be built in the end of the building process. Then scaffolding and lifts can be used directly on the main slab during the building process.

2.3 Suspended ceiling

To prevent flanking transmission in the upper main slab a gypsum board ceiling is suspended from the slab. The number and type of gypsum boards and the air space is calculated for each situation. A normal suspended steel grid without any elastic hangers have been used in both Filmstaden Scandinavia and in Filmstaden Täby. Both cinemas have excellent sound insulation. Elastic hangers can gain a few dB at higher frequencies but nothing in the critical low frequency domain. They could actually have negative effect on sound insulation because of the spring resonance. By excluding elastic hangers we take away a quite severe cost in the project.

The speakers are mounted directly to the gypsum ceiling. This means there are no actual vibration isolation between the speakers and the main slab.

So, why is there no problem with structure borne sound through the steel rods in the suspended ceiling? It has to do with the coupling between the steel rods to the concrete slab. The very high impedance difference between the steel rod and the concrete slab causes reflection of vibrational waves in the frequency range of interest, so very little vibrational energy is transmitted to the concrete slab.

Sound absorbing ceiling is suspended below the gypsum ceiling.

2.4 Walls

Walls are made of common Gypsum boards and steel studs. Walls up to 10 m height can be built without any support at the sides. Higher walls will need mid-height support to a steel frame. A total wall thickness of about 600 mm is common if corridors or other spaces are placed between cinema theatres.

In some cinemas, the theatres have to be placed right to each other without any corridor in between. In that case this common wall cannot be avoided. One example of a wall having very high sound insulation at low frequencies is from Filmstaden Täby. In that case the maximum allowed thickness of the wall was 500 mm. Still the requirement was a level difference of 48 dB at the 31,5 Hz octave band. This requirement together with the maximum allowed wall thickness of 500 mm makes it impossible to use light weight walls of gypsum boards.

An asymmetric wall type was used, consisting of a brick wall on one side and a gypsum wall on the other. This type of wall get the best of both worlds, heavy walls and light weight walls. The brick wall is built on vibration isolation to prevent structure borne noise is excited in the slab.

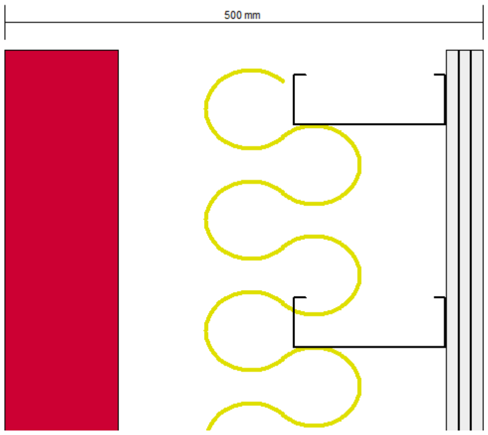

Figure 4: Example of a wall for high sound insulation requirements and limited thickness.

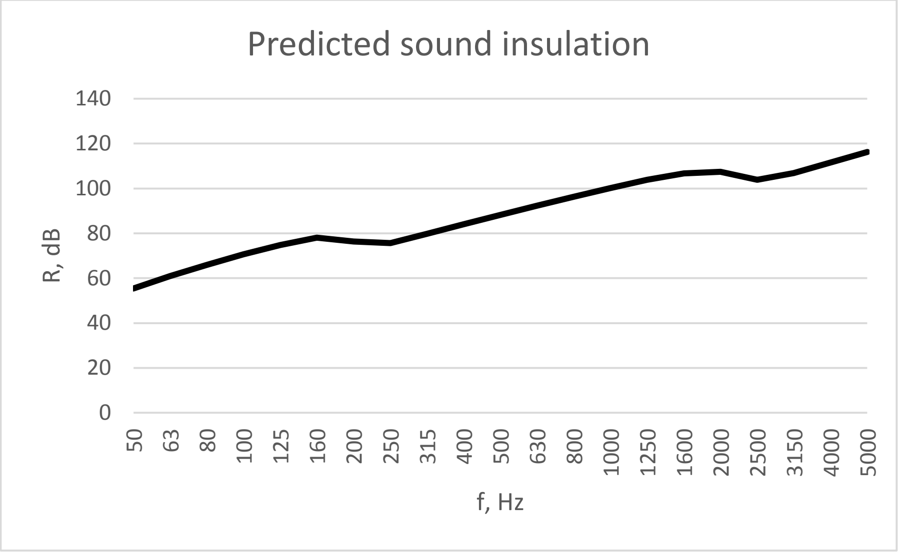

Figure 5: Calculated sound reduction of the wall in figure 4, $R_w = 91$ dB. Flanking transmission will limit the field value.

