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The Hard Case - Improving Room Acoustics in Cuboid Rooms by using Diffusors - Scale model measurements

by Jakob Vennerød

A student project report on scale model measurements, NTNU, Trondheim, 2013

ABSTRACT

Small cuboid rooms with absorption in the ceiling only, are the basis of this report. Long reverberation times and flutter echoes are common challenges in such rooms, and it is suggested to mount diffusing elements on the walls to avoid this. The hypothesis is that a two-dimensional sound field will arise in such rooms, resulting in a long reverberation time, which can be reduced by adding wall-mounted diffusors. Measurements in a 1:4 scale model were performed to verify the two-dimensional sound field behavior, and hard, rectangular diffusors were mounted at the walls in hope of reducing the reverberation time. In addition, the room was simulated in CATT-Acoustic to determine a suitable choice of scattering coefficients.

The results show that reverberation times ten times longer than predicted with traditional formulae can be expected at high frequencies. This indicates a two-dimensional sound field. In the low frequency area, this effect was not observed, as the absorbing ceiling turned out to be much more effective. Diffusors proved to reduce the reverberation time considerably, but their number, size and placement must be chosen carefully. Using equally thick diffusors will create a comb-filtering effect, which is unwanted. Both the long and the short wall should be treated. Preferably, diffusors should be placed as low as possible on the walls to obtain best performance. Smaller vertical window profiles can help, but are much more effective when mounted horizontally. The best achieved reduction in reverberation time was from 4 to 0.8 seconds in full-scale, without adding any absorbents.

akuTEK navigation:

Home
Papers
Articles
Title Index
akuTEK Research
Concert Hall Acoustics

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The Hard Case - Improving Room Acoustics in Cuboid Rooms by using Diffusors

Scale Model Measurements

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Preface

This report is a result of the Specialization Project in Signal Processing, Acoustics and Media, conducted at the Norwegian University of Science and Technology from January to May 2013. Magne Skålevik suggested the project topic as a continuation of his work on small room acoustics – namely his article *The Hard Case*. First and foremost, the report presents measurements done in a scale model of a small room.

The author would like to thank co-supervisor Magne Skålevik for his project suggestion and much appreciated guidance and motivation throughout the project. In addition, Professor Ulf Kristiansen deserves credit for being the primary supervisor and responsible teacher with helpful advice during the work and report writing. Finally, thanks to Staff Engineer Tim Cato Netland who has been very helpful with providing the measurement equipment, and the Engineering Workshop staff Tore Berg & Tore Landsem who constructed the scale model.

Trondheim, May 2013
Jakob Vennerød

Abstract

Small cuboid rooms with absorption only in the ceiling is the basis of this report. Long reverberation times and flutter echoes are common challenges in such rooms, and it is suggested to mount diffusing elements on the walls to avoid this. The hypothesis is that a two-dimensional sound field will arise in such rooms, resulting in a long reverberation time, which can be reduced by adding wall-mounted diffusors.

Measurements in a 1:4 scale model were performed to verify the two-dimensional sound field behaviour, and hard, rectangular diffusors were mounted at the walls in hope of reducing the reverberation time. In addition, the room was simulated in CATT-Acoustic to determine a suitable choice of scattering coefficients.

The results show that reverberation times ten times longer than predicted with traditional formulae can be expected at high frequencies. This indicates a two-dimensional sound field. In the low frequency area, this effect was not observed, as the absorbing ceiling turned out to be much more effective. Diffusors proved to reduce the reverberation time considerably, but their number, size and placement must be chosen carefully.

Using equally thick diffusors will create a comb-filtering effect, which is unwanted. Both the long and the short wall should be treated. Preferably, diffusors should be placed as low as possible on the walls to obtain best performance. Smaller vertical window profiles can help, but are much more effective when mounted horizontally. The best achieved reduction in reverberation time was from 4 to 0.8 seconds in full-scale, without adding any absorbents.

Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

In the field of room acoustics, practical calculation of room acoustic parameters such as reverberation time is often limited to using simple formulas such as Sabine's well-known reverberation time formula. For certain geometrical shapes and uneven distribution of sound absorbing materials, these simplified calculations can give large errors because the assumptions made do not hold. Often, longer reverberation times will be measured in cases where there are parallel surfaces with little or no absorbing materials. To avoid disturbing acoustical phenomena, the surfaces must be treated in some way with absorbers or diffusors.

1.1 The Hard Case

One of these cases is *The Hard Case*, presented by M. Skålevik at Forum Acusticum 2011 [1]. The problem is a very common room type – a cuboid room with hard walls and an absorbing ceiling. Such rooms can be classrooms, offices, meeting rooms, recording studios or rehearsal rooms for music. They all have a common need for acoustic control, because good speech intelligibility and a good listening environment is important. Skålevik argues that such rooms have problems with coloration because of the harmonic behaviour of modal resonances, which unfortunately matches well with the harmonic behaviour of voices and instruments.

The acoustical treatment in The Hard Case is limited to the absorbing ceiling and hard elements placed at the walls, acting as diffusors. No sound absorbing materials can be added to the walls or the floor. Skålevik proposes a "virtual test facility" consisting of two infinitely large parallel surfaces where he shows that the one-dimensional modal reverberation time can be rather long if the surfaces have small amounts of scattering. Introducing hard, rectangular elements to the walls will increase the modal scattering coefficient and the reverberation time will decrease. By consequence, Skålevik argues that these elements can reduce the coloration of voices and music. In addition, the hard walls will create an almost two-dimensional sound field at higher frequencies, where the sound will bounce between the hard, parallel surfaces and create *flutter echo*. Flutter echo is rapid echoes occurring in a periodic pattern and is a well-known problem in small rooms.

A hypothesis can then be framed: Long modal reverberation time and flutter echo is a problem in cuboid rooms with an absorbing ceiling. Adding hard, rectangular diffusors to the walls can reduce the reverberation time and eliminate flutter echo. The null hypothesis is that diffusors will not affect the reverberation time and flutter echo at all.

1.2 Problem description

M. Skålevik defined a problem as the basis of this project:

> *"How many, and how thick, wall-mounted hard rectangular elements are needed in a cuboid room with a sound absorbing ceiling to achieve diffuse-field conditions (i.e. a reverberation time close to predictions with Sabine's formula, elimination of flutter echo and other non-diffuse behaviour)?"*

To investigate this problem, several methods were suggested, including scale model or full-scale measurements, computer simulations or pure theoretical considerations. Since there is quite a lot of previous work on the theoretical part, the main objective of this report will be scale model measurements and some computer simulations.

Measurements will be performed in a 1:4 scale model of a cuboid room with an absorbing ceiling. Then, hard rectangular diffusors will be mounted on the walls to hopefully reduce the reverberation time and flutter echo. Also, smaller diffusing elements, namely window profiles used as stiffeners in window walls, will be investigated in the scale model. Since a scale model will exhibit the same physical behaviour as a full-scale room, the results are expected to give a good indication on how the diffusing elements will act in a real size cuboid room.

1.3 Report structure

Chapter 2 consists the relevant theoretical background in room acoustics, generally, and The Hard Case, particularly. In Chapter 3, the scale model measurement method is presented along with the most significant aspects of room acoustic measurements. Chapter 4 presents the results obtained from the scale model measurements and Chapter 5 presents the computer simulation results. Finally, the results are discussed in Chapter 6 and the conclusions are drawn in Chapter 7.

Since the report contains quite a large amount of measurement results, the reader is referred to Appendix B and C if it desired to study the results in detail.

CHAPTER 2 Theory

This chapter presents some of the most important concepts of small room acoustics and scale model measurements. First, an overview of the classical diffuse field theory and reverberation time will be given, along with more recently developed theory on two-dimensional sound fields. In addition, measures on the linearity of the decay curve will be discussed, as well as a new measure called the *apparent scattering coefficient*. Then, the modal behaviour of small rooms will be explained. Finally, using a scale model and how this affects the measurement results will be discussed.

2.1 Reverberation time

2.1.1 Classical diffuse field theory

The reverberation time is normally regarded as the most important acoustic parameter of a room. The parameter is defined as the time it takes for the sound pressure level to decrease by 60 dB when a sound source is turned off. A simple way to analyse the acoustics of an enclosed space (a room) is to assume a diffuse field. The assumption is that the sound energy distribution is equal everywhere, and the sound pressure level will be the same at every point in the room. If, in addition, the sound absorption is equal at all surfaces, and not too large, Sabine's well-known formula is applicable. The assumption above gives the differential equation for sound energy in a room [2, p. 335]:

$$V\frac{d\epsilon}{dt} + \frac{Ac}{4}\epsilon = \Pi \quad \text{[W]} \tag{2.1}$$

Here, V is the room volume, ϵ is the energy density, A is the absorption area, c is the speed of sound and Π is the input acoustic power. Sabine's formula can then be derived as the -60 dB decay time when removing the power source:

$$T_{Sabine} = \frac{55.3}{c}\frac{V}{S\bar{\alpha} + 4mV} = \frac{0.161V}{S\bar{\alpha} + 4mV} \quad \text{[s]} \tag{2.2}$$

Here, A has been replaced by $S\bar{\alpha}$, the surface area of the room multiplied by the average absorption coefficient. Note that the term $4mV$ has also been introduced, where m is a frequency-dependent absorption coefficient representing the air absorption. A good approximation of m between 1.5 and 10 kHz [2, p. 338], is

$$m = 5.5 \times 10^{-4}(50/RH)(f/1000)^{1.7} \tag{2.3}$$

which is only dependent on the frequency, f, and the relative humidity (RH, given in percent).

When $\bar{\alpha}$ gets large, Sabine's approximation is inaccurate, and will give a reverberation time larger than zero even in a room with perfectly absorbing surfaces. Eyring's equation, based on the *mean free path* $L = 4V/S$ [3] of a sound ray traveling in an enclosure, is more accurate for rooms with high average absorption:

$$T_{Eyring} = \frac{0.161V}{-S\ln(1-\bar{\alpha}) + 4mV} \quad [\mathrm{s}] \tag{2.4}$$

Sabine and Eyring's equations are the two most important formulas for predicting reverberation time in three-dimensional diffuse sound fields. When dealing with a two-dimensional sound field, such as found in *The Hard Case*, different equations must be applied.

Reverberation time in a two-dimensional (2D) sound field

Several articles have been published regarding reverberation times in 2D sound fields. 2D sound fields appear in 3D spaces when the surface absorption factors are significantly larger in one of the directions, such as in the z-direction. A common example is a room with hard walls, a hard floor and an absorbing ceiling, i.e. *The Hard Case*. The result is that less sound energy travels in the z-direction than in the x- and y-direction, creating almost two-dimensional wave propagation.

Tohyama and Suzuki's equation [4] is based on Kosten's mean free path in a two-dimensional space, $L = \pi S_{xy}/L_{xy}$, where S_{xy} is the surface and L_{xy} is the circumference of the 2D sound field. The equation is given by

$$T_{Tohyama} = \frac{0.128S_{xy}}{-L_{xy}\ln(1-\bar{\alpha}_{xy})} \quad [\mathrm{s}] \tag{2.5}$$

where $\bar{\alpha}_{xy}$ is the average absorption coefficient of the walls.

Neubauer and Kostek present several other formulas for calculating the reverberation time in rooms with non-uniformly distributed absorption, along with their own new reverberation time formula [5].

2.1.2 Measurement of reverberation time

Normally, the reverberation time is estimated from the measured room impulse response, by using M. Schröder's energy decay curve [6] calculated with

$$E(t) = \int_t^\infty h^2(t)dt \tag{2.6}$$

where h(t) is the room's impulse response. Figure 2.1 shows an example of a decay curve. In a diffuse field, the decay curve would be perfectly linear, but most real rooms have non-linear decay curves caused by non-diffusivity in the room. Non-uniform distribution of the sound absorption, as well as coupled rooms, can give quite non-linear decay curves. The last part of the decay curve will also flatten out, as this is the point where the impulse response reaches the noise floor.

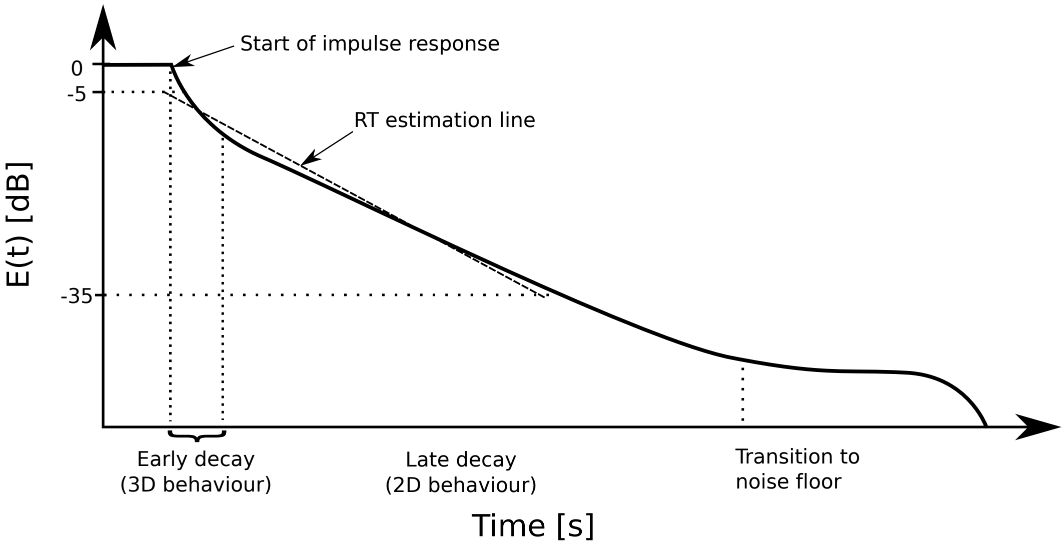

Figure 2.1: Illustration of the energy decay curve calculated with the Schröder method. Note the steeper early decay, which represents the 3D sound field, while the late decay represents the 2D sound field.

The reverberation time is calculated by a least squares fit line, and can be estimated from different parts of the decay curve. The most common parameters are T_{30} (from -5 dB to -35 dB), T_{20} (-5 dB to -25 dB), and Early Decay Time, (EDT, 0 to -10dB). Note that a non-linear decay curve will result in different reverberation times depending on which part of the decay curve is evaluated. The procedure described here is used in ISO 3382-1 [7] .

2.1.3 Non-linear decay curves

ISO 3382-2 [7, p. 18] defines two parameters for evaluating non-linear decay curves. First, a non-linearity parameter ξ given as

$$\xi = 1000(1 - r^2) \quad [‰], \quad r^2 = \frac{\sum_{i=1}^{n}(\hat{L}_i - \bar{L})^2}{\sum_{i=1}^{n}(L_i - \bar{L})^2} \tag{2.7}$$

with $\hat{L}_i, L_i$ and $\bar{L}$ being the estimated curve values, measured curve values and mean measured value, respectively. The standard defines typical values of ξ from 0 ‰ to 5 ‰, and larger values than 10 ‰ indicates a far from straight decay curve.

In addition, the standard defines the simpler curving parameter C

$$C = 100\left(\frac{T20}{T30} - 1\right) \quad [\%] \tag{2.8}$$

which has typical values from 0 % to 5 %, and values larger than 10 % indicate a far from straight curve.

The two parameters can be used for determining whether the measured reverberation times are very dependent on the calculation range or not. Reverberation times in non-diffuse sound fields such as The Hard Case may be very dependent on the calculation range.

2.2 Apparent scattering coefficient

To quantify the effects of a measure in either room acoustics or building acoustics it is often desired to have a single-valued number instead of a frequency dependent value. The value should also be simple to measure and be applicable when predicting reverberation times in similar rooms. Examples of such values are the weighted absorption coefficient, α_W (ISO 11654 [8]), and the weighted sound reduction index, R_W (ISO 717 [9]). α_W describes the absorptive properties of a material with a single value, which makes it easier for acousticians and architects to choose between different materials. R_W describes the sound insulation of a wall in a similar manner.

If the sound field is assumed to be two-dimensional, Tohyama's formula (2.5) can be used to find the relation between reverberation time and the wall absorption coefficient:

$$T_{Tohyama} = \frac{0.128S}{-L\ln\left(1-\bar{\alpha}_{xy}\right)} \quad [\mathrm{s}] \tag{2.9}$$

$$\Rightarrow \bar{\alpha}_{xy} = 1 - \exp\left(-\frac{0.128S}{LT}\right) \tag{2.10}$$

where S and L is the surface and circumference of the two-dimensional field, and $\bar{\alpha}_{xy}$ is the surface averaged absorption coefficient on the walls. Note that T and $\bar{\alpha}_{xy}$ are frequency-dependent. Now, assume that by adding diffusors to the walls, the apparent wall absorption will increase because energy is diverted from the 2D sound field to the vertical sound field, and thus it will eventually be absorbed by the ceiling. This apparent increase in wall absorption can be calculated with

$$\Delta\bar{\alpha}_{xy} = \bar{\alpha}_{xy,new} - \bar{\alpha}_{xy,old} = -\exp\left(-\frac{0.128S}{LT_{new}}\right) + \exp\left(-\frac{0.128S}{LT_{old}}\right) \tag{2.11}$$

and the apparent scattering area can be defined as

$$S'(f) = S_{walls}\Delta\bar{\alpha}_{xy}(f) \quad [\mathrm{m}^2\,\mathrm{Sabine}] \tag{2.12}$$

where the $'$ denotes *apparent* since it is based on measurements. To obtain a single numbered value, it is suggested to take the mean value of $S'(f)$ in the desired frequency range, e.g. $\bar{S}_{125-5000}$. The choice of this frequency range will depend on the fundamental acoustical properties of the room, as well as the working range of the diffusors.

Finally, the *apparent scattering coefficient* is introduced, defined as

$$\bar{s}' = \frac{\bar{S}'}{S_{walls}} \tag{2.13}$$

which is actually the same as $\Delta\bar{\alpha}_{xy}$, and therefore a measure of *how the total sound absorption increases by introducing diffusors*. It is also possible to introduce a *surface compensated* apparent scattering coefficient, defined as

$$\bar{s}'' = \frac{\bar{S}'}{S_d} \tag{2.14}$$

where S_d is the total surface area of the diffusors.

2.3 Modal behaviour in 2D and 3D sound fields

In an enclosed space, such as a 2D or 3D sound field, there will always be resonances in the acoustic system. These resonances are normally called modes or standing waves. The dimensions of the space and the boundary conditions determine the resonance frequencies of the modes. In a 3D rectangular space with hard walls, length L, width W and height H, the resonance frequencies are governed by the mode equation:

$$f_{l,m,n} = \frac{c}{2}\sqrt{\left(\frac{l}{L}\right)^2 + \left(\frac{m}{W}\right)^2 + \left(\frac{n}{H}\right)^2} \quad \text{[Hz]} \tag{2.15}$$

Here $[l, m, n]$ indicate the mode number in the $[x, y, z]$ direction. The pressure distribution in space will be

$$\begin{aligned} p_\omega(x, y, z) &= \mathbf{A}\cos(\mathbf{k}_x x + \phi_x)\cos(\mathbf{k}_y y + \phi_y)\cos(\mathbf{k}_z z + \phi_z) \quad \text{[Pa]} \\ \mathbf{k}_i &= k_i + j\alpha_i, \quad i = [x, y, z] \end{aligned} \tag{2.16}$$

where α_i represents the damping in the system mainly caused by absorbing boundaries. Introducing more damping will lower the resonance amplitude and reduce the resonance frequencies. In a 2D sound field, the z-component of the equations can be neglected, which results in much fewer resonances. This has implications on the Schröder frequency, which is discussed later in this section.

The half-power bandwidth of a mode is given by the equation

$$B = \frac{\ln 10^6}{2\pi T} \approx \frac{2.2}{T} \quad \text{[Hz]} \tag{2.17}$$

where T is the reverberation time of the mode. The half-power bandwidth is defined as the frequency difference between the -3 dB points at each side of the resonance frequency. Naturally, this requires a damped system. The definition of the half-power bandwidth is illustrated in Figure 2.2.

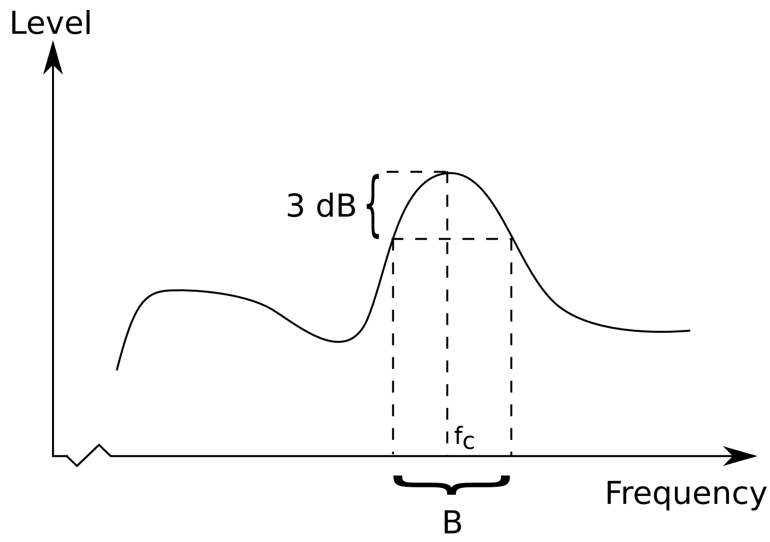

Figure 2.2: Half-power bandwidth of a mode.

A normal approach to differentiate between the modal region and the diffuse field region (or more correctly, the upper frequency limit of the modal region), is to calculate the Schröder frequency [10]:

$$f_S = 2000\sqrt{\frac{T}{V}} \quad [\mathrm{Hz}] \tag{2.18}$$

Here, T is the reverberation time and V is the room volume. However, M. Skålevik suggests to use a different formula for 2D sound fields [11]. The number of modes below a frequency f in a 2D sound field can be calculated in the same way as the 3D case, shown in [12, p. 77]. This gives

$$N(f) = \frac{\pi S f^2}{c^2} \tag{2.19}$$

$$\frac{dN}{df} = \frac{2\pi S f}{c^2} \tag{2.20}$$

and Schröder's criterion

$$\frac{dN}{df} B > 3 \tag{2.21}$$

can be used to find the Schröder frequency in a 2D sound field

$$f_{S,2D} \approx 25000\frac{T}{S} \quad [\mathrm{Hz}] \tag{2.22}$$

where S is the surface area of the 2D field. Note that the 2D Schröder frequency will be higher in most ordinary rooms.

2.4 Scale model considerations

The majority of the results in this report originates from the scale model measurements. A scale model is simply a smaller model of an acoustic structure, and this requires corrections to the previous equations when comparing scale model measurements to full-scale measurements.

When the dimensions of a model is reduced by a factor X (i.e. 1:X-scale), the wavelengths must also be scaled correspondingly. This results in inverse frequency scaling:

$$f_{model} = X f_{full} \quad [\text{Hz}] \tag{2.23}$$

As a consequence, the measurement equipment must be capable of measuring higher frequencies, and the materials in the model must be selected to absorb sound X times higher in frequency. In addition, the reverberation time will be scaled by

$$T_{model} = 0.161 \frac{V_{model}}{S_{model}\bar{\alpha}} = 0.161 \frac{V_{full}/X^3}{S_{full}\alpha/X^2} = \frac{T_{full}}{X} \quad [\text{s}] \tag{2.24}$$

This creates one complication: The air absorption does not increase linearly with frequency, but with an exponent of 1.7. The $4mV$ term divided by the wall absorption area, $S\bar{\alpha}$, will then increase with an exponent of 0.7 as the scale increases. This results in much more relative air absorption in small scale models, often requiring other gases than air to prevent too much air absorption. The relation in Equation (2.24) can be derived from Eyring or Tohyama's formula in a similar manner.

When comparing the measurement results to expected results in a full-scale room, the relative difference in air absorption must be considered in the following way:

- Since the dimensions and wavelengths are scaled, the relation $T_{full}(f/X) = XT_{scale}(f)$ arises, assuming the ceiling absorption is equal for f/X in the model and f in the full-scale room.
- When air absorption is taken into account, the factor $4mV$ will increase by $X^{1.3}$ at f/X Hz. However, the surface absorption increases with X^2, and this increases the surface-to-air absorption ratio A_s/A_{air} in the full-scale room.
- Consequently, the up-scaled reverberation time curve will increase in the high frequency area when including the difference in air absorption.

CHAPTER 3

Scale model measurements

The measurement equipment and method will be discussed in this chapter. First, the scale model used in the measurements is described, along with the diffusors that will be mounted on the walls. Then, an overview over the equipment used to measure impulse responses is given. This includes both the hardware (loudspeakers, microphones and sound card) and the measurement software. Finally, the measurement procedure needed to do reliable and repeatable measurements is explained.

3.1 Description of the scale model

The 1:4 scale model, illustrated in Figure 3.1, is a box of 18 mm plywood with inner dimensions of 237 × 147 × 84.5 cm, corresponding to a full-scale room of 9.5 × 5.9 × 3.4 m. The dimensions were chosen realistically, from a selection of rooms measured at the University campus.

Table 3.1: Examples of some room dimensions at NTNU compared to the up-scaled dimension of the model.

Room	L	W	H	Volume	Surface
Antenna lab	8.0	6.6	2.4	127	176
Acoustics meeting room	8.0	6.6	2.7	143	184
Acoustics computer lab	8.6	5.5	3.0	142	179
Electro council room	11.6	7.3	3.0	254	283
Meeting room F453	4.7	4.5	2.8	59	94
Meeting room B343	10.3	6.0	3.0	185	221
Meeting room EL21	11.2	7.6	2.5	213	264
Group room G022	8.2	6.6	3.0	162	197
Group room G034	6.9	6.5	3.0	135	170
Group room B206	12.5	5.7	3.0	214	252
Reading room C228	5.8	5.6	3.0	97	133
Average	8.7	6.2	2.9	157	196
Model room, upscaled	9.5	5.9	3.4	191	217

As shown in Table 3.1, the up-scaled model room is a little higher than the other ones, as the height is given without a suspended ceiling, which reduces the effective height by 0.4 m. The volume and surface area is also a bit larger, as the study targeted classrooms and meeting rooms that are slightly larger than the measured group rooms.

Initial measurements showed a very high reverberation time peak, almost three seconds, at 315 Hz. This gave a suspicion that there were wall resonances influencing the reverberation time. Consequently, the model was reinforced with wooden studs on the outside, and the reverberation time at 315 Hz dropped to under two seconds. This shows that stiff enough walls are important to reduce extra reverberation from the plate resonances.

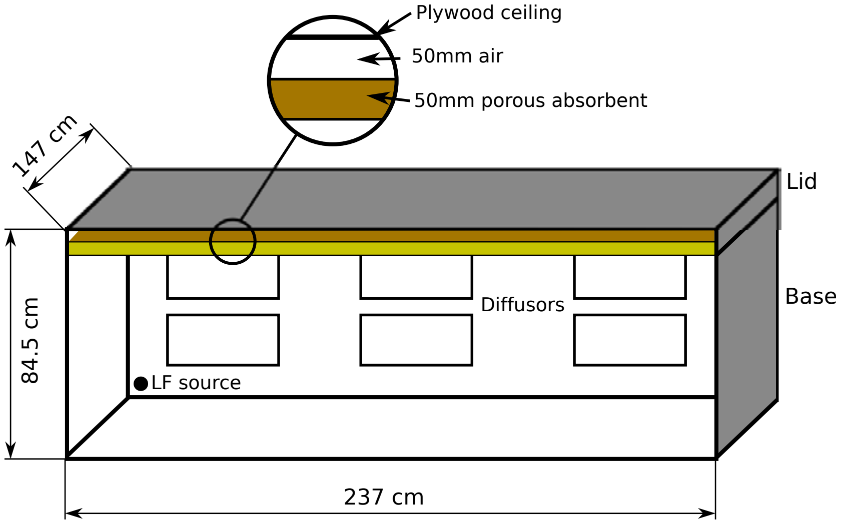

Figure 3.1: Illustration of the scale model interior. The lid can be lifted off to change the measurement setup inside the model. Notice the placement of the low-frequency (LF) source.

In the lid a 50 mm synthetic porous absorbent is hung with a 50 mm air gap, to maximize the ceiling absorption. The absorption coefficient can easily be calculated with a simple Delaney-Bazley model, with the WinFlag software by Vigran [13]. Figure 3.2 shows an estimate of the random- and normal-incidence absorption coefficients, assuming a flow resistivity of 5 kPa s/m^2.

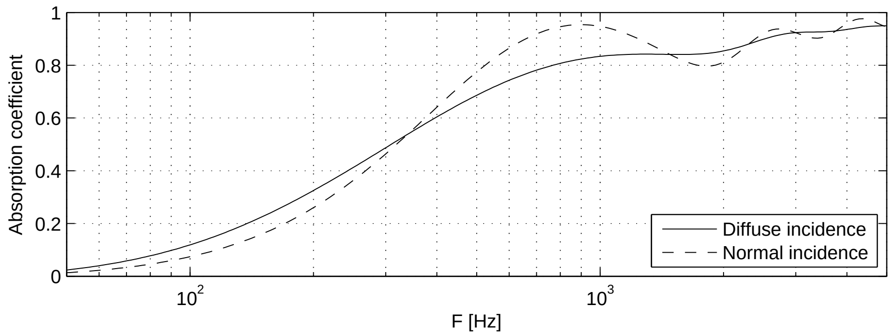

Figure 3.2: Estimated absorption coefficient of the suspended ceiling.

This is a rough estimation, but Vigran [14, p. 155] shows that the porous absorber and air gap thicknesses are much more important for the low-frequency performance than the flow resistivity. One can then assume that the suspended ceiling is good absorber ($\alpha > 0.5$) from about 350 Hz and up.

3.1.1 Diffusors

Measurements were performed with two types of diffusors. The first category is hard, rectangular diffusors made of 22 mm chipboard with dimensions 50×25 cm, and different depths ranging from 22 mm to 112 mm. To ease the construction work, the diffusors were made of chipboard frames with a solid top plate, giving a hollow box. This should not affect the stiffness of the diffusor particularly, but there is a possible risk of cavity resonances in the diffusor. Assuming an average slit width of 0.3 mm, which is more than observed on the diffusors, the Helmholtz resonance

$$f_H = \frac{c_0}{2\pi}\sqrt{\frac{S}{Vd}} \quad \text{[Hz]} \tag{3.1}$$

is under 200 Hz for all diffusor configurations. Hence, the risk of resonance is in the bottom end of the frequency area of interest. Threaded rods with nuts were used to mount the diffusors on the walls. A sketch of the diffusor construction is shown in Figure 3.3.

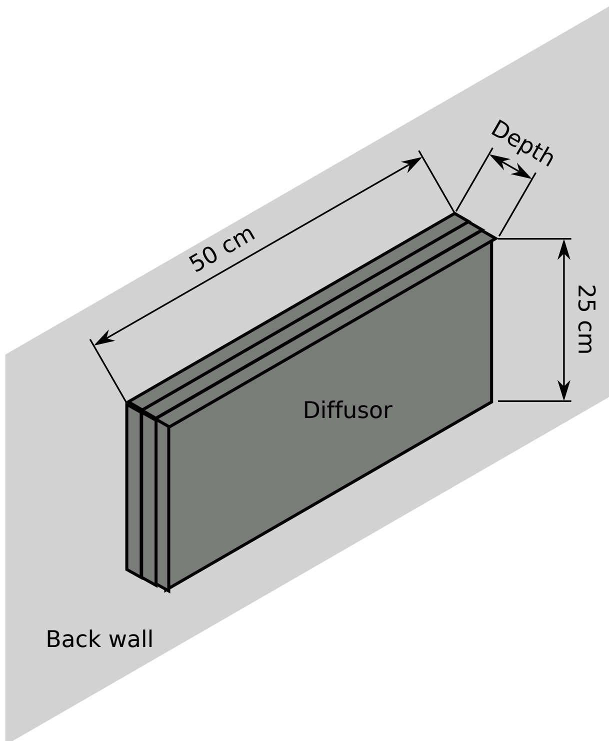

Figure 3.3: Construction of hard, rectangular diffusors.

The second category of diffusors is window profiles made of wooden studs. Window profiles are used for stiffening large window surfaces that are often found in office buildings, schools and atriums. Typical sizes are 5-20 cm width and depth, and they are used both vertically and horizontally, depending on the ceiling height. Three types of window profiles were measured: 38×16 mm, 65×20 mm and 70×35 mm. All the profiles were 70 cm long, giving the possibility of both vertical and horizontal mounting. The profile dimensions may seem small, but remember that this is 1:4 scale, so they represent medium to large window profiles with sizes of 56 - 280 mm.

Ten hard, rectangular 22 mm thick diffusors with 20, 30 and 40 mm frames were constructed, and ten window profiles of each dimension were cut. Most measurements are done with diffusors on one long and one short wall, from now on described as the "L-form", as indicated with grey fields in Figure 3.5. This was done to reduce the workload and material costs. Measurements were done to document the differences between L-form and diffusors on all the walls.

3.2 Measurement equipment

The measurement chain needed to cover a wide frequency range, from the lowest scale model resonance frequency of 72 Hz to the higher octave bands of 20 - 25 kHz (the 6.3 kHz octave band in a full-scale room corresponds to 25 kHz in the scale model). In addition, the source should be as omni-directional as possible to comply with the ISO 3382 standard. To fulfil these demands in the best way possible, two types of sources were used. In the low frequency range, a 2" AuraSound driver mounted at the mouth of a sealed aluminium pipe was used. It was mounted flush with the wall, so it can essentially be regarded as a wall-mounted point source at frequencies below 1.5-2 kHz. The mounting position is shown in Figures 3.1 and 3.5. Placing the loudspeaker in the corner will excite all the room modes equally, according to Equation (2.16).

To measure the higher frequencies, the requirements in ISO 3382 should be fulfilled in the best way possible both with respect to measurement positions and source directivity. Since the dodecahedron (12-sided) loudspeaker is a common source type for standard room acoustic measurements, a small-scale dodecahedron was constructed for the measurements. The body was made of 12 thin plastic pentagons, each fitted with a SEAS 1" dome tweeter.

Directionality and frequency response of the low- and high-frequency loudspeakers was verified in the anechoic chamber at NTNU. The pipe loudspeaker rolls off with $\sim$12 dB/octave below 200Hz and is quite omnidirectional ($\pm$2.5 dB) below 2 kHz. The dome tweeters roll off with $\sim$12 dB/octave below 3 kHz, and the dodecahedron speaker is quite omnidirectional for most frequencies (at worst $\pm$6 dB in the 8 kHz octave band). The loudspeakers' directivity plots and frequency responses are included in Appendix D. Figure 3.4 shows the two loudspeakers.

At the receiver side, two 1/4" Brüel & Kjær free-field microphones with B&K preamps and a Norsonic power supply were used. 1/4" microphones are less directional than standard 1/2" microphones, and this was considered important since the sound field is not assumed to be 3D-diffuse in the model. The reason for using a different power supply was to reduce the electrical noise, since the Norsonic power supply has the possibility of +40 dB gain, which gave much less noise than

(a) Pipe (LF) loudspeaker. The 2” driver at the right end.

(b) Dodecahedron (HF) loudspeaker

Figure 3.4: Sound sources used in the measurements.

increasing the sound card gain.

3.2.1 Equipment list

The equipment list in Table 3.2 includes all equipment in the measurement chain.

Table 3.2: List of equipment used in the measurements.

Device	Manufacturer	Model	Serial Number	# of units
LF loudspeaker	AuraSound	NSW2-326-8A	N/A	1
HF loudspeaker	SEAS	25TFFN/Q	N/A	12
Power amplifier	Quad	50E	11852	1
2-Channel Sound Card	Focusrite	Saffire Pro 24	PT6930703571	1
1/4” Measurement microphone	Brüel & Kjær	4939	2546543/ 2546544	2
Microphone preamplifier	Norsonic	1201	22038/ 22039	2
Microphone power supply	Norsonic	336	20597	1
Measurement Software	Morset Sound	WinMLS 2004	N/A	1
Laptop	Apple	Macbook Pro	760178U9ATM	1

3.2.2 Software

WinMLS 2004 was used to measure impulse responses in the model with the sine-sweep method. The sampling rate was set to 96 kHz, and the sweep time was 8 seconds. This gave a high enough signal-to-noise ratio to calculate the reverberation time in all octave bands needed.

The version of WinMLS that was used, could only measure reverberation times to 10 kHz in 1/3-octave bands. This was a constraint, since minimum 16 kHz (4 kHz in full-scale) was desired. To avoid this barrier, the sampling frequency in the .wmb impulse response files were modified such that WinMLS believes that it is 24 kHz, not 96 kHz. This gives the ability to calculate reverberation times up to 40 kHz with WinMLS. However, the measured reverberation times will be four times longer, as the impulse response duration is now four times longer. Theoretically, this sampling rate tweak will actually give the same effect as up-scaling the model to real size, except for the non-linear relationship in the air absorption.

Post-calculations, frequency response calculations and plotting was done with MATLAB R2012a.

3.3 Method

For each model configuration, e.g. a particular diffusor setup or a completely empty room, 18 measurements were performed. Three source positions were used, as shown in Figure 3.5: The pipe loudspeaker in the corner (S0) and two positions (S1, S2) for the dodecahedron loudspeaker. Six receiver positions were used (R1-R6). Since two microphones were available, two receiver positions were measured simultaneously.

The acoustic centre of the dodecahedron loudspeaker was 40 cm above the floor, which corresponds to 160 cm in full-scale. Microphone one (R1, R3, R5) was placed 30.5 cm above the floor, and microphone two (R2, R4, R6) was placed 42 cm. This corresponds to 122 cm and 168 cm in full-scale, respectively.