3 Ventilation

3.1 Ventilation concept

The space below the seating area is used as an air distribution chamber. The floor in the chamber is covered with sound absorption material. Every chair is supplied with air through an individual ventilation opening in the floor below the seat. This design permits large volumes with air supplied at low speed, ensuring quiet operation. Used air is taken out of the theatre through large openings in the ceiling, close to the screen. This concept is a common design in theatres and has been proven to work well, also in these two theatres.

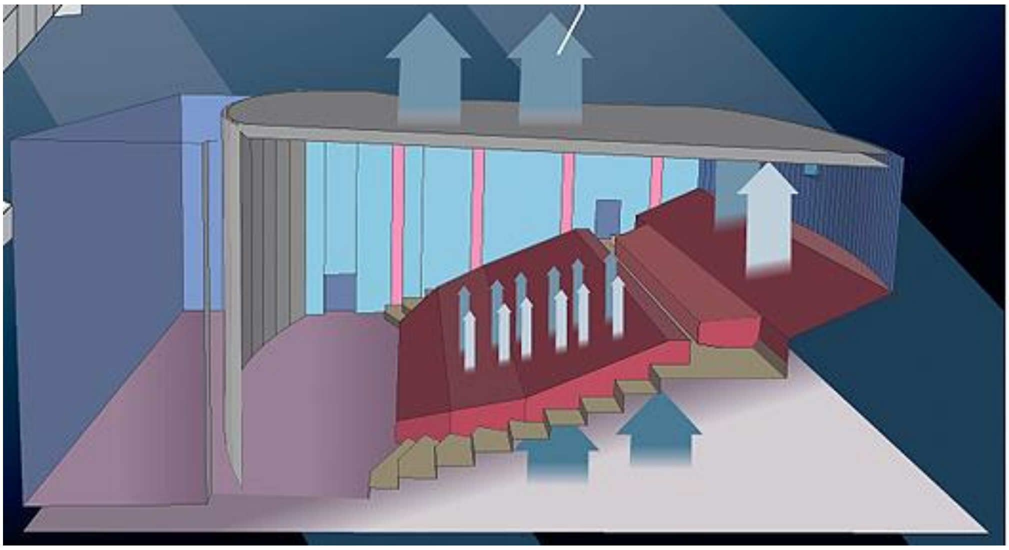

Figure 6: Ventilation air is supplied through the gallery.

4 Room acoustics

The walls are cladded with cassettes of highly perforated steel sheets (perforated steel cassettes was a aesthetic solution required by the client), with different acoustic materials and objects behind. These objects are different types of absorbers and diffusers. To reduce cost the diffusers were made of standard dimensions of timber. Diffusor panels were oriented primly to get maximum diffusion for sound waves arriving from the directions corresponding to cinemas surround speakers and suppress flutter echoes between cinemas sidewalls.

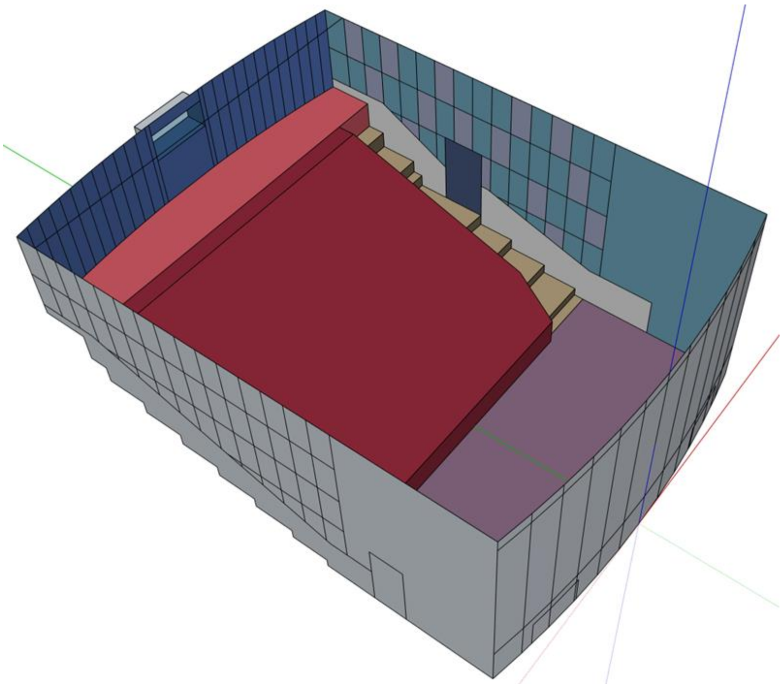

Figure 7: The acoustics of the cinemas were simulated using CATT-Acoustic software.