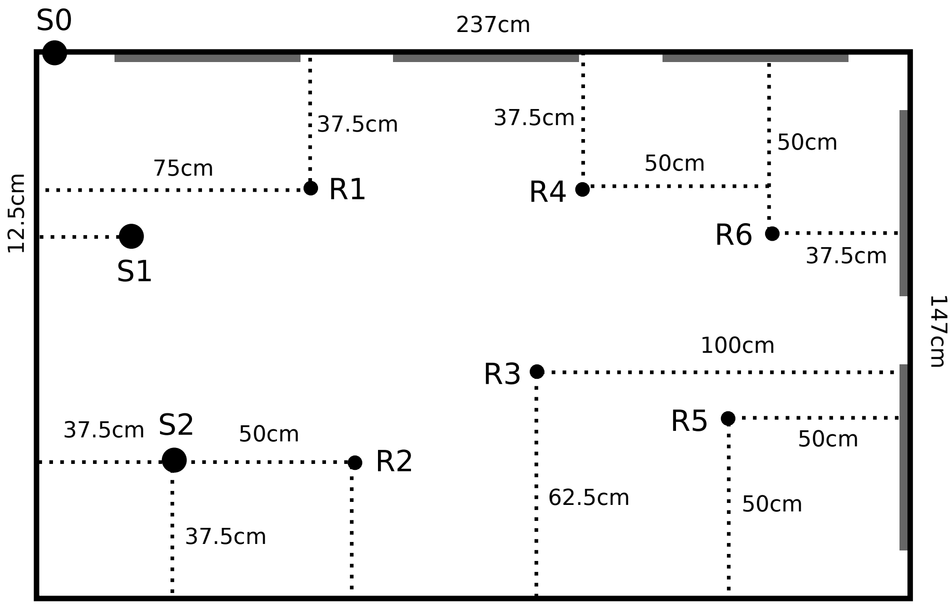

Figure 3.5: Measurement positions in the scale model. Source positions indicated S0-S2, receiver positions indicated R1-R6. Diffusors mounted on "L-form" are shown.

Each measurement day, the temperature and relative humidity was logged with a budget thermo-hygrometer. The temperature stayed at 17° - 19° C, and the relative humidity was in the interval of 24 - 28%. In addition, the microphones were calibrated each morning.

CHAPTER 4

Measurement results

In this chapter, the most significant measurement results are presented. This includes the reverberation times, detailed study of the decay curve, the frequency responses and the calculated apparent scattering coefficients. In most cases, the results are averaged for each measurement series, e.g. the reverberation time is the mean reverberation time for all six receiver positions and two source positions. It is normal to operate with mean reverberation time, since it is often quite similar at different points in the room.

The reverberation times and apparent scattering coefficients are interesting both for the rectangular diffusor case and window profile case, as both showed to affect the reverberation time considerably. The modal behaviour shown in the frequency response is mainly affected by larger objects, so only the responses for measurements with rectangular diffusors is included.

The physical positioning of the different diffusor configurations is illustrated in Appendix A. Since the amount of results is quite large, and not all results are equally important for the core investigations in this report, many of the results are only included in Appendix B and C. From now on, the reader is referred to the appendix if more detail is desired.

4.1 Reverberation time

Since the dodecahedron loudspeaker had low efficiency in the low frequency area, the reverberation times in the frequency bands 160 - 400 Hz (model frequency) were measured with the corner-mounted pipe loudspeaker. For 500 Hz and above, WinMLS reported enough signal-to-noise ratio to calculate accurate reverberation times with the dodecahedron. All the results are T_{30}, i.e. the reverberation time calculated from -5 to -35 dB on the Schröder curve. In addition, the results are averaged over all six receiver positions and two source positions, S1-S2. Below 500Hz, there was only one source position, S0.

The lower frequency axis contains the measured frequency bands, and the upper frequency axis represents the frequency bands in a full-scale room. Correspondingly, the left y-axis is the actual scale model reverberation time, while the right y-axis is the expected reverberation time in a full-scale room, which is four times longer.

4.1.1 Effect of the ceiling absorbent

Since the basis for the investigation is a hard-walled cuboid room with an absorbing ceiling, it is important to know how the absorbing ceiling affects the room acoustical parameters. Figure 4.1 shows how the absorbent reduces the reverberation time.

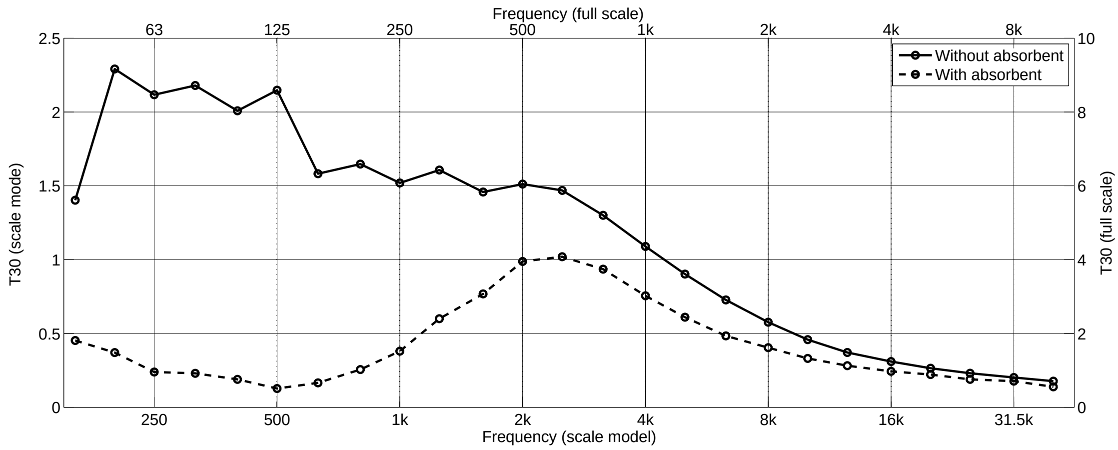

Figure 4.1: Mean reverberation time (T_{30}) with and without absorbing ceiling.

Without the absorbent, the reverberation time is long in the low frequency area, where the air absorption is small. Higher up in frequency, air absorption becomes dominant, and the reverberation time is less affected by the absorbent. It is possible to estimate the absorption areas of the walls and ceiling by using Eyring's Equation (2.4). In addition, the air absorption area $4mV$ can be estimated with m from Equation (2.3). Figure 4.2 shows the theoretical air absorption, the wall and floor absorption (calculated from the empty room absorption minus the theoretical air absorption) and the ceiling absorption (calculated from the treated room absorption minus the remaining walls and theoretical air absorption). The approximation of m is not valid above 10 kHz, and this results in surface absorption areas below zero at high frequencies.

It is clear from both figures that the absorbent is quite effective at mid to low frequencies. This conforms with the estimated absorption coefficient in Figure 3.2, which decreases with lower frequency. In the mid to high frequencies, the effective absorption area decreases drastically, which indicates the formation of a 2D sound field, because the effective absorption is much smaller than expected in a 3D-diffuse sound field. This shows that Sabine or Eyring's equation cannot be used with the predicted absorption coefficients. There is still one unanswered question: Why is the 2D sound field is not so apparent below 1 kHz? The lowest theoretically obtainable reverberation time with Eyring's equation is 0.1 second, and this value is almost reached at 500 Hz. This will be discussed further in Chapter 6.

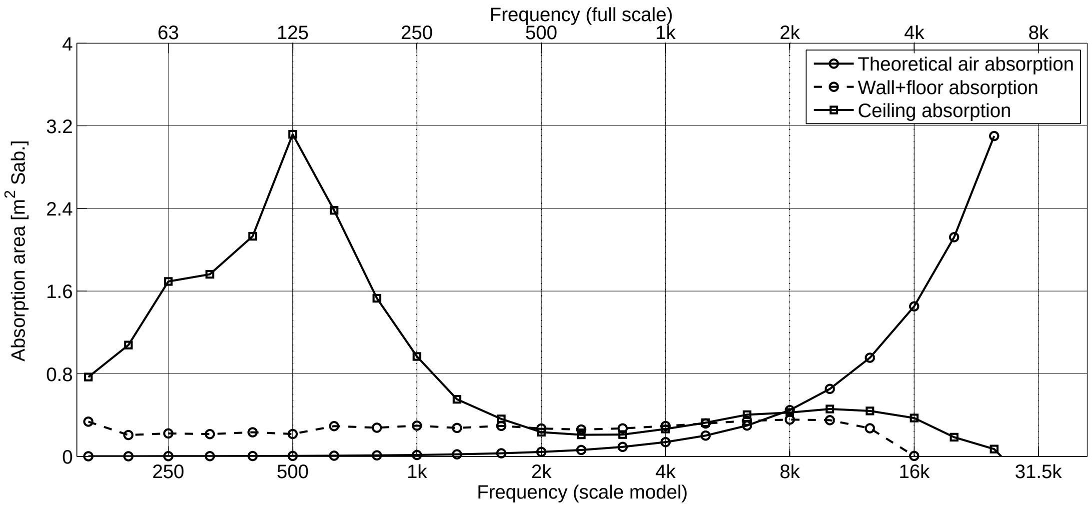

Figure 4.2: Calculated absorption areas with Eyring's formula, Equation (2.4). The air absorption is estimated with Equation (2.3), and the wall+floor and ceiling absorption areas are calculated from the measured reverberation times in Figure 4.1.

4.1.2 Statistical spread

It is interesting to know how the statistical spread is within one measurement series. Since the results from two measurement series can be almost the same, it is important to know whether it is possible to say whether the differences are statistically valid. Figure 4.3 shows the reverberation time without diffusors, and the upper and lower boundaries of a 95% two-sided confidence interval from the Student t's distribution, which can be used for small sample sized with unknown standard deviation [15, p. 1053]. This means that the probability for the true mean reverberation time, $\bar{T}_{30}$, to lie in the interval, is 95%, assuming a normal distributed reverberation time.

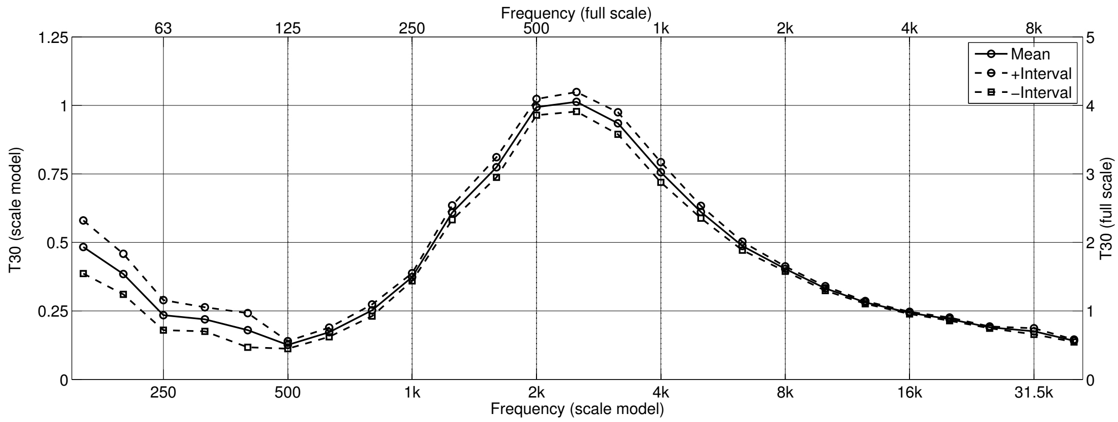

Figure 4.3: Mean reverberation time along with the bounds of a 95% confidence interval (upper and lower lines).

Above 400 Hz, the interval is rather small, since 12 measurement positions were used. From 400 Hz and below, the number of measurement positions is six, which gives a larger confidence interval. This is also caused by more spread in the measurements.

4.1.3 Applying hard, rectangular diffusors to the walls

Now, hard, rectangular diffusors measuring 50 × 25 cm are added to the walls. This section shows how this affects the reverberation times.

Effect of diffusor depth

To investigate the effects of different diffusor depths, 10 diffusors were placed horizontally at two walls, six at the long wall and four at the short wall, as shown in Figure A.1, Setup A. The possible mounting depths were 22, 42, 52, 62, 72, 82, 92 and 112 mm. Figure 4.4 shows the obtained reverberation times for a selection of these depths, while the measurements with all depths can be found in Appendix B.

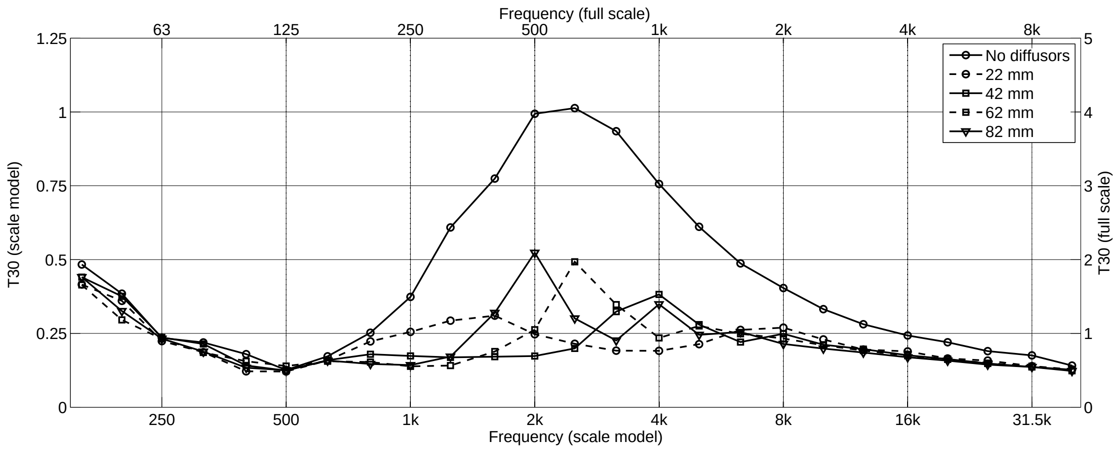

Figure 4.4: Mean reverberation time measured with diffusors of different depth.

Applying diffusors to the walls shows a drastic reduction of the reverberation time, from a maximum of one second at 2.5 kHz to maximums of 0.3 - 0.5 seconds, depending on diffusor depth. Interestingly, the largest diffusors do not provide the largest reduction, but the reduction is largely frequency-dependent and it seems like there is a correlation between diffusor depth and the peak of the curve. A spectrogram of an impulse response, shown in Figure 4.5, reveals that there are peaks in the decay at $N \times 1500$ Hz for the case where the depth is 112 mm. This corresponds to wavelengths of 22.9/N cm. Thus it seems like the diffusor is ineffective at frequencies with wavelengths of 2/N times the diffusor depth. This is also the case for other diffusor depths, shown in Appendix B, Figure B.3.

The spectrogram can be compared to a simple theoretical analysis: Assuming a plane wave hits the wall, one part of the wave front will be reflected by the wall, while another part will be reflected by the diffusor. The sum of these two reflected

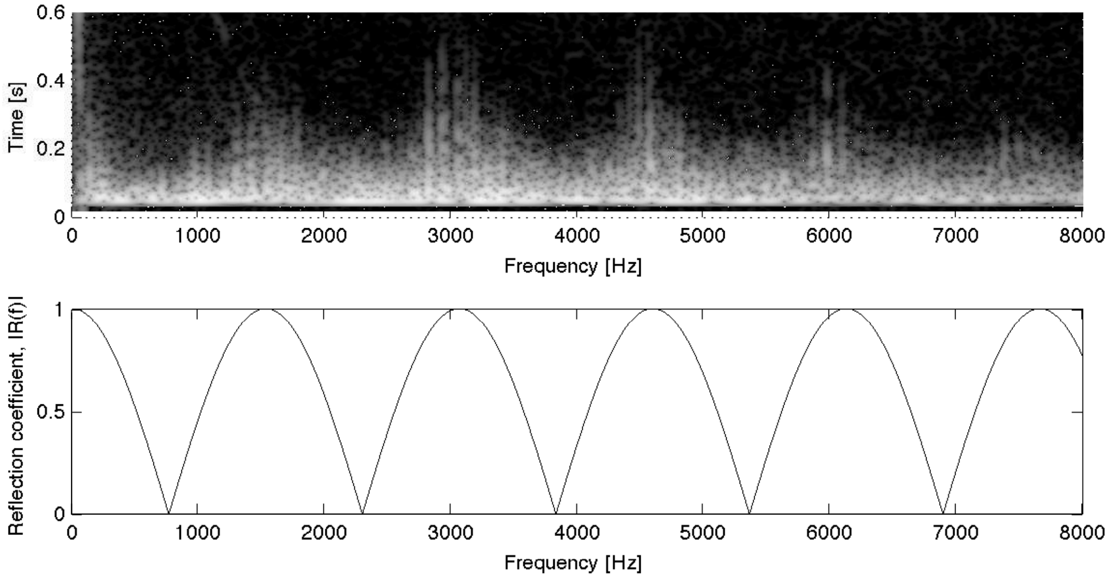

Figure 4.5: Top: Spectrogram measured at source position 0, receiver position 1, diffusor depth 112 mm. Bottom: Reflection coefficient from a 112 mm diffusor.

waves will be $|R(f)| = A(e^{jkx} + e^{jk(x+2d)}) = Ae^{jkx}(1 + e^{jk2d})$. Assuming $A = 1/2$, this expression will equal one when $\lambda = 2d/N$ and zero when $\lambda = 4d/(1+2N)$. It follows that the waves will be reflected in phase when $\lambda = 2d/N$ and the diffusor may not be particularly effective. This could be a plausible explanation for the reverberation peaks, as the simplified reflection coefficient $|R(f)|$ looks very similar to the spectrogram, as shown in Figure 4.5.

Using different diffusor depths at the same time seems to flatten the reverberation time curve, compared to using equal diffusor depths. This is shown in Figure B.2, Appendix B. The depths used are included in Figure A.1, Setup N.

There is no obvious correlation between diffusor size and the measured reverberation time below 500 Hz, and it does not seem like the diffusors matter at all in this frequency area. In the 630-1000 Hz bands, there is definitely a tendency showing lower reverberation time for deeper diffusors.

Effect of diffusor coverage area

Because of architectural reasons, it is desirable to treat the room with as few diffusors as possible. Thus, the percentage of covered area needed is crucial. The configuration with ten diffusors described earlier will here be referred to as the "100 %" configuration, even though the covered area is actually only 21 %.

Figure 4.6 shows the mean reverberation time with the 100 %, 70 %, 50 % and 30 % configurations, using setup A-D (in Figure A.1) respectively.

Little difference can be seen when reducing the coverage to 70 %. A moderate reverberation time increase can be seen when reducing the coverage further. This

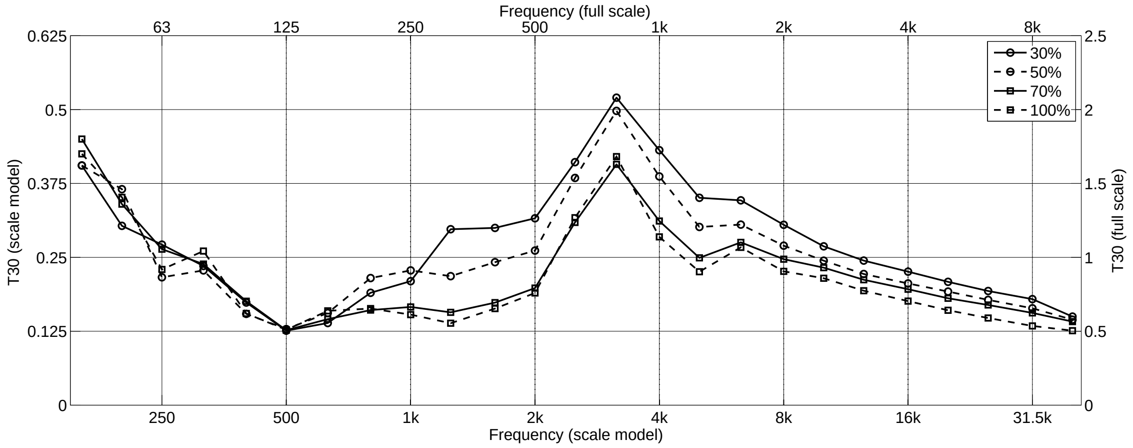

Figure 4.6: Mean reverberation time with different total diffusor area. The diffusor depth is 52 mm.

indicates that around $70 \times 21\,\% \approx 15\,\%$ total area coverage may be the sweet spot for this particular diffusor size. It is nevertheless difficult to predict the optimal coverage area with other diffusor dimensions.

Effect of diffusor placement

Equally important as the diffusor depth and area is the placement. To characterize the effects of different placements, a selection of possible configurations has been measured. A brief sum-up of the results follows below, and the reverberation time results can be found in Appendix B. The setups referred to are illustrated in Appendix A.

1. Placing the diffusors at the long wall or short wall gives roughly the same results, slightly in favour of the short wall configuration from 1 to 2 kHz. Since the short wall has four diffusors, and the long wall has six, the short wall configuration would be preferred. Diffusing both walls is preferred, as flutter echo is avoided in both horizontal directions. See the results in Figure B.4.
2. "Mirroring" the diffusor setup, i.e. placing diffusors across each other on the parallel walls (Setup J) gives no particular advantage or disadvantage over placing them at the opposite ends (Setup E, similar on walls 3 & 4), except for a little shorter reverberation time at 1-1.25 kHz. See the results in Figure B.5.
3. Placing the diffusors at the top end of the walls (Setup F) is considerably worse than placing them at the bottom end (Setup G). The latter gives a bit higher reverberation time at high frequencies, but is quite close to the up + down (Setup A) configuration for mid to low frequencies. This indicates that the diffusors close to the ceiling have much less effect on the reverberation time. See the results in Figure B.6.

4. Whether to align the diffusors horizontally or vertically (Setup K) is also important. The results are in favour of horizontal mounting, with significant improvements for both 22mm and 52mm depths. Especially the mid frequencies between 2 and 8 kHz are affected. See the results in Figure B.7.
5. Combining all the diffusors to one large block at each wall, as in Setup H, causes the reverberation time to increase for almost all frequencies above 630 Hz. See the results in Figure B.8.
6. Most of the measurements were done with diffusors on one long and short wall only (L-form), and it is interesting to see how this compares to distributing the diffusors over all four walls, as in Setup I. The L-form gives longer reverberation times at some frequencies, especially at the peak at 2.5-3.15 kHz. See the results in Figure B.9.
7. Removing the 30 mm frame from the 52 mm diffusor leaves an air space behind the diffusor. Interestingly, this lowers the peak at 3.15 kHz. The reverberation time increases at low frequencies, and decreases at high frequencies. See the results in Figure B.10.

4.1.4 Applying window profiles to the walls

Since studying the acoustic effects of window profiles was not the primary part of the project, these results will be not be presented in the same detail as the previous diffusor results. This does not mean that the results are nonessential, because window profiles may be the only way to treat the walls. The reduction in reverberation time is significant, too.

Window profiles with four parameters were measured: The profile dimensions, horizontal or vertical mounting, one or two walls and lying or standing (i.e. width > depth, w > d, or opposite). Here, the depth is the dimension perpendicular to the wall, and the width is the dimension parallel to the wall.

1. Three different sizes were measured, 38×16, 65×20 and 70×35 mm, mounted horizontally with w > d. The results are not surprising, with a lower reverberation time for larger profiles, especially at mid to low frequencies. The largest profile has the same depth-dependent peak as the diffusors. See the results in Figure B.11.
2. Horizontal (Setup M) versus vertical (Setup L) mounting does not matter much when w < d, but when w > d the difference is much larger, in favour of the horizontal mounting. See the results in Figure B.12.
3. Mounting window profiles on the long wall only gives a much longer reverberation time in the 2 - 6.3 kHz area. Again, the horizontal placement is superior. See the results in Figure B.13.

4.2 Decay curve linearity

Reverberation time is a single number, and the complete decay process is not represented fully by this single numeric value. Figure 4.7 shows an example of the sound decay, with different diffusor depths. The longest decay curve, with no diffusors, is quite straight, while the shorter decay curves seem to have an upward curvature. In the first part, up to about 10 ms, the decay is quite independent of diffusor size, indicating a 3D sound field where the initial reflections dominate. The gentler part of the slopes, which is most prominent with no diffusors, indicate the 2D behaviour. The vertical components of the sound field are quickly hidden behind the horizontal components. These types of decays were much investigated by Nilsson [16], who propose to divide the sound field into two parts, the horizontal (grazing) part and the vertical (non-grazing) part.

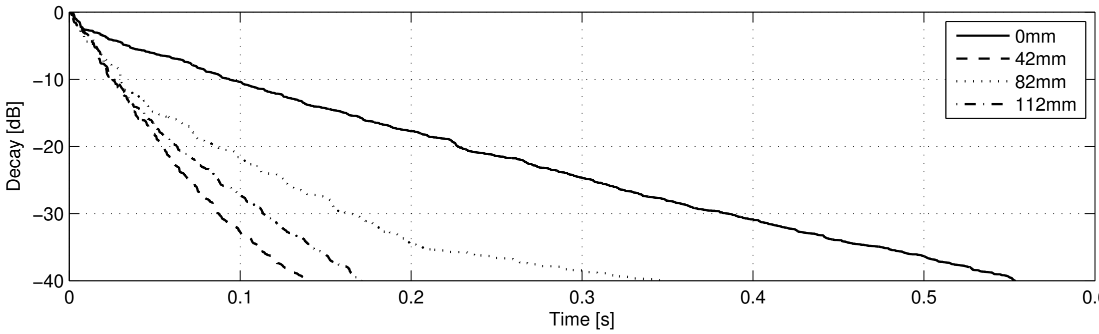

Figure 4.7: Energy decay at 2 kHz, calculated with Schröder's equation (2.6). The lines represent different diffusor depths, along with naked walls (depth = 0 mm). Source position 1, receiver position 6.

Two measures for the decay curve linearity was introduced in the theory chapter: The curvature parameter, C, and the non-linearity parameter, ξ. To briefly investigate these parameters, C was calculated from the mean reverberation time, and ξ was calculated from the decay curves obtained in source position 1, receiver position 6.

Figure 4.8 shows the C parameter as defined in Equation (2.8). The values seem very random, but there is a tendency that the parameter is positive (indicating an upwards curvature) and that mounting diffusers causes the values to increase at certain frequencies. This implies that the decay curve is more linear in the untreated room. The C parameter for T_{10} (-5 to -15 dB), instead of T_{20} is included in the appendix in Figure B.14.

The measured ξ parameter shown in Figure 4.9 is quite varying for different frequencies, but without any diffusors the values lie below 10 ‰ above 800 Hz, indicating a fairly straight decay curve. Introducing diffusors increases the non-linearity parameter, but no particular depth-frequency relation can be seen. Below 800 Hz the values are not usable because the signal-to-noise ratio is less than 35 dB, and the integration of noise will cause the decay curve to flatten out, as seen in Figure 2.1. The peak at 4 kHz indicates that the decay curve is strongly non-linear with 82 mm diffusors.

Finally, it is interesting too see the differences between T_{30}, T_{20} and T_{10}. Figure 4.10 shows that the differences are significant, with a tendency of lower reverberation times for narrower evaluation intervals. This does also indicate an upwards

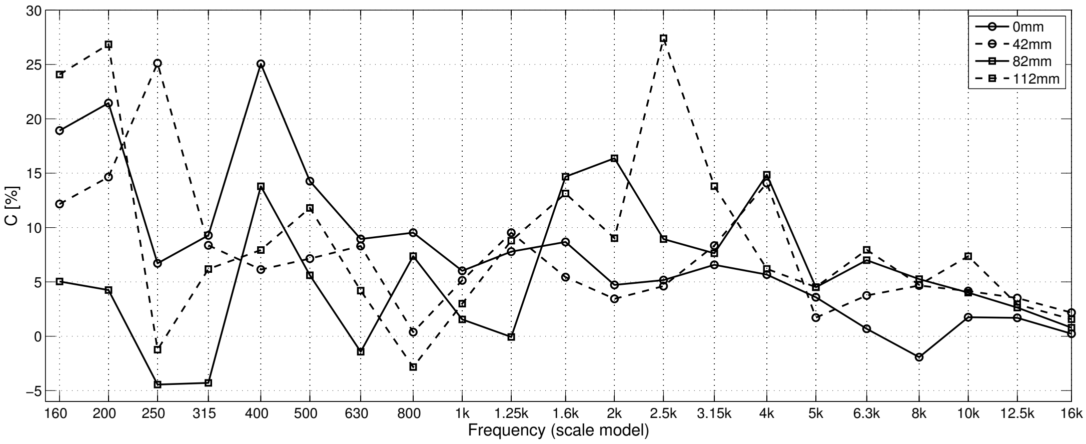

Figure 4.8: Calculated C parameter for different diffusor depths, from Equation (2.8). The values are calculated from the mean T_{20} and T_{30}

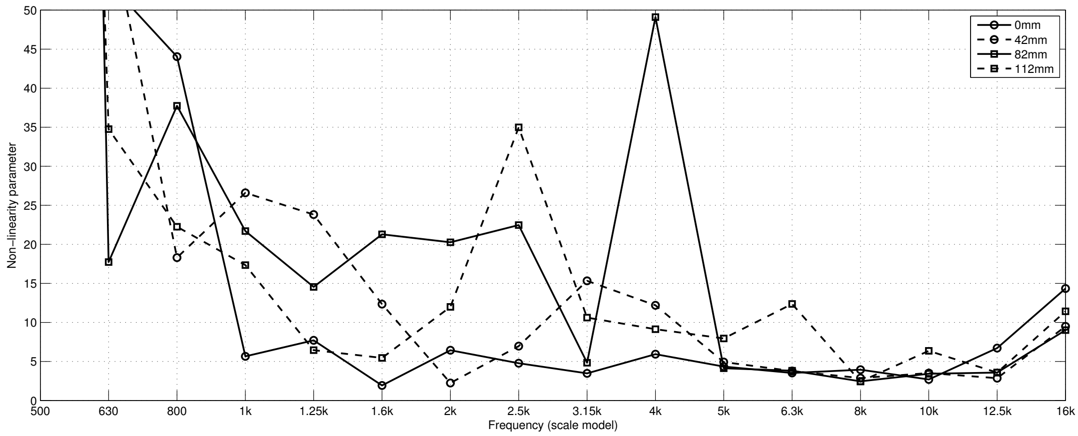

Figure 4.9: Calculated ξ parameter, from Equation (2.7). Source position 1, receiver position 6.

curved reverberation decay.

4.3 Frequency response

Since the diffusors did not give significantly different reverberation times in low frequency area, it is desirable to analyse the low-frequency behaviour of the diffusors in some other way. One approach is to study the frequency response in the modal region, i.e. below the Schröder frequency. This frequency is about 1.1 kHz according to Equation (2.18) and 7.18 kHz according to Equation (2.22), assuming a reverberation time of one second. It is also possible to determine the Schröder frequency by counting the number of horizontal modes below f, $N(f)$, in the scale model and using Schröder criterion $\frac{dN}{df}B > 3$. Equation (2.22) gives an

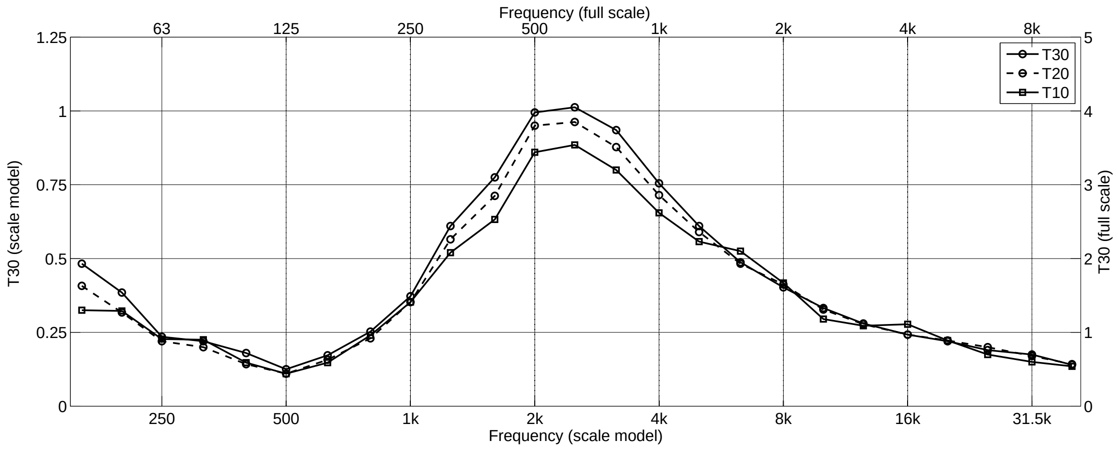

Figure 4.10: Mean reverberation times: T_{30}, T_{20} and T_{10}, measured without diffusors.

approximation, and it turns out that counting $N(f)$ gives almost the same result, $f_{S,2D} = 7150$ Hz. The 2D and 3D Schröder frequencies are quite different, but it is likely that the real low frequency limit of the diffuse field is somewhere between the two.

Figure 4.11 shows the modal behaviour of the room with and without the ceiling absorbent. The responses are calculated as the mean energetic frequency response over all six measurement positions, i.e.

$$L(f) = 10 \log_{10} \left(\frac{1}{6} \sum_{i=1}^{6} |X(f)|^2 \right) \quad \text{[dB]} \tag{4.1}$$

where $X(f)$ is the Fast Fourier Transform (FFT) of the impulse response. The cylinder source was used to measure the frequency responses.

It is obvious that adding the absorbent vastly reduces the resonances in the whole frequency area between 100 Hz and 1 kHz. Especially in the 400 - 700 Hz region (where the reverberation times are shortest) the resonances cannot be clearly distinguished when the ceiling absorbent is installed. The frequency response in the 100-1000 Hz range is roughly within ± 6 dB, disregarding the loudspeaker drop-off below 250 Hz. It is also evident that determining the -3dB peaks for the resonance frequencies is impossible in most cases because the modes are overlapping each other. Consequently, determining the modal reverberation time by $T = 2.2/B$ is not possible for most modes.

Treating the walls with diffusors should ideally give reduced modal behaviour, and therefore flatten the frequency response. Figure 4.12 shows the response between 700 and 800 Hz, with diffusors of depth 0 (no diffusors), 42, 82 and 112 mm. The 750 Hz peak is almost identical with 42mm depth as with no diffusors, but reduced in amplitude and increased in bandwidth for the larger depths. However, the modal overlap makes it difficult to determine the -3dB bandwidth accurately.

The frequency response with diffusors from 100 Hz to 1 kHz is included in

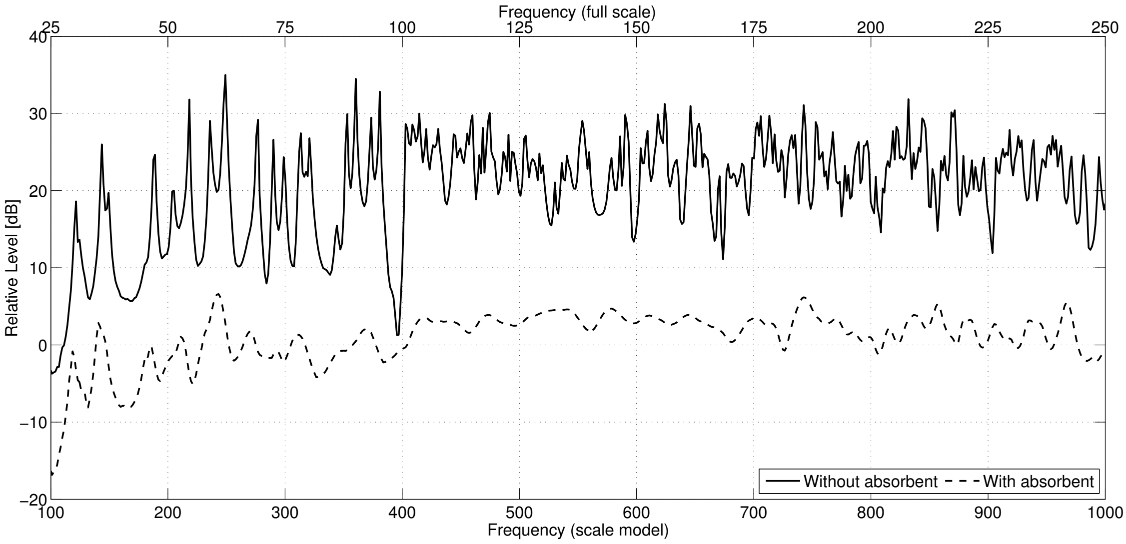

Figure 4.11: Energy averaged frequency response with or without absorbent. Note that the response without absorbent has been shifted upwards to increase readability.

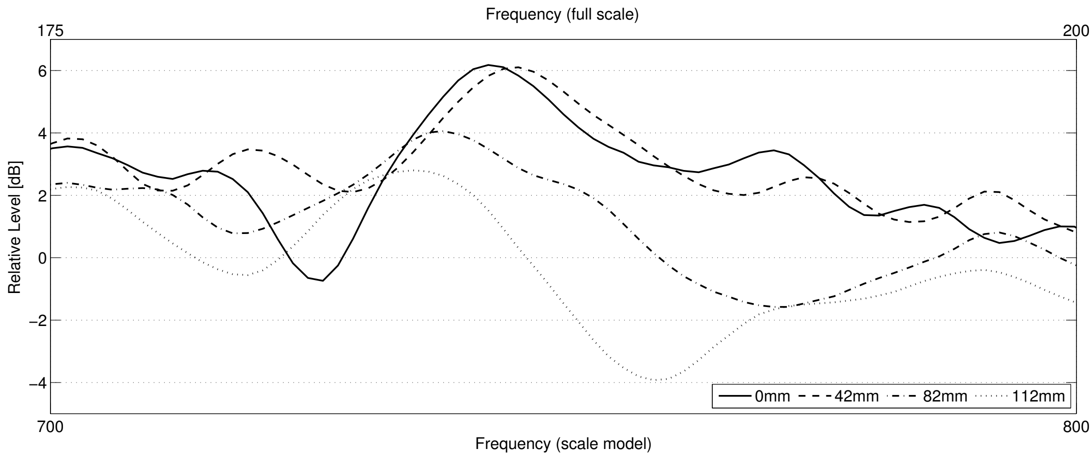

Figure 4.12: Energy averaged frequency response from 700 to 800 Hz. Measured with different diffusor depths. Diffusors are placed on L-form (Setup A).