Diffusers were developed from standard dimension of timber. The sound scattering and diffusion were calculated with BEM based method.

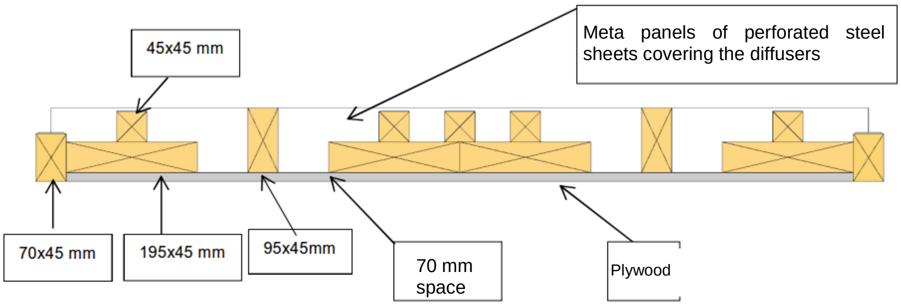

Figure 8: Diffusers were custom built using standard dimensions of timber.

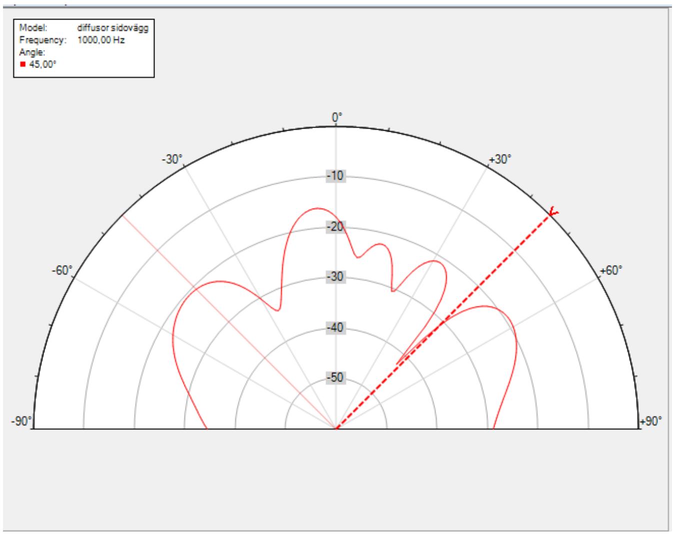

Figure 9: The diffusion from the sound diffusing panels was simulated using boundary element method.

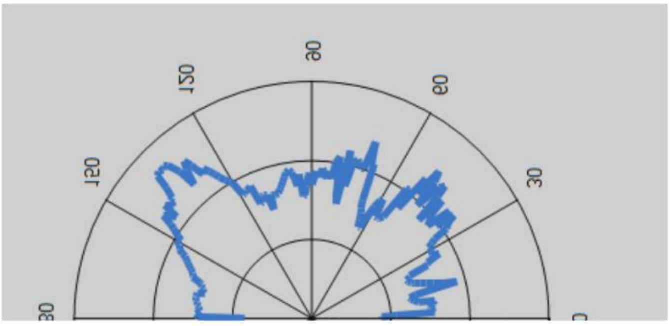

Figure 10: The diffusion can also be simulated using wave based methods. Here is a result from the software Olive Tree Lab suite [7].

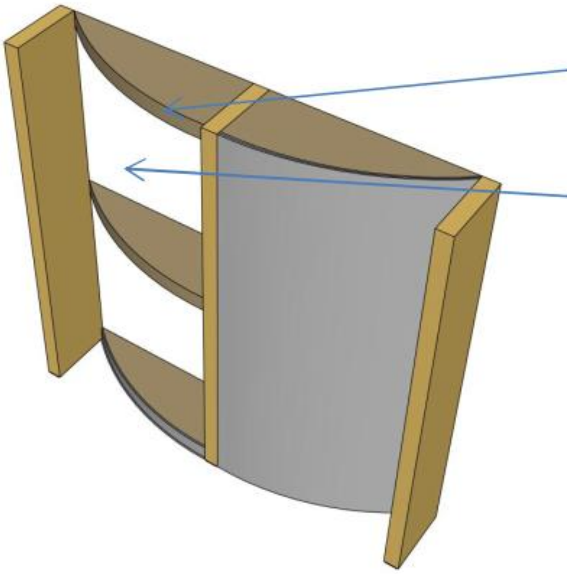

Figure 11: Another type of volumetric diffuser.