Figure B.15 in Appendix B. The response is flattened in most areas, but a few resonance peaks are actually increased and narrowed. To measure the flatness of the response, Cox, D'Antonio and Avis' method [17, p. 644] was used. They propose calculating the sum of square deviation from a least squares fit line, given by the equation

$$\epsilon = \sum_{n=1}^{N} (L_{p,n} - m f_n + c)^2 \tag{4.2}$$

where $L_{p,n}$ is the measured frequency response at frequency f_n, and m and c are the least squares fit coefficients.

Table 4.1: Sum of square deviation from the linear fit. Frequency area: 100 - 1500 Hz.

Depth [mm]	0	22	42	52	62	72	82	92	112
Error ($/10^3$)	10,01	10,14	11,78	12,36	11,08	9,75	8,05	7,84	7,43

The calculations in Table 4.1 show a slight increase in the deviation sum for small diffusor depths, but reduction for large diffusor depths. Beyond a certain depth, it seems like the deeper the diffusors are, the smoother the frequency response becomes in the modal area, although the visible improvement in the frequency response is not that evident.

4.4 Apparent scattering coefficient

In Section 2.2, three measures for the diffusor performance were introduced. Table 4.2 shows the results for the most important diffusor configurations, for two frequency ranges. The first range, 500 Hz - 20 kHz, is based on the common measurement range for reverberation time [7, p. 9], corresponding to 125 Hz - 5 kHz in full-scale. The lowest frequency band (100 Hz) was excluded since no improvement was seen here. The second range, 1250 Hz - 5 kHz, is based on the range where the reverberation time was longest without diffusors, and since most improvement was seen here, the values will be somewhat higher.

Table 4.2: Apparent scattering area S', apparent scattering coefficient s' and surface compensated apparent scattering coefficient, s'', for a selection of diffusor configurations. S_d is the total diffusor area.

Configuration	Setup	S_d	$S'_{500-20k}$	$S'_{1250-5k}$	$s'_{500-20k}$	$s'_{1250-5k}$	$s''_{500-20k}$	$s''_{1250-5k}$
L-form	A	1.25	0.63	0.92	10.9 %	15.9 %	0.50	0.73
70% area	B	0.88	0.57	0.85	9.8 %	14.7 %	0.65	0.97
50% area	C	0.63	0.38	0.58	6.6 %	10.2 %	0.61	0.94
30% area	D	0.38	0.31	0.44	5.4 %	7.7 %	0.83	1.18
Not mirrored	E	1.00	0.46	0.65	8.1 %	11.3 %	0.46	0.65
Mirrored	J	1.00	0.46	0.66	8.0 %	11.4 %	0.46	0.66
Only up	F	0.63	0.23	0.36	4.0 %	6.2 %	0.37	0.57
Only down	G	0.63	0.54	0.84	9.4 %	14.6 %	0.87	1.35
Combined	H	1.25	0.42	0.62	7.2 %	10.7 %	0.33	0.49
Spread	I	1.25	0.69	1.02	12.0 %	17.7 %	0.55	0.82
Vertical	K	1.25	0.49	0.71	8.5 %	12.2 %	0.39	0.56

The apparent scattering coefficients and apparent scattering areas are largest for Setup A and I, while the surface compensated apparent scattering coefficients are largest for Setup D and G. This is, of course, because the relative diffusor covered area is 30 % and 50 % for Setup D and G, respectively.

The complete results of S', s' and s'' are listed in Appendix C.

CHAPTER 5

Computer simulations

Room acoustic parameters are often predicted with computer simulation software before the actual room is built. Such simulations use the geometry, material properties and environmental properties to predict the sound decay, normally with ray-tracing and image source methods. Thus it would be valuable if the measured properties of the diffusors could be quantified for use in computer simulations. Two popular software options are Odeon [18] and CATT-Acoustic [19], and the latter will be used to determine whether it is possible to incorporate the diffusor data in to the computer model. The software uses a combination of ray tracing, cone tracing and image sources to predict the impulse response. Odeon works in a similar way, so CATT-Acoustic was chosen since it was available at the University.

5.1 Creating a computer model

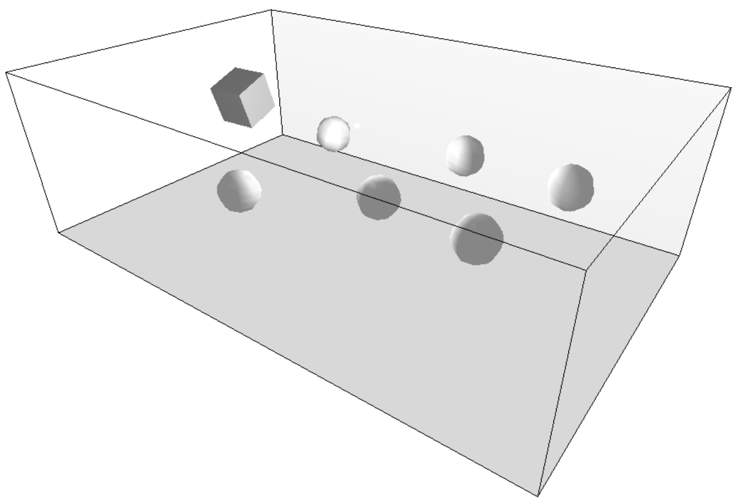

Figure 5.1: 3D rendering of the CATT-Acoustic computer model. The cube represents the source and the spheres represent the receivers.

Figure 5.1 shows how the model constructed in CATT-Acoustic. It is a simple shoebox with one source and six receivers spread across the room. Because the simulations were performed before the scale model measurements, the material and environmental parameters were not known and had to be estimated from experience. The following parameters were used:

- The wall absorption coefficient was set to 1% in all frequency bands, which is a reasonable value for an untreated concrete wall [2, p. 341].
- The ceiling absorption coefficient was set to 99%. For some reason, areas with 100% absorption makes the simulations unstable, and the software manual recommends to use less than 100% absorption on all surfaces.
- The air temperature and relative humidity was left at the default of 20° C, 50% RH.
- The surface scattering coefficient, s, was the free parameter which relates to the diffusor performance. Note that the scattering coefficient was set equal on all four walls.
- Source position 1 was used, as well as all six receiver positions. Figure 3.5 shows the measurement positions in the horizontal plane, but unfortunately the microphone heights were not the same as in the model. R1-R6 were equally spaced 30-42.5 cm from the floor, while the source was kept at 42.5 cm, which is only 2.5 cm higher than in the scale model measurements.
- The number of rays was 50 000, which is much more than the recommended 10 000, and the ray truncation time was longer than the obtained reverberation times. This ensures statistically reproducible results.
- The computer model dimensions were $2.4 \times 1.5 \times 0.75$ m, which is marginally larger than the scale model. This should not affect the computed reverberation time more than 2 %.

All the parameters except the surface scattering coefficient were kept constant during the simulations.

5.2 Simulation results

Since the relative humidity was set to 50 %, which is twice the size of the measured humidity in the scale model, the results obtained at higher frequencies are not accurate. Consequently, only the results from the octave bands of 125 - 2000 Hz are included, since the air absorption accounts for less than 10% of the total absorption when $T = 1$ s in the 2 kHz band. Since all other parameters were equal in each frequency band, the obtained reverberation times could be averaged from 125 to 2000 Hz and over all six measurement positions, without creating significant errors. This gives one reverberation time value from one scattering coefficient value.

Figure 5.2 shows the obtained reverberation time as function of the surface scattering coefficient, as well as curve fittings found with MATLAB's *Curve Fitting Toolbox* [20]. Since the results looks like a variant of the reciprocal function $1/x$, a combination of a rational function and the power function was used, $T(s) =$

$a/(s^b + c)$. This gave a quite good fit on the interval. The curves are described by the following equations:

$$T_{30,fit} = \frac{4.836}{s^{1.035} + 0.7339} \quad [\text{s}] \tag{5.1}$$

$$T_{20,fit} = \frac{2.449}{s^{0.8063} + 0.02782} \quad [\text{s}] \tag{5.2}$$

$$EDT_{fit} = \frac{1.691}{s^{0.7638} + 0.7517} \quad [\text{s}] \tag{5.3}$$

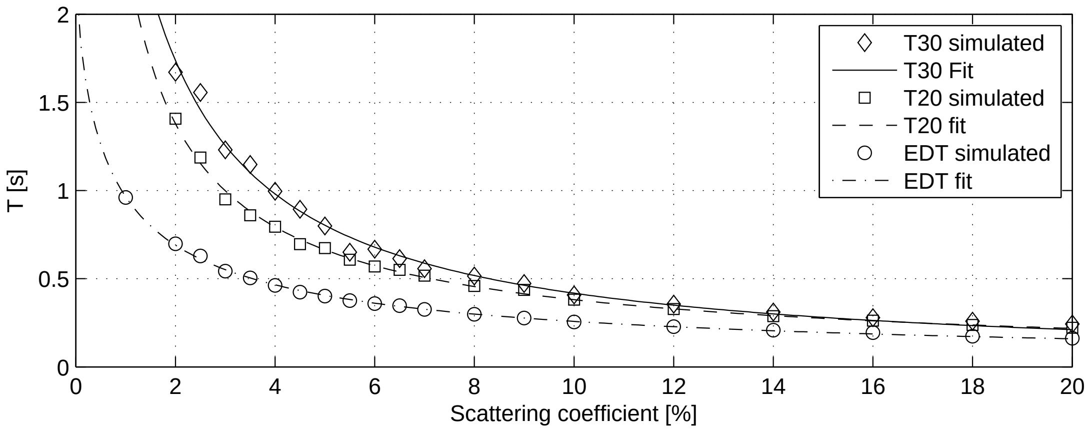

Figure 5.2: Simulated and curve fitted reverberation time as function of the wall scattering coefficient.

The required scattering coefficient can now be estimated from the measured reverberation time with Equations (5.1) - (5.3). But how does this translate to a full-scale room? The expected reverberation time is four times larger in a full-scale room, so ideally the simulated $T_{model}(s)$ and $T_{full-scale}(s)/4$ should be identical. Figure 5.3 shows that the results are almost identical for $s > 10$, but the full-scale simulation tends to give a little shorter reverberation times for lower values of s. The reason for this is the air absorption - for longer reverberation times the air absorption is more significant and a larger room has more air absorption, assuming the frequency range is kept equal. The reverberation time is averaged from 125 to 2000 Hz for both rooms.

5.3 Suggested choice of scattering coefficients

Due of the shape of the reverberation time curve in Figure 4.3, there is no obvious choice of the wall absorption and scattering coefficients. Below 2kHz, the apparent scattering seems to increase due to the absorption in the ceiling. The wall absorption will not change when introducing a ceiling absorbent, so it may be wise to keep this at 1-2%, and adapt the scattering coefficient to the measured reverberation times. This can be done by finding the expected reverberation time without air absorption, T^*:

$$T^* = \frac{0.161V}{0.161V/T - 4mV} \quad [\text{s}] \tag{5.4}$$

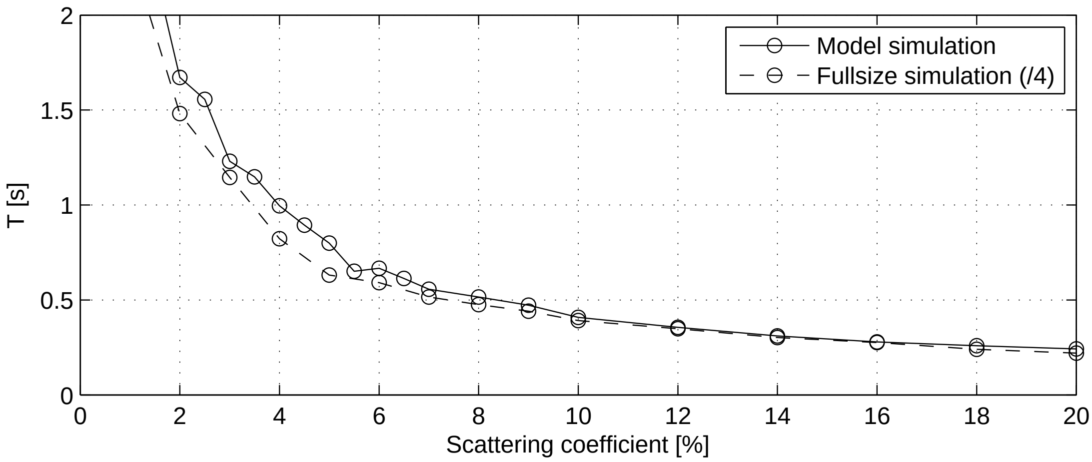

Figure 5.3: Difference between simulating in model scale or in full-scale. Note that the reverberation time obtained in the full-scale room is divided by 4 for comparison.

where T is the measured reverberation time and $4mV$ is the estimated air absorption calculated with equation (2.3). The scattering coefficient to be used in CATT-Acoustic can then be found using Equation (5.1). Note that the removal of air absorption with Equation (5.4) may not be accurate when the sound field is either completely or partly two-dimensional. However, for practical purposes the air absorption will dominate over the scattering effect in the high frequency area. Table 5.1 shows which scattering coefficients are needed to match scale model measured, compensated for air absorption, and CATT-Acoustic computed reverberation times. The values are given in the 500 Hz - 16 kHz octave bands, which correspond to 125 Hz - 4 kHz in full-scale. This is the default frequency range in CATT-Acoustic, and the most relevant to measurements done by the ISO 3382 standard.

Table 5.1: Suggested scattering coefficients for CATT-Acoustic, for a selection of diffusor setups (all with depth 52mm). Values are given in percent.

Configuration	Setup	500	1k	2k	4k	8k	16k
L-form	A	33	27	22	14	15	11
70% area	B	33	25	21	12	13	8
50% area	C	33	18	16	10	11	7
30% area	D	33	20	13	8	10	5
Not mirrored	E	32	22	17	10	13	9
Mirrored	J	30	19	17	10	13	9
Only up	F	32	13	12	7	11	8
Only down	G	34	27	21	11	11	5
Combined	H	33	24	16	10	10	7
Spread	I	33	27	25	14	15	10
Vertical	K	33	24	18	12	11	8

The full table of CATT-Acoustic scattering coefficients are given in Appendix C.

CHAPTER 6

Discussion

In this chapter, the most important results found in Chapters 4 and 5 are discussed. The aim is to find out in what degree the conducted study answers the questions asked in Section 1.1, what the main findings are and their implications, how this compares to other's findings and finally whether the error sources are small enough for the study to be reliable.

6.1 Summary of the problem

As stated in the introduction, The Hard Case is a common room type, which has some fundamental acoustical problems. The two-dimensional sound field created by parallel, hard walls makes traditional reverberation time calculation with Sabine's formula inapplicable, and the reverberation time is much longer than wanted in many cases. M. Skålevik suggested to mount diffusors on the walls to lower the reverberation time and eliminate the flutter echo. This also makes way for traditional formulas, like Sabine's equation, to be applicable. The question is: How many and how large diffusors are needed? This was investigated in scale model measurements.

6.2 The fundamental situation - *The Hard Case*

The first scale model measurements showed a large reduction in reverberation time at low frequencies (below 1 kHz) when installing the absorbing ceiling. This corresponds to the frequency range below 250 Hz in full-scale. Thus, the absorbent seems to be very effective at low frequencies, around full performance compared to the predicted absorption coefficient calculated with WinFLAG. At high frequencies, Figure 4.2 shows that the effective ceiling absorption area calculated with Eyring's formula (2.4) is much smaller than the ceiling surface, especially over 1 kHz. The effective absorption coefficient $\bar{\alpha} = A_{ceil}/S_{ceil}$ is then well below 1 in the high frequency area, which is contradictory to what is expected of a porous absorber. A normal porous absorber will have high absorption for wavelengths shorter than 4 times the thickness t, i.e. the absorber is efficient when $t > \lambda/4$.

If the ceiling absorbent is perfectly absorbing, Eyring's formula gives a reverberation time of 0.1 seconds. Neglecting air absorption, this is the lowest achievable reverberation time in the 3D-diffuse field. Now, by calculating the average absorption coefficient $\bar{\alpha}$ from the initial reverberation time in Figure 4.1, Eyring's formula gives a value of 0.02 below the air absorption dominated frequency area. Using this number as the wall absorption coefficient in Tohyama's formula (2.5) results in a reverberation time of three seconds. At 2 - 2.5 kHz, the sound field is closer to the Eyring prediction numerically, but more in the same order of magnitude as Tohyama's prediction. This indicates a combination of a 2D and 3D sound field, probably with strong 2D components later in the decay curve, as is likely to be the case in the 2 kHz decay curve shown in Figure 4.7. Around 500 Hz, the sound field seems close to 3D, as it is not possible to obtain a much lower reverberation time without adding more absorption. Remember that this is well below the Schröder frequency, so diffuse field behaviour cannot be assumed, but nevertheless the absorber is very effective. Above 2.5 kHz the air absorption dominates, which does not exclude the possibility of a 2D sound field.

The reasoning above indicates the formation of a two-dimensional sound field in the high frequency area, but how come this does not happen in the low frequency area? The walls are almost perfectly reflective and absorbs/transmits little energy, only about 2 %. The only way for the energy to be absorbed must then be in the ceiling. Low-frequency pressure waves travelling in the horizontal direction are quickly damped, and this means the absorber has effective *grazing* wave absorption. Since the suspended ceiling is in practice a floating porous absorber with no physical vertical barriers, waves can travel inside the absorber, parallel to the ceiling. Normally, absorbers are assumed *locally reacting*, which means their absorptive properties are only dependent of the local pressure at a point. This is not the case at low frequencies and may be the reason for the effective absorption of grazing waves. One must also remember that the absorbent used in the measurements consists of 50 mm porous material + 50 mm air, which translates to 20 cm porous material + 20 cm air in full-scale. Normal ceiling absorbers are 10 - 40 mm with 0 - 20 cm air gap, so the low frequency absorption will probably be significantly less in ordinary rooms.

One thing that may influence on the measured reverberation time is slanting of the walls. If a wall is not completely vertical such that a wave traveling horizontally is reflected slightly upwards, the sound energy will quickly be directed towards the ceiling, depending on the slanting angle. If the wave is reflected slightly downwards, more energy will be concentrated in the lower area of the room. Measured vertical deviation was in the range of 0-2 mm between parallel walls, which amounts to 0-2.6 ‰ vertical deviation per wall. The Norwegian Building Specification NS 3420 [21, p. 12-13] requires a maximum deviation of 3 ‰ for inner walls with normal ceiling height, so the walls are not slanted more than expected in a real room.

In addition, the measurement equipment is likely to affect the measurements. In particular, the dodecahedron loudspeaker is a significant diffusing element due to two reasons: It is situated right in the middle of the horizontal sound field caused by itself, and its size (13 cm in diameter) is not negligible, since effective scattering can be expected when $\kappa a > 1$, i.e. above approximately 800 Hz.

Even though the reverberation time is not as extreme as predicted with Tohyama's formula, the low absorber efficiency in the high frequency range results in reverberation time up to four seconds when transforming to full-scale. This is extremely long for a classroom or meeting room, so action must be taken to improve the acoustics.

6.3 Introducing diffusors to the walls

All the measurements with diffusors show a reduction in reverberation time above the low frequency area where there is not much to gain without additional absorbers. Consequently, the hypothesis in Section 1.1 has been confirmed. Above 630 Hz, improvement can be seen in all frequency bands for all diffusor depths from 22 to 112 mm, using Setup A in Appendix A. However, there is an unwanted effect: Different diffusor depths cause peaks in the reverberation time curve, as high as 0.5 seconds (2 seconds in full-scale) at 2 kHz with a depth of 82 mm. Analysing the spectrogram of the impulse responses shows long decays at frequencies corresponding to when the waves reflected from the wall and diffusors are in phase. This is exactly what M. Skålevik has predicted in his paper [1, sec. 6]. The perceivable diffusor effect will not be optimal and perhaps even disturbing since some frequency bands will be much more reverberant, and therefore amplified. The comb-filtering issue is less apparent with the smallest diffusor depths because the interference will be moved higher up in frequency. Note that the apparent scattering coefficient given in Table C.1 is quite similar for all diffusor depths. One can then argue for using as low depth as possible to save space.

Measurements with diffusors of random depths ranging from 22 to 112 mm shows that this effect is nearly eliminated, as shown in Figure B.2. Suppose the diffusors are a quantization of a wave shaped wall, the random depths will represent a more complex wave than using equal depths all over, which can be regarded as a coarse quantization of a sine wave. The complex wave is likely to have less periodical effects in the frequency domain.

Measurements show that around 15 % total coverage area seems to be the lower limit before an increase in the reverberation time is observed. Note that this value is only valid for the particular room size, diffusor size and their placement. This indicates that the more diffusing elements that are added to the walls, the less additional reduction in reverberation time is obtained. An example can be seen in Table C.1 – s'' is significantly larger for 30% coverage, which means the scattering area per diffusor is large. A similar behaviour is observed when adding absorbers: The first absorbing elements in a room are much more effective than the next ones.

Diffusor placement is equally important as depth and coverage area. The calculated apparent scattering coefficient in Table 4.2 shows that distributing the diffusors over all four walls, i.e. Setup I, is beneficial over the "L-configuration" in Setup A. Placing the diffusors at a low height (Setup G) is also much more effective than placing them high. This can roughly be compared to slanting the walls such that sound energy is diverted up or down in the room. It is unfortunate, as floor space is valuable and preferably diffusing elements should be placed high on the walls. However, many rooms will have furniture, which will act as good diffusors, and one can then regard the space above the furniture as The Hard Case. Diffusors will then be needed at the middle part of the wall.

As for the window profiles, measurements show that larger dimensions give shorter reverberation times, but the most important parameter is the width to depth ratio. Placing the profiles such that the width is larger than the depth performs better. In addition, vertical profiles perform worse due less energy being scattered away from the horizontal plane. Finally, both a short and a long wall should be treated to avoid a one-dimensional sound field between parallel walls. Consequently, wide horizontal window profiles mounted at least on two walls is the ideal choice. If vertical profiles is the only practical solution, one can expect about 50 % reduction in the reverberation time with the largest profiles of 70×35 mm, assuming the width is larger than the depth.

Due to the short reverberation time at low frequencies, it was difficult to identify the lower frequency limit of the diffusors. Inspecting the frequency response below 1 kHz does not give much more information, except a somewhat more linear frequency response with large diffusor depths. Note that there is already empirical results on the lower frequency limit, measured by Sommerville and Ward [22]. They show that hard rectangular elements act as diffusors when the depth is larger than $\lambda/7$. This is confirmed by the measurements, and it seems like the diffusors are even more effective. As an example, 22 mm diffusors should be effective from 2.2 kHz, but seems to work well above 1 kHz. The full effect is seen from 2 kHz and above.

No particular conclusions can be drawn about the frequency responses, except the fact that the absorbing ceiling eliminates most of the resonant behaviour. Adding diffusors does not flatten the frequency response significantly more. In addition, the decay curves seem to get less linear compared to measurements with naked walls. The 2D sound field is dominant at 2 kHz without diffusors, which results in a very straight decay curve (except a steep initial part). With diffusors, the combination of a 2D and 3D sound field seems to create decays with more upwards curvature.

6.4 How many and how large diffusors are needed?

According to Eyring's formula, the lowest theoretical reverberation time obtainable with a perfectly absorbing ceiling is around 0.1 second. As shown in the measurements, this is very difficult, even with a considerable amount of diffusors. The Norwegian Standard for building acoustics, NS 8175 [23] requires the reverberation time to be 0.4-0.5 seconds (Class A-C) in a full-scale classroom or meeting room, which is equivalent to 0.1-0.125 seconds in the model. To achieve this, different types of diffusors, more of them, and more absorbents need to be added. Normally, people, furniture and perhaps curtains will contribute.

Even though the requirements cannot be matched by the diffusors alone, it is important to determine which configuration is optimal. The measurements show that:

- Equal diffusor depths should be avoided. This creates comb-filtering effects, which give long decays at certain frequencies. Thick diffusors are not necessary to get significant improvements, but low-frequency performance deteriorates if the diffusors are 4 cm thick (full-scale). 8 cm is sufficient and reduces the reverberation time at 250 Hz (full-scale) 40 % more than 4 cm thickness does.

- Preferably, diffusors should be placed on the lower parts of the walls, as they are much more effective there.
- At least one long and one short wall should be treated, to avoid flutter echo and one-dimensional sound propagation.
- Symmetry considerations are less important. Mirror symmetric placement gives almost the same result as asymmetric placement.
- Horizontal diffusor placement (i.e. more total horizontal edge length) is preferable, but not crucial.
- Horizontal, wide window profiles can help considerably. Vertical profiles are less effective, but can reduce the initial reverberation time 50 % if the profiles are wide enough.

The largest apparent scattering coefficient, i.e. the shortest reverberation time, was obtained with diffusors of random depth on L-form (Setup N) or 52 mm depth spread over all four walls. The mean reverberation time from 500 Hz - 20 kHz was about twice as large as the theoretical minimum of 0.1 second.

6.5 Predicting reverberation times with CATT-Acoustic

Computer simulations with CATT-Acoustic yield a relation between the wall scattering coefficient, s, and the simulated reverberation time, T. This relation can actually be approximated by a simple equation for the room in question. Measurement results can then be matched to the simulated reverberation times, resulting in a set of scattering coefficients for each diffusor configuration.

The results are highly situation-dependent, which means they could probably not be used for significantly different rooms. Nevertheless, investigations show that many rooms are in the same category as the model, especially classrooms and meeting rooms. Simulations with CATT-Acoustic can then be a helpful tool to predict the reverberation time with diffusors and perhaps other absorbers or diffusors. There is no real advantage in simulating exactly the same room as the scale model, but effects of additional acoustic treatment can be investigated.

6.6 Error analysis

Equally important as analysing the measurements result is identifying sources of error. Acoustic measurements are prone to both systematic and random errors. Computer simulations can have systematic errors caused by inaccurate assumptions or programming errors.

When measuring impulse responses and calculating the reverberation time, the signal-to-noise ratio must be sufficiently high. This was the case for most measurements, but random sounds could have disturbed some measurements. Checking all signal-to-noise ratios reported by WinMLS would have been a huge job, so only the initial measurements were checked and the measurement chain was not altered after this. After the measurements were done, some anomalies were detected: Sometimes, WinMLS predicts a completely wrong reverberation time even though the decay curve looks correct. This occurred only at the lower frequencies, and all obvious errors in the interesting frequency area were removed. There is however a chance that small, unnoticeable errors are included in the measurements, since it is impossible to know whether the errors are only extreme or can be both extreme and small.

In addition, shortcomings with the model construction could influence the measurements. Wall vibrations or crooked walls can occur. Initially, there were unwanted wall resonances that had to be removed, but there is still a chance of resonating walls, which can influence the reverberation time.

CHAPTER 7
Concluding remarks

This report concerns *The Hard Case* – room acoustics in a small room with an absorbing ceiling only. In such rooms, a two-dimensional sound field will arise, which results in long reverberation times and flutter echo. Scale model measurements have been performed to analyse such a room, and diffusors have been mounted at the walls to suppress the two-dimensional sound field, which prevents unwanted acoustical properties.

Initial measurements in the model showed that the 2D sound field could not be proven to exist in the low frequency area. The measured reverberation times were almost as low as expected in a 3D-diffuse sound field. The reason for this has not been found, but it is suggested that the absorber works very well for grazing waves at low frequencies, and the 2D behaviour will quickly be damped as the waves travel parallel to the ceiling. In the high frequency area, the 2D sound field is dominating, indicating a peak reverberation time of 4 seconds in a full-scale room.

The effect of hard, rectangular diffusors was the main investigation in this project. Measurements show that using a set of equally thick diffusors results in a comb-filtering effect, which makes them effective only at certain frequencies, and diffusors of different thickness is preferable. Thick diffusors are not necessary, as much improvement is seen with a depth of 8 cm (full-scale). A large diffusor area is not necessarily needed, as little improvement is seen when increasing the total coverage area beyond 15 %. On the other hand, this is likely to be room-dependent.

In addition, measurements show that diffusor placement is crucial. Low placement, diffusion in both horizontal directions, spreading of diffusors and horizontal mounting is important to achieve the best results. Symmetry considerations are not that important.

Diffusion from window profiles was also measured, showing best performance with wide, horizontally mounted profiles. Vertical profiles have less effect, but about 50 % reduction in reverberation time can be expected if they are large enough. Wider profiles are in general more effective than deep profiles.

The scattering coefficients needed to simulate the diffusors in CATT-Acoustic were calculated. A simple equation relating the predicted reverberation time to the scattering coefficient was derived. By knowing the reverberation time for a particular diffusor setup, a suitable scattering coefficient can be found, and used to simulate effects of further acoustic treatment in the room. However, the influence of air absorption, both in the scale model and a full-scale room, must be thoroughly considered.

Conclusively, the study conducted shows that a cuboid room with hard walls and an absorbing ceiling will have a very long reverberation time, and introducing diffusing elements at the walls will reduce this problem considerably. At best, an average full-scale reverberation time of 0.8 seconds was achieved with diffusors.

7.1 Suggestions for further work

To gain more understanding on how *The Hard Case* and two-dimensional sound fields behave, some further work is suggested.

The low-frequency behaviour in the model was somewhat surprising. It would be interesting to know exactly why the measured reverberation times are so much shorter than in the high frequency range. This could be studied in several ways, for example in a full-scale room with a realistic absorbent. If the reverberation time curve has a similar shape, the grazing-wave absorption should be investigated. This could be done in a one-dimensional setup, such as a quadratic duct with an absorber inside, much like a ventilation duct damper.

In addition, the perceivable effects of flutter echo could be investigated. This could be done by auralizing the impulse response and perform listening tests. For example, how annoying is flutter echo from one set of parallel walls, compared to two sets, i.e. four naked walls? And is it possible to quantize flutter echo with a number? A. Løvstad says in his thesis that it is [24]. It would also be interesting to know how the diffusors affect the perceived room acoustics, compared to what the numbers in this report states.

More work is needed to verify whether the *apparent scattering coefficient* is usable or not. Here, the selection of reverberation time formula is crucial. In addition, the scattering coefficients suggested for CATT-Acoustic should be tested in rooms with significantly different dimensions.

Instead of studying a set of diffusors in a particular room, one could study how one rectangular diffusor on an infinite wall will divert energy away from the horizontal plane. This can be done with measurements or computer modelling. Other simple diffusor shapes should also be investigated to see if the rectangular box is really the best choice.

It is also important to find out how much the furniture and people in a room will contribute to diffusion. How important are they compared to wall-mounted diffusors?

Finally, one could implement E. Nilsson's Statistical Energy Analysis model [16] and determine which coupling loss factors are needed to model the different diffusor setups.

Bibliography

[1] Magne Skålevik. Small Room Acoustics - The Hard Case. In *Forum Acusticum*, 2011.

[2] Lawrence E. Kinsler, Austin R. Frey, Alan B. Coppers, and James V.Sanders. *Fundamentals of Acoustics*. John Wiley and Sons, Inc, 1999.

[3] C.W.Kosten. The Mean Free Path in Room Acoustics. *Acustica*, 10:245–250, 1960.

[4] M. Tohyama and A. Suzuki. Reverberation Time in an Almost-Two-Dimensional Diffuse Field. *Journal of Sound and Vibration*, 111(3):391–398, 1986.

[5] R.O. Neubauer and B. Kostek. Prediction of Reverberation Time in Rectangular Rooms with Non-Uniformly Distributed Sound Absorption. *Archives of Acoustics*, 26(3):183–201, 2001.

[6] M. Schroeder. New Method of Measuring Reverberation Time. *Journal of the Acoustical Society of America*, 37:409, 1965.

[7] International Organization for Standardization. *ISO 3382 – Measurement of Room Acoustic Parameters*, 2008.

[8] International Organization for Standardization. *ISO 11654 – Sound Absorbers for use in Buildings – Rating of Sound Absorption*, 1997.

[9] International Organization for Standardization. *ISO 717 – Rating of Sound Insulation in Buildings and of Building Elements – Part 1: Airborne Sound Insulation*, 2013.

[10] M. Schroeder. Die statistischen Parameter der Frequenzkurven von grossen Räumen. *Acustica*, 4(2):594–600, 1954.

[11] Magne Skålevik. Schroeder Frequency Revisited. In *Forum Acusticum*, 2011.

[12] Heinrich Kuttruff. *Room Acoustics*. Spon Press, 4 edition, 2009.

[13] WinFlag 2.4. http://www.nvo.com/winmls/winflag24/, retrieved 06.05.2013.

[14] Tor Erik Vigran. *Building Acoustics (Norwegian version)*. Tapir akademisk forlag, 2002.

[15] Erwin Kreyzig. *Advanced Engineering Mathemathics*. John Wiley and Sons, Inc, 2006.

[16] Erling Nilsson. *Decay Processes in Rooms with Non-Diffuse Sound Fields*. PhD thesis, Lunds Tekniska Högskola, 1992.

[17] Peter D'Antonio Trevor J. Cox. Room Sizing and Optimization at Low Frequencies. *J. Audio Eng. Soc.*, 52(6):640–651, June 2004.

[18] Odeon Room Acousics Software. http://www.odeon.dk/, retrieved 14.05.2013.

[19] CATT-Acoustic v. 8.0i. http://www.catt.se/, retrieved 13.05.2013.

[20] MATLAB Curve Fitting Toolbox v.3.2.1. http://www.mathworks.se/products/curvefitting/, retrieved 15.05.2013.

[21] Standards Norway. *NS 3420 – Beskrivelsestekster for bygg, anlegg og installasjoner – Del 1: Fellesbestemmelser*, 2012.

[22] T. Sommerville and F.L. Ward. Investigations of Sound Diffusion in Rooms by means of a Model. *Acustica*, 1(1):40–48, 1951.

[23] Standards Norway. *NS 8175 – Lydforhold i bygninger – Lydklasser for ulike bygningstyper*, 2012.

[24] Anders Løvstad. Evaluation of Objective Echo Criteria. Master's thesis, Norwegian University of Science and Technology, 2003.

APPENDIX A

Diffusor setups

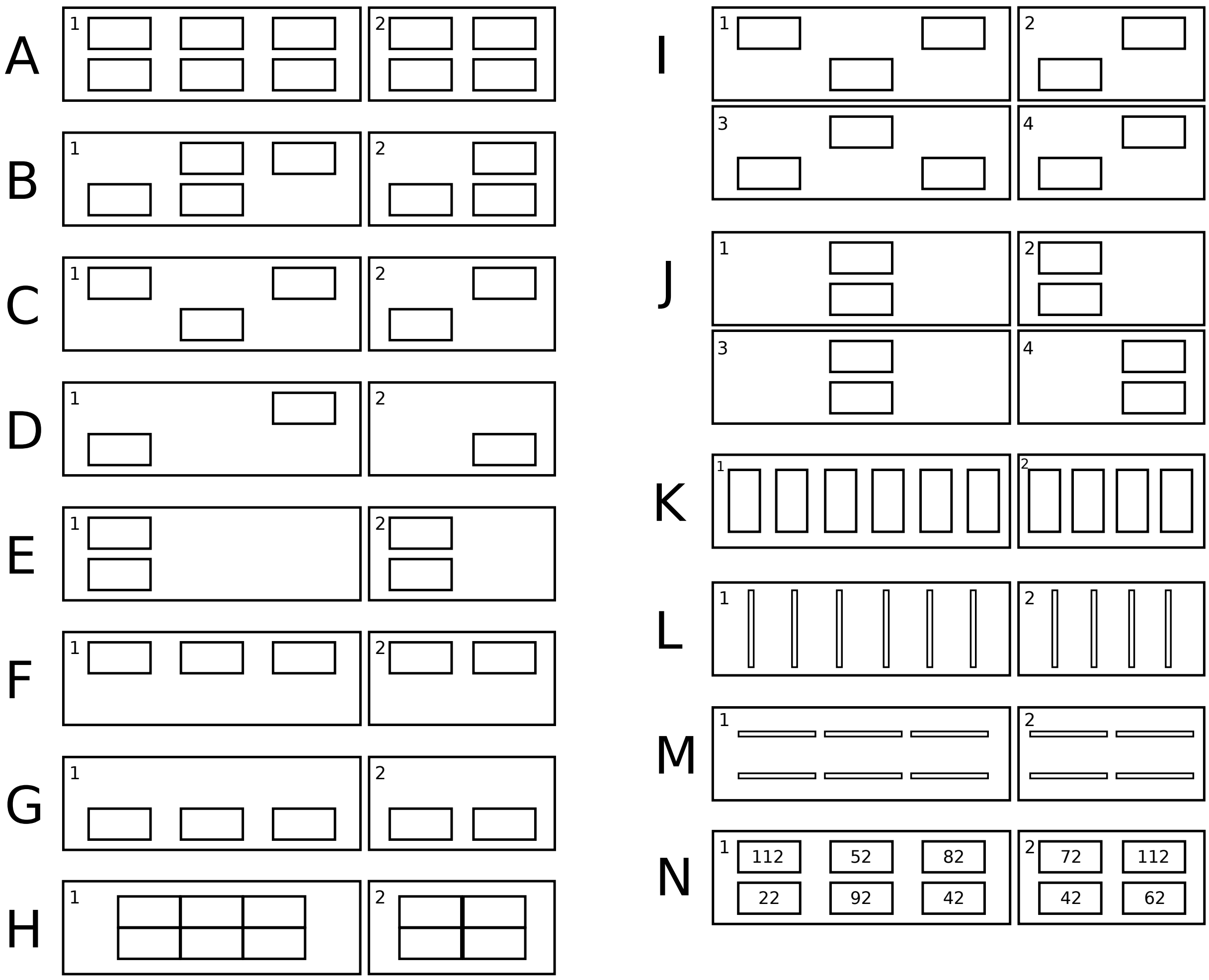

Figure A.1: Diffusor placement at the walls. Numbers 1-4 indicate the walls, clockwise. Wall 1 is the bottom wall in Figure 3.5. Note that in Setup E, the same diffusor setup is used on wall 3&4 as on wall 1&2.