4.1 Structure borne noise and vibration from the plant room

On the floor above the cinemas in Filmstaden Scandinavia a large plant room is located. The fans in the plant room supplies air for the shopping centre Mall of Scandinavia. There were ten large fans, each with a mass of 10 tons, located right above the theatres. Structure-borne noise was not allowed to disturb the audience during a movie. The projector booths are hanging from the plant room floor in steel rods. The projectors are sensitive for vibrations as they project the picture almost 30 m to the screen.

Figure 12: In the plant room above the cinema ten fan units, 10 tons each, is located, possibly causing structure borne noise and vibration.

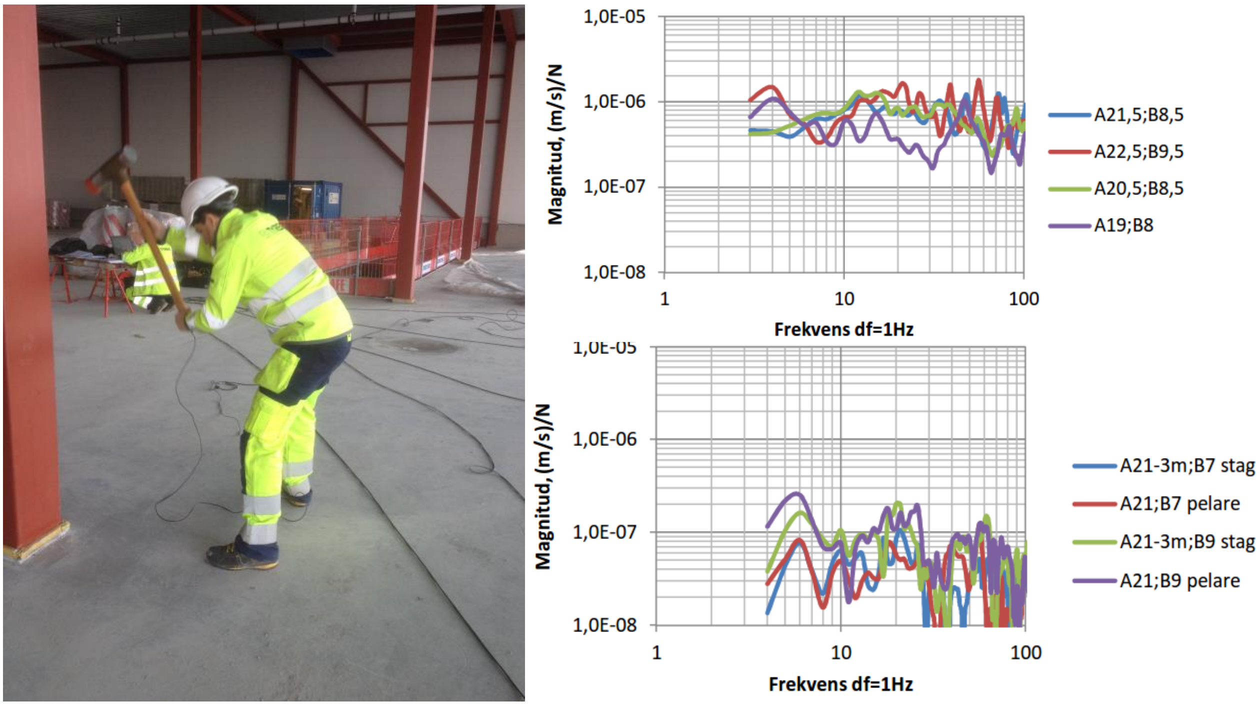

Figure 13: Left: Mobility measurements were performed by Tyréns with an impedance hammer on the plant room slab to be able to predict vibrations from the fan units. Upper right: Point mobility at the location of the fan units. Lower right: Transmission mobility from the location of the fan unit to the steel rod in which the projector booth is hanging.

From the mobility measurements we could see the resonance frequencies in the building. 4 Hz is the first resonance of the framework beam with 24 m span passing above the IMAX theatre. 4 Hz is also the first resonance of the precast hollow slab with 16,2 m span. 12 Hz is the first resonance of the precast hollow slab with 8,1 m span.

To be able to predict the vibration and structure-borne sound levels in the cinema below plant room we needed the source force spectrum for the fan units. This was measured by Tyréns at the factory where the fan units are being built.

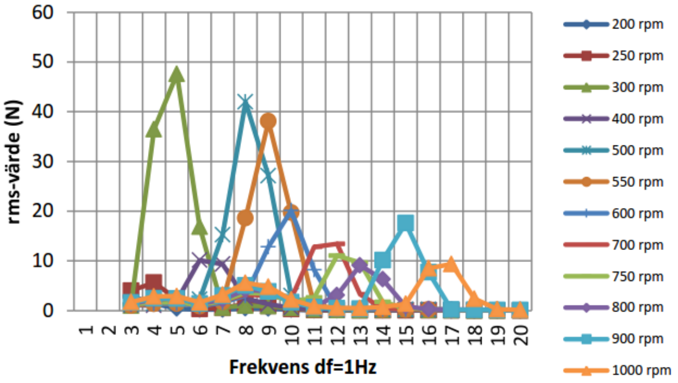

Figure 14: Measurements of the exciting force of the fan unit were performed by Tyréns at the factory of the manufacturer. The fans have variable speed and the force is concentrated to the rpm of the unit. This means that excitation of almost all resonance frequencies in the building is possible.

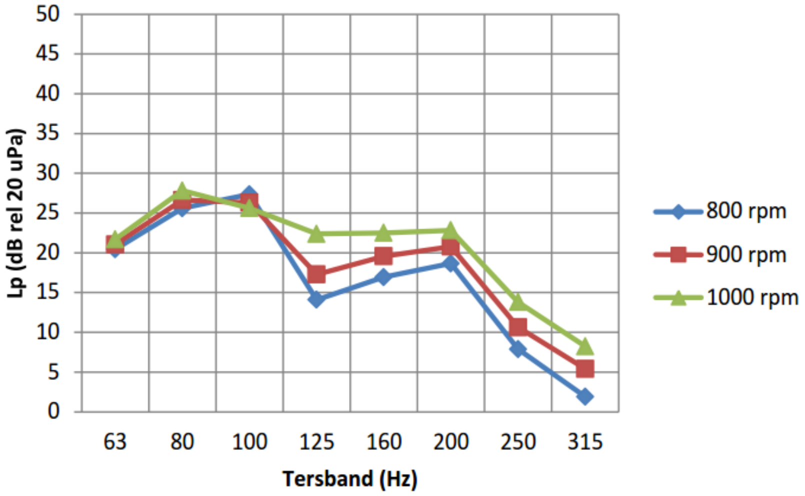

Figure 15: Calculated structure-borne sound level in the cinema below the plant room. The level is well below the requirement NC25. The two peaks in the diagram is the shovel tone (7 times the rpm) and its first multiple.

5 Measurements

Field measurements have been made both in Filmstaden Täby and in Filmstaden Scandinavia. Some of the results are presented here. All measurements are fulfilling the requirement.

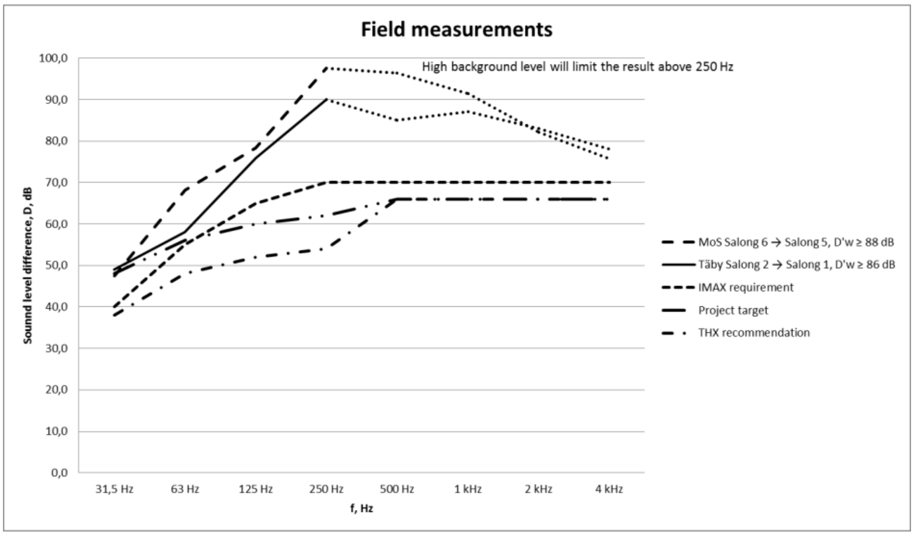

Figure 16: Field measurement of the wall in figure 14, $D'_w \geq$ 86-88 dB.