APPENDIX B

Additional measurement results

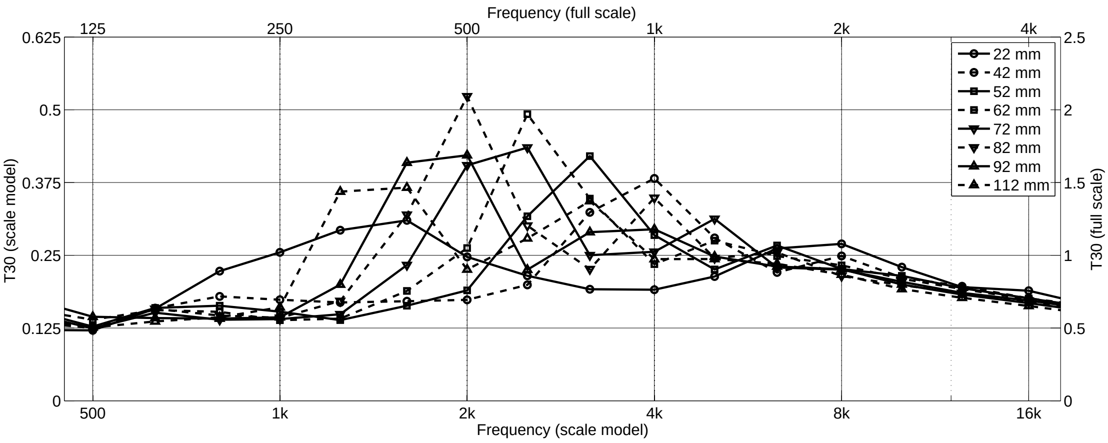

Figure B.1: Mean reverberation time, with diffusors of different depths. Close up from 500 Hz - 16 kHz.

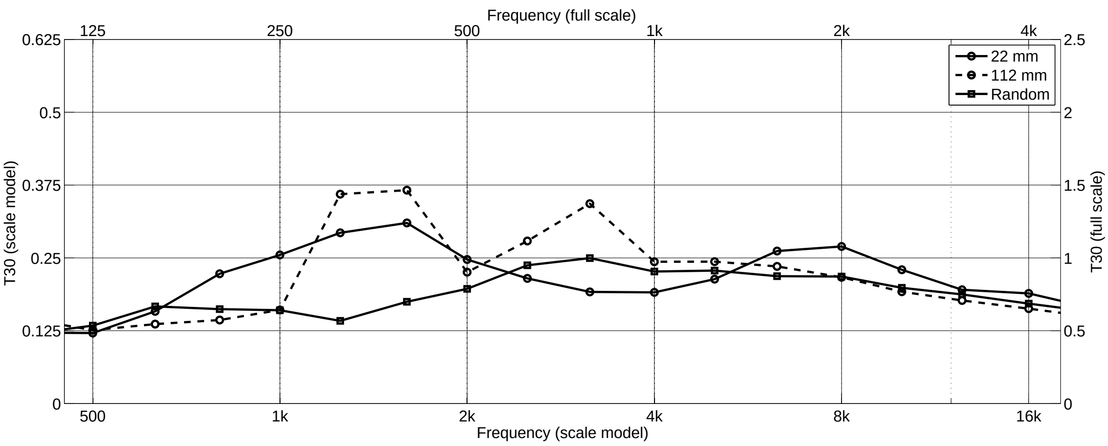

Figure B.2: Mean reverberation time, with diffusors of random depth, along with the minimum and maximum diffusor depths. Close up from 500 Hz - 16 kHz.

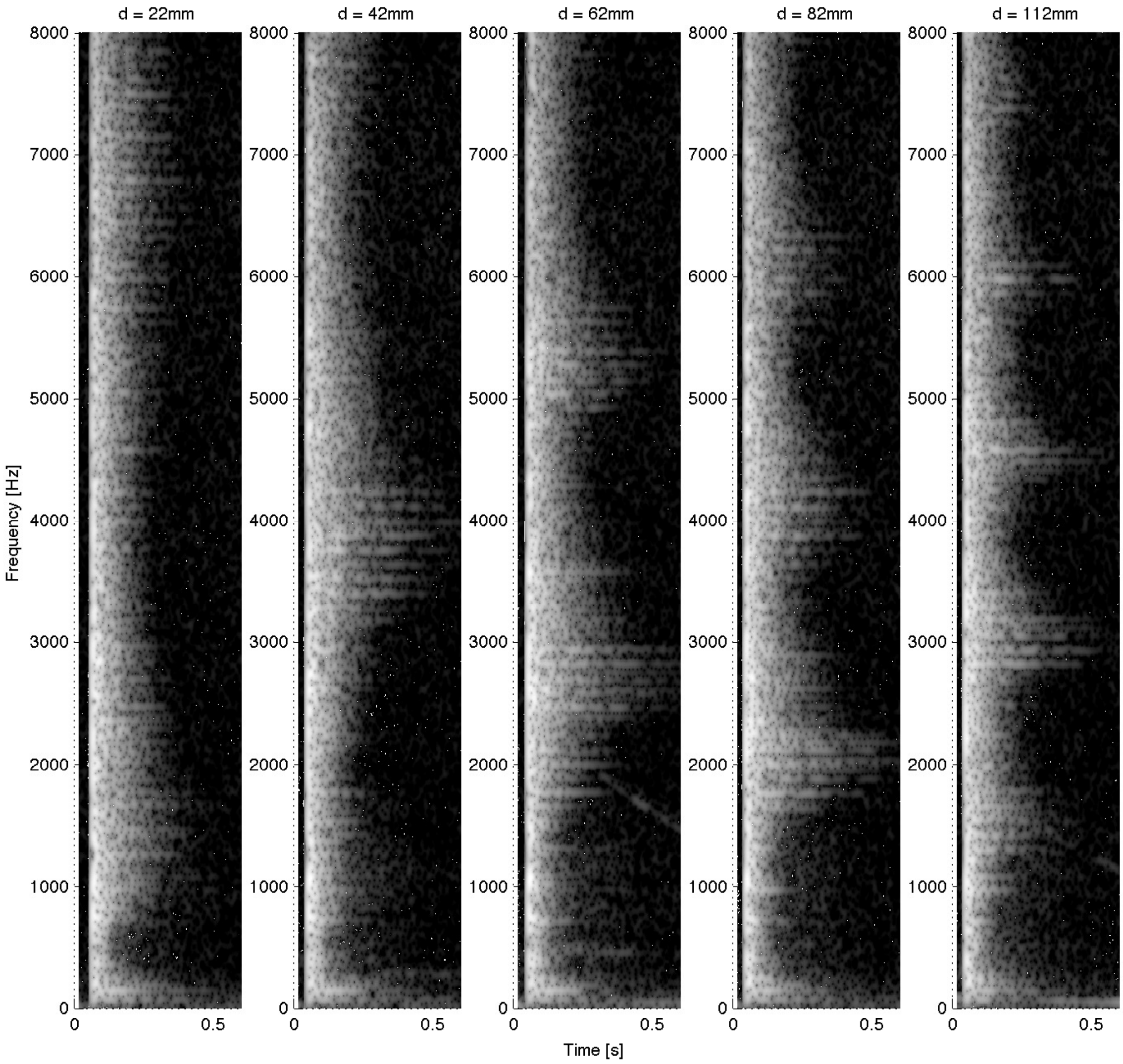

Figure B.3: Spectrograms measured with different diffusor depths. Notice the periodicity caused by the comb-filtering effect. Source position 0, receiver position 1.

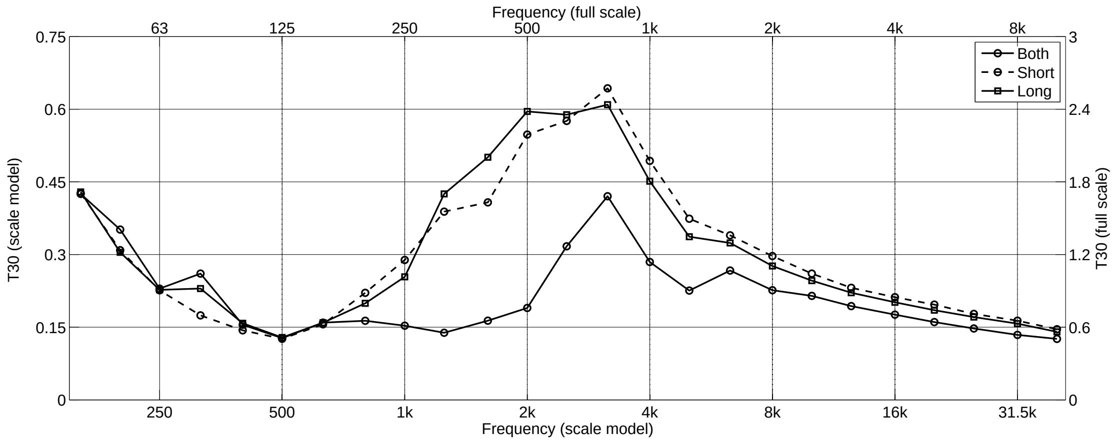

Figure B.4: Mean reverberation time. Diffusors placed horizontally on the long wall, short wall or both (Setup A), with a depth of 52 mm.

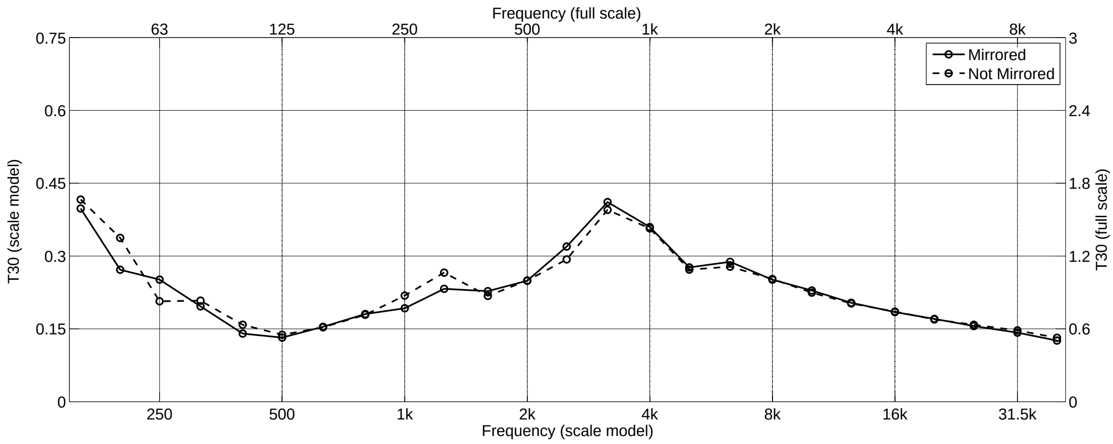

Figure B.5: Mean reverberation time. Diffusors not mirrored (Setup E) and mirrored (Setup J), with a depth of 52 mm.

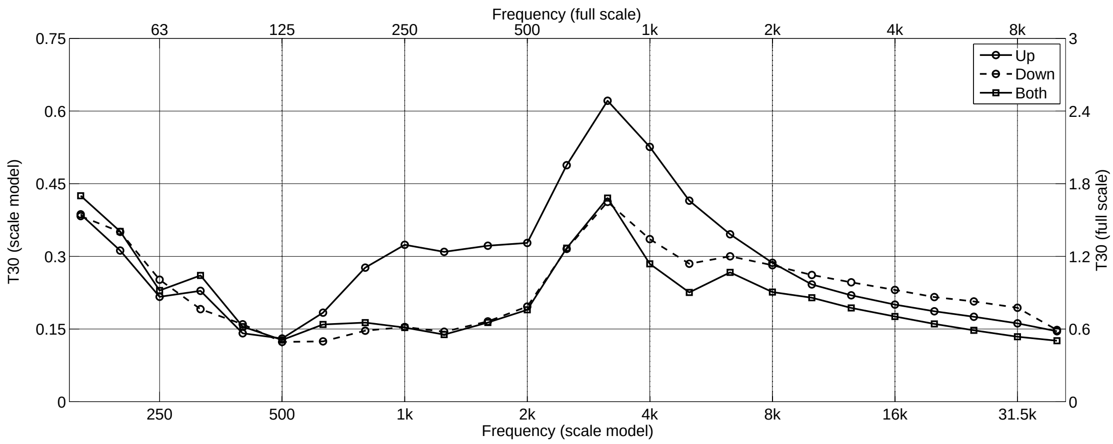

Figure B.6: Mean reverberation time. Diffusors placed high on the wall (Setup F), low on the wall (Setup G), or both (Setup A) with a depth of 52 mm.

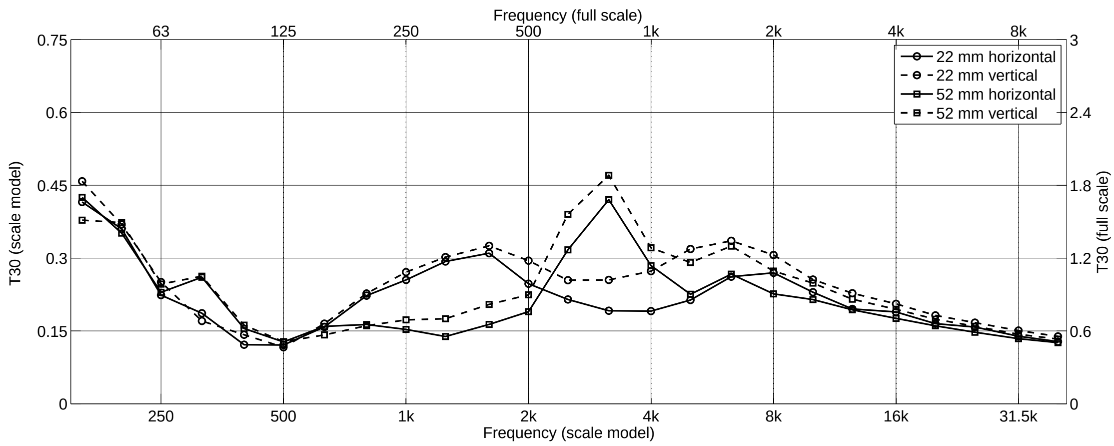

Figure B.7: Mean reverberation time. Diffusors placed horizontally (Setup A) or vertically (Setup K), with depths of 22 mm and 52 mm.

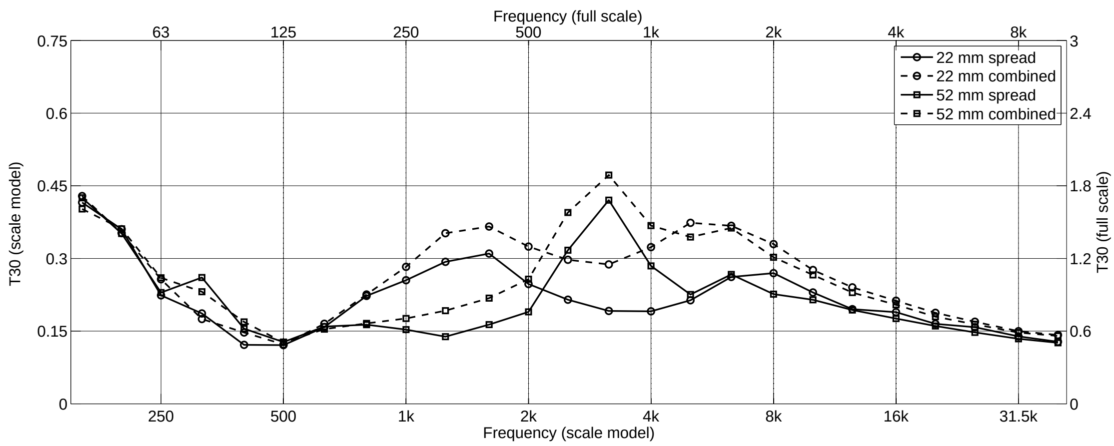

Figure B.8: Mean reverberation time. Diffusors placed spread (Setup A) or combined (Setup H), with depths of 22 mm and 52 mm.

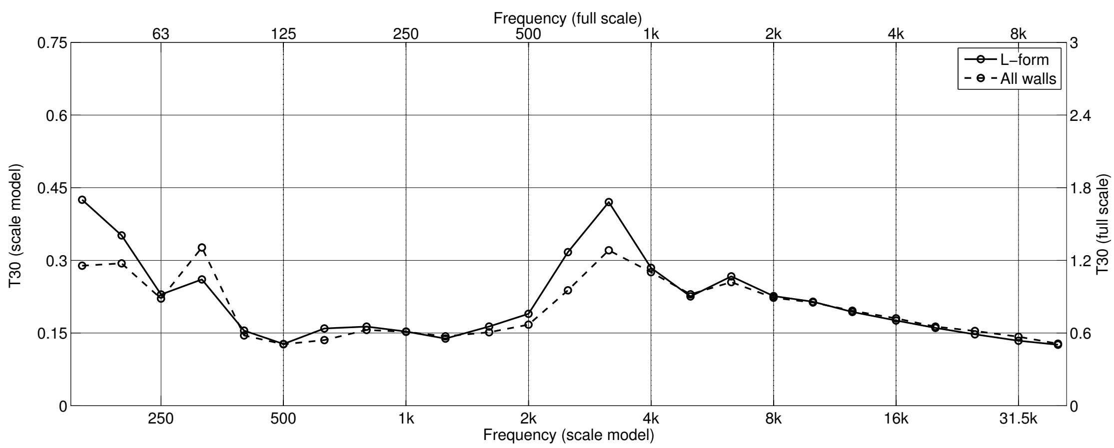

Figure B.9: Mean reverberation time. Diffusors on two walls (L-form, Setup A) or four walls (Setup I), with a depth of 52 mm.