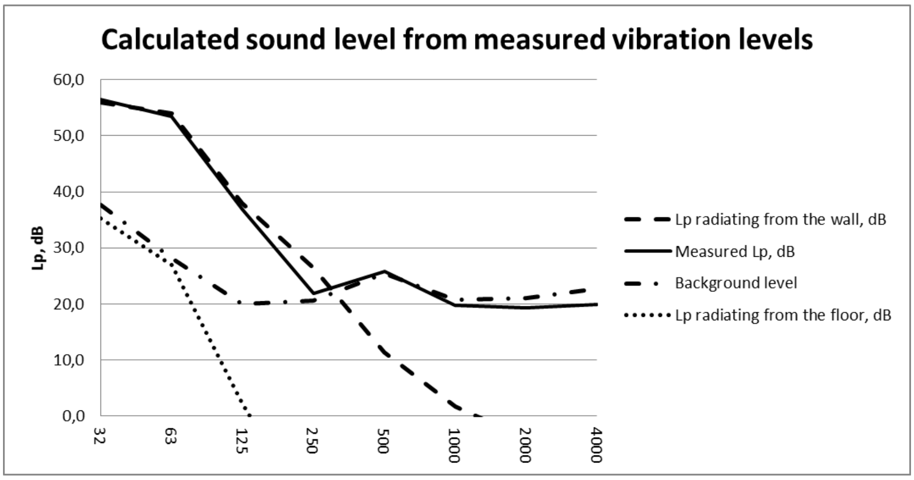

Figure 17: Field measurement of the vibrations in the brick wall and floor and calculated radiated sound level compared to measured sound level. Almost all sound is radiated from the wall. The floating floor is performing very well with very low sound radiation.

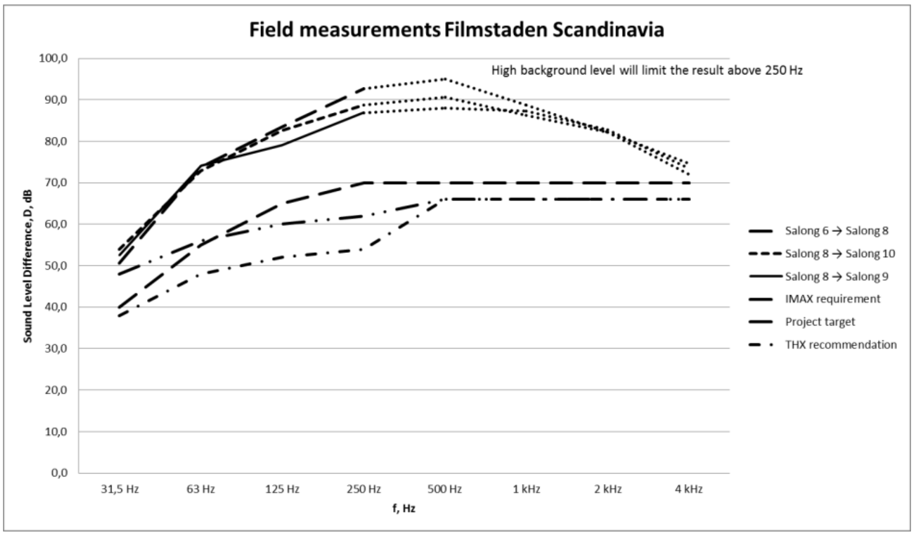

Figure 18: Field measurement of level difference between theatres in Filmstaden Scandinavia with lightweight walls and corridor in between.

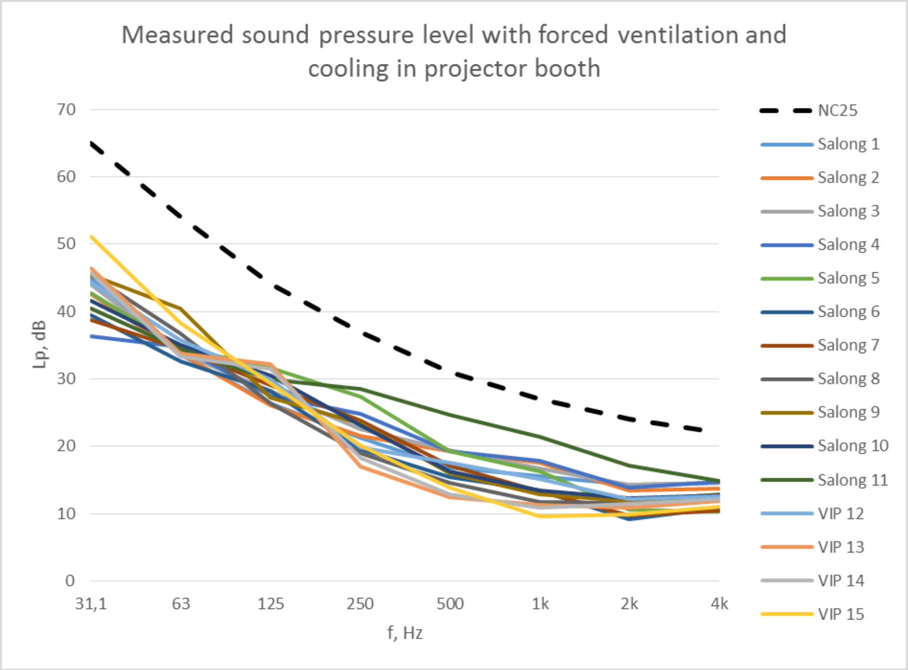

Figure 19: Field measurement of sound pressure level in all theatres in Filmstaden Scandinavia. Mean level in audience area. All levels are well below the criteria curve NC25

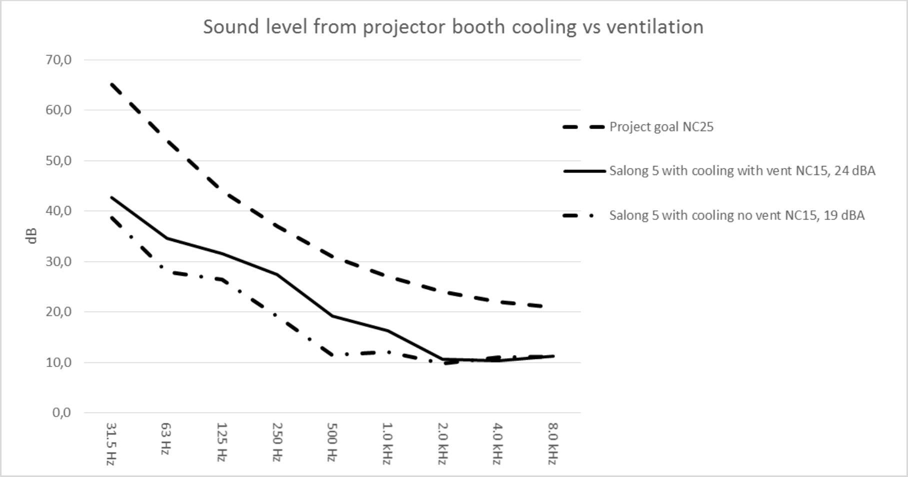

Figure 20: Field measurement of sound pressure level from projector booth cooling vs ventilation in Filmstaden Scandinavia. Mean level in audience area.

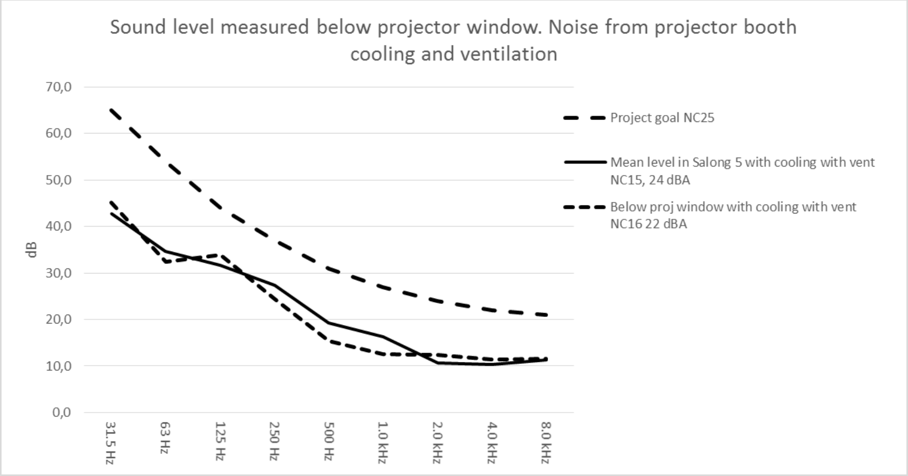

Figure 21: Field measurement of sound pressure level with noise from projector booth cooling and ventilation in Filmstaden Scandinavia. At a location below the projection window.

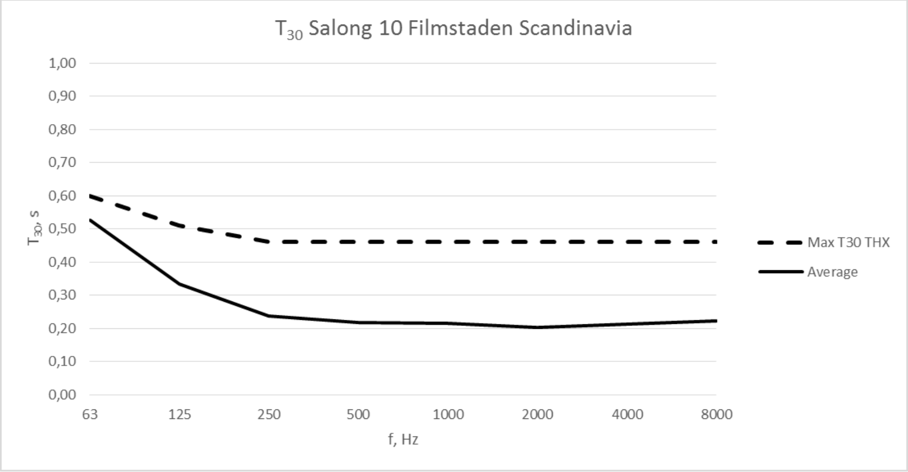

Figure 22: Field measurement of T30 in salong 10

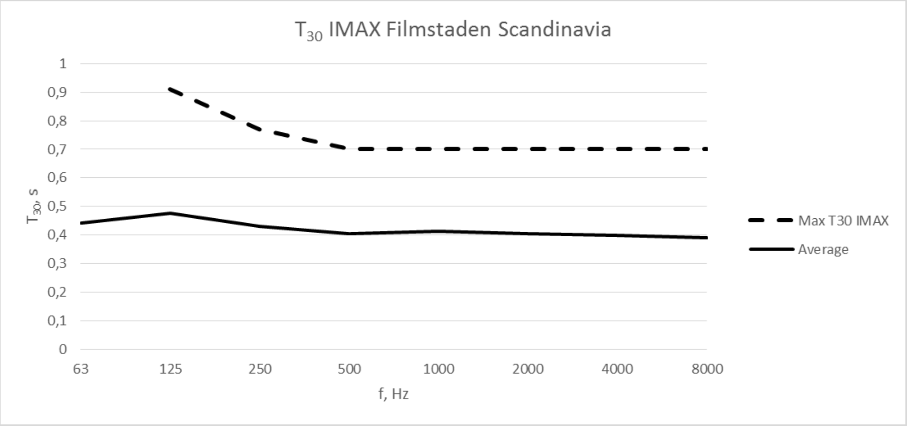

Figure 23: Field measurement of T30 in the IMAX theatre

6 Summary

A new building system for cinemas was developed to reach high acoustic demands and on the same time decrease cost and time consumption during the building process. The system has been used with several revisions in Filmstaden Täby and in Filmstaden Scandinavia in Stockholm. Experience and measurements have shown that the concept is successful in delivering high class cinemas at good cost efficiency.

References

[1] *Folkhälsomyndighetens allmänna råd om höga ljudnivåer*, FoHMFS 2014:15.

[2] Cremer L, *Theorie des Klopfschalles bei Decken mit Schwimmendem Estrich*, Acoustica vol 2, p. 167-179 (1952)

[3] L. Ver, *Acoustical and vibrational performance of Floating Floors*, *BBN Inc*, *Report No 1830 (1969)*

[4] Gudmundsson, *Sound insulation of floating floors. A study of parameters*, Lund Institute of Technology, Report TVBA-30117 (1984)

[5] C. Nilsson, *Acoustical properties of floating floors*, J. Acoust. Soc. Am. Vol 61 (1977)

[6] G. Widén, *Monterbart ljudisolerande flytande golv*, Report H-9279-A

[7] Olive Tree Lab is a software developed by Pemard Ltd, www.olivetreelab.com