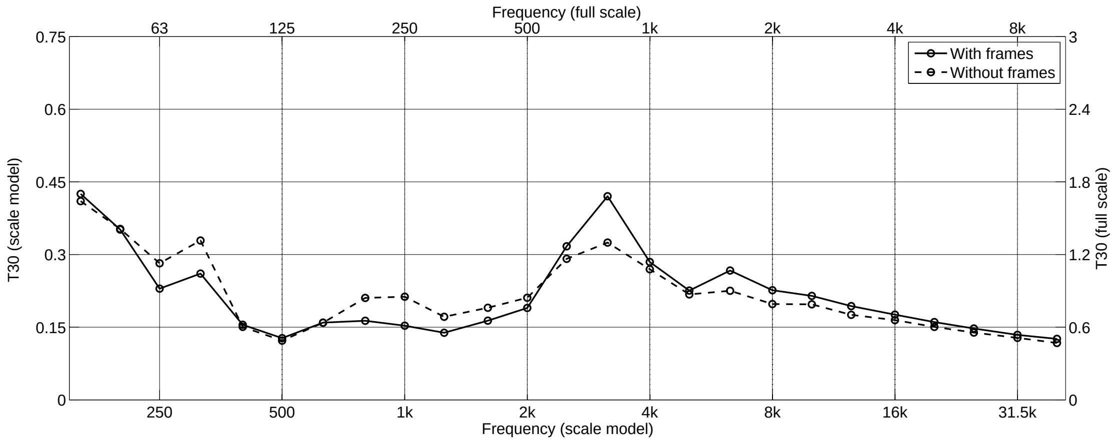

Figure B.10: Mean reverberation time. Diffusors placed as in Setup A, with and without frames, the depth is 52 mm.

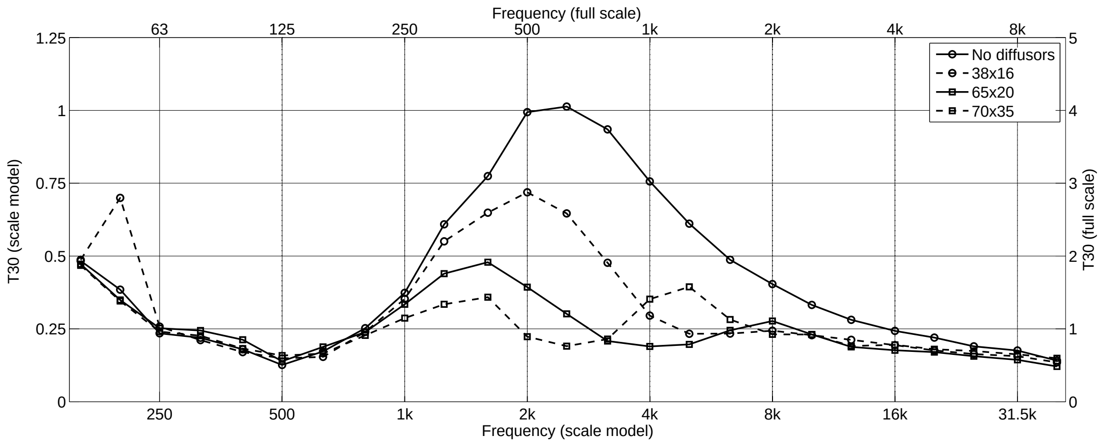

Figure B.11: Mean reverberation time. Window profiles of different depths, mounted horizontally (Setup M). Width > depth for all measurements.

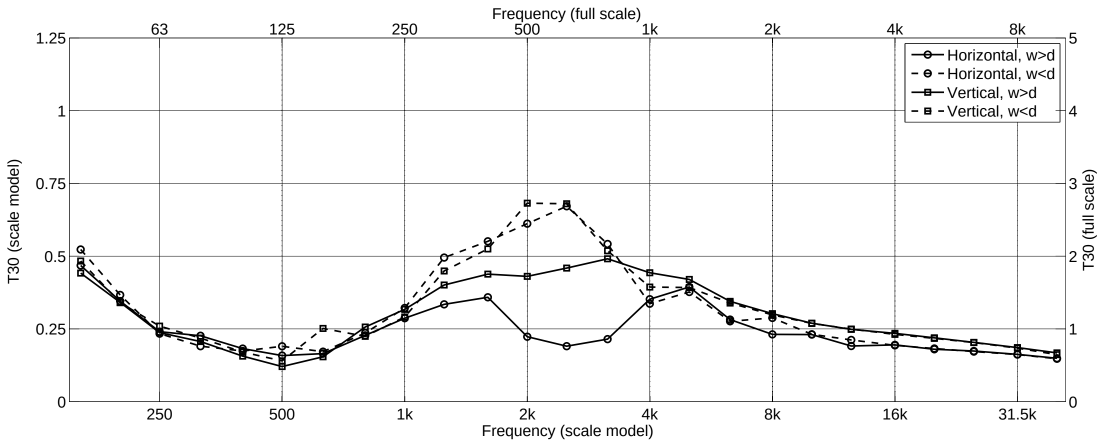

Figure B.12: Mean reverberation time. Window profiles mounted vertically or horizontally (Setup L or M), and with width<depth or width>depth. The dimensions are 70 × 35 mm.

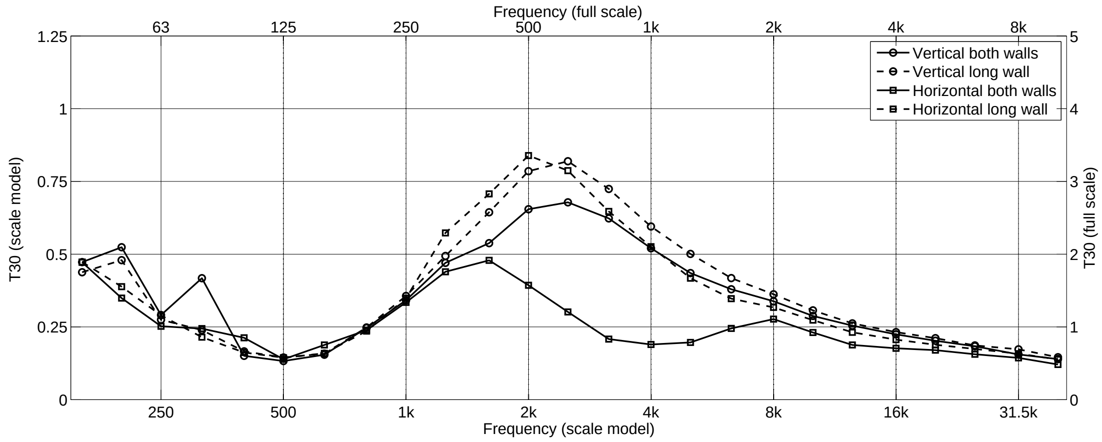

Figure B.13: Mean reverberation time. Window profiles mounted horizontally or vertically on the long wall or on L-form. The dimensions are 65 × 20 mm, and width>depth.

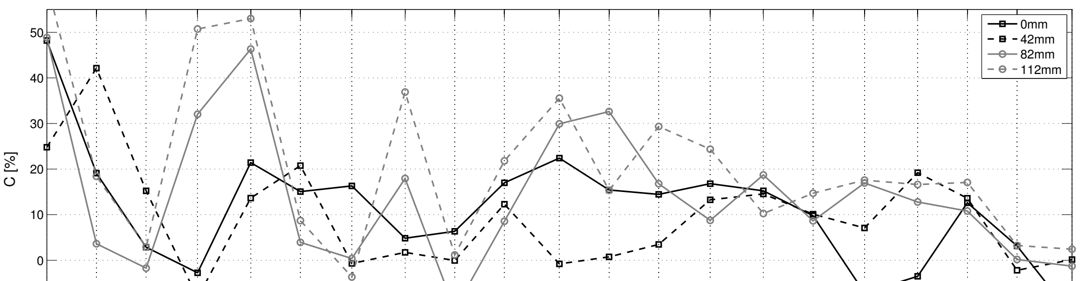

Figure B.14: Calculated C parameter for different diffusor depths, from Equation (2.8). The values are calculated from the mean T_{10} and T_{30}.

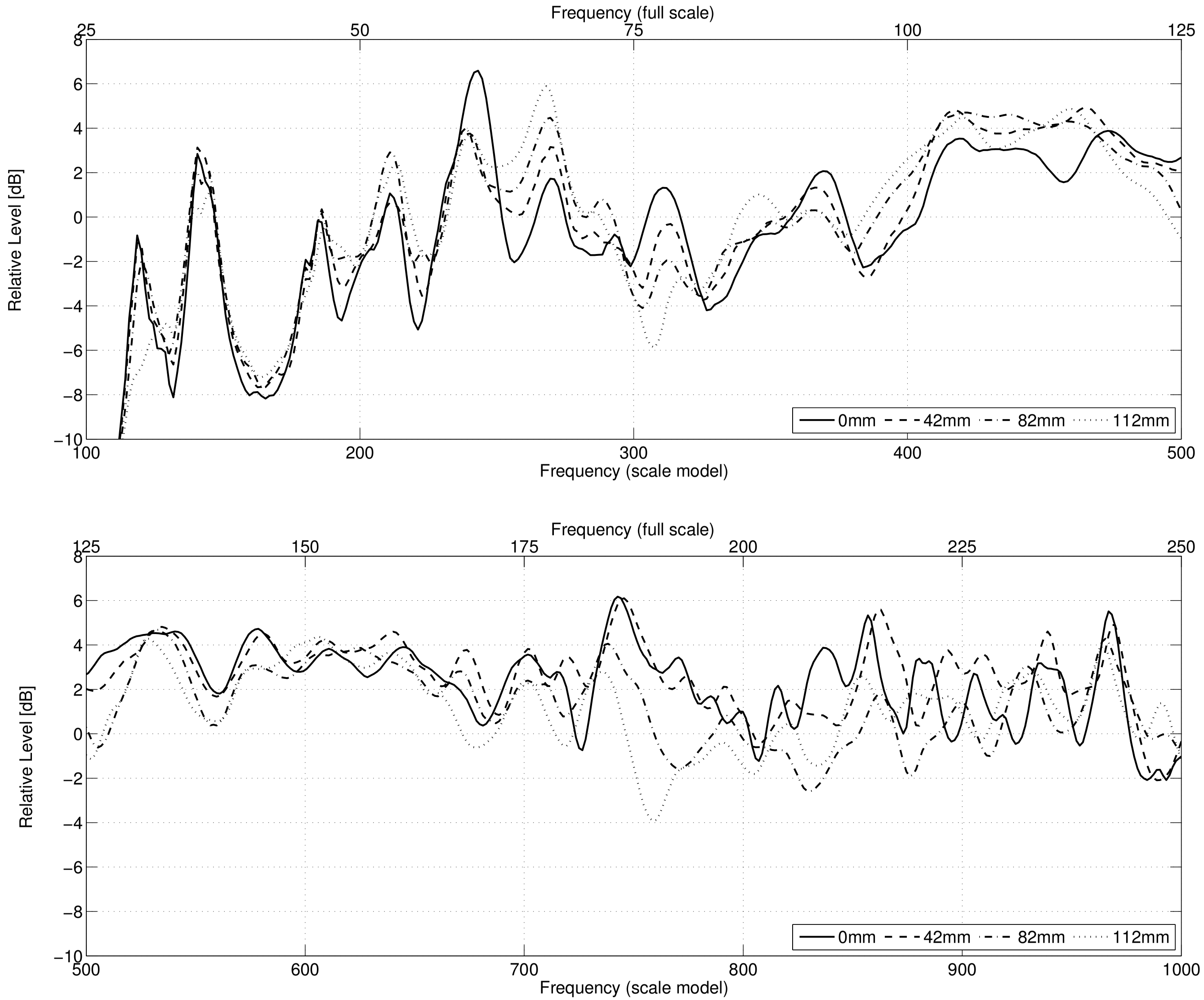

Figure B.15: Energy averaged frequency response from 100 to 1000 Hz. Measured with different diffusor depths. Diffusors are placed on L-form (Setup A).

APPENDIX C

Tabulated scattering coefficients

Configuration	Setup	Depth	S_d	$S'_{500-20k}$	$S'_{1250-5k}$	$s'_{500-20k}$	$s'_{1250-5k}$	$s''_{500-20k}$	$s''_{1250-5k}$
Not mirrored	E	52	1.00	0.46	0.65	8.1 %	11.3 %	0.46	0.65
Mirrored	J	52	1.00	0.46	0.66	8.0 %	11.4 %	0.46	0.66
30% area	D	52	0.38	0.31	0.44	5.4 %	7.7 %	0.83	1.18
50% area	C	52	0.63	0.38	0.58	6.6 %	10.2 %	0.61	0.94
70% area	B	52	0.88	0.57	0.85	9.8 %	14.7 %	0.65	0.97
Random depths	N	N/A	1.25	0.69	1.03	12.0 %	17.8 %	0.55	0.82
L-form	A	22	1.25	0.53	0.87	9.2 %	15.1 %	0.43	0.70
	A	42	1.25	0.62	0.91	10.7 %	15.8 %	0.49	0.73
	A	52	1.25	0.63	0.92	10.9 %	15.9 %	0.50	0.73
	A	62	1.25	0.60	0.80	10.3 %	13.9 %	0.48	0.64
	A	72	1.25	0.60	0.73	10.4 %	12.6 %	0.48	0.58
	A	82	1.25	0.57	0.68	9.9 %	11.8 %	0.46	0.54
	A	92	1.25	0.57	0.67	9.9 %	11.6 %	0.46	0.53
	A	112	1.25	0.58	0.65	10.1 %	11.3 %	0.47	0.52
Only short wall	A†	52	0.50	0.21	0.25	3.6 %	4.4 %	0.41	0.51
Only long wall	A†	52	0.75	0.23	0.24	4.1 %	4.2 %	0.31	0.32
Only up	F	52	0.63	0.23	0.36	4.0 %	6.2 %	0.37	0.57
Only down	G	52	0.63	0.54	0.84	9.4 %	14.6 %	0.87	1.35
Vertical	K	22	1.25	0.38	0.64	6.6 %	11.2 %	0.31	0.52
	K	52	1.25	0.49	0.71	8.5 %	12.2 %	0.39	0.56
Combined	H	22	1.25	0.30	0.52	5.2 %	9.0 %	0.24	0.42
	H	52	1.25	0.42	0.62	7.2 %	10.7 %	0.33	0.49
Spread	I	52	1.25	0.69	1.02	12.0 %	17.7 %	0.55	0.82
Without frames	A	52	1.25	0.62	0.87	10.7 %	15.2 %	0.49	0.70

Table C.1: Apparent scattering area S', apparent scattering coefficient s' and surface compensated apparent scattering coefficient, s'', for a selection of diffusor configurations. †Wall 1 and 2 have no diffusors, respectively.

Configuration	Setup	Width	Depth	S_d	$S'_{500-20k}$	$S'_{1250-5k}$	$s'_{500-20k}$	$s'_{1250-5k}$	$s''_{500-20k}$	$s''_{1250-5k}$
38x16, horizontal	M	16	38	0.11	0.07	0.05	1.2 %	0.9 %	0.61	0.48
- long wall only	M	16	38	0.11	0.03	0.02	0.5 %	0.4 %	0.28	0.21
38x16, vertical	L	16	38	0.11	0.07	0.09	1.2 %	1.6 %	0.61	0.83
38x16, horizontal	M	38	16	0.27	0.26	0.30	4.5 %	5.2 %	0.97	1.12
65x20, horizontal	M	20	65	0.14	0.12	0.13	2.1 %	2.3 %	0.86	0.93
65x20, vertical	L	20	65	0.14	0.13	0.16	2.3 %	2.7 %	0.95	1.12
65x20, horizontal	M	65	20	0.46	0.41	0.67	7.1 %	11.6 %	0.90	1.47
- long wall only	M	65	20	0.46	0.12	0.11	2.0 %	1.9 %	0.26	0.24
65x20, vertical	L	65	20	0.46	0.12	0.17	2.1 %	2.9 %	0.27	0.37
- long wall only	L	65	20	0.46	0.06	0.10	1.1 %	1.7 %	0.13	0.21
70x35, horizontal	M	35	70	0.24	0.18	0.24	3.2 %	4.1 %	0.77	0.99
70x35, vertical	L	35	70	0.24	0.13	0.22	2.2 %	3.9 %	0.53	0.93
70x35, horizontal	M	70	35	0.50	0.41	0.68	7.2 %	11.8 %	0.83	1.37
70x35, vertical	L	70	35	0.50	0.19	0.30	3.4 %	5.2 %	0.39	0.61

Table C.2: Apparent scattering area S', apparent scattering coefficient s' and surface compensated apparent scattering coefficient, s'', for a the window profile measurements. S_d is the total diffusor area.

Configuration	Setup	Depth	500	1k	2k	4k	8k	16k
Not mirrored	E	52	32	22	17	10	13	9
Mirrored	J	52	30	19	17	10	13	9
30% area	D	52	33	20	13	8	10	5
50% area	C	52	33	18	16	10	11	7
70% area	B	52	33	25	21	12	13	8
Random depths	A	N/A	31	26	21	17	15	11
Short and long wall	A	22	35	16	17	21	11	9
	A	42	34	24	24	10	13	11
	A	52	33	27	22	14	15	11
	A	62	30	30	16	17	14	11
	A	72	34	30	10	15	15	11
	A	82	33	29	8	11	16	12
	A	92	29	29	10	13	15	12
	A	112	33	26	18	16	15	13
Only short wall	A†	52	33	14	7	7	10	6
Only long wall	A†	52	33	16	7	8	11	8
Only up	F	52	32	13	12	7	11	8
Only down	G	52	34	27	21	11	11	5
Vertical	K	22	36	15	14	14	10	7
	K	52	33	24	18	12	11	8
Combined	H	22	34	15	13	12	9	6
	H	52	33	24	16	10	10	7
Spread	I	52	33	27	25	14	15	10
Without frames	A	52	34	20	20	14	17	12

Table C.3: Suggested scattering coefficients for CATT, for the different diffusor setups.
†Wall 1 and 2 have no diffusors, respectively.

Configuration	Setup	Width	Depth	500	1k	2k	4k	8k	16k
No diffusors				33	11	4	4	6	4
38x16, horizontal	M	16	38	30	11	4	5	9	7
- long wall only	M	16	38	32	11	4	5	8	5
38x16, vertical	L	16	38	29	13	5	6	8	5
38x16, horizontal	M	38	16	29	13	5	6	8	5
65x20, horizontal	M	20	65	28	12	5	13	13	8
65x20, vertical	L	20	65	26	12	5	8	9	8
65x20, horizontal	M	65	20	30	14	6	7	8	6
- long wall only	M	65	20	30	12	10	21	11	11
65x20, vertical	L	65	20	29	12	4	7	9	7
- long wall only	L	65	20	32	12	6	7	8	5
70x35, horizontal	M	35	70	29	12	5	6	7	5
70x35, vertical	L	35	70	22	13	6	11	10	8
70x35, horizontal	M	70	35	30	14	6	9	10	5
70x35, vertical	L	70	35	27	15	18	11	14	8

Table C.4: Suggested scattering coefficients for CATT, for the window profiles.

APPENDIX D

Source directivity measurements

Figures D.1 - D.3 shows the directivities of the loudspeakers, measured in the anechoic room at NTNU. The pipe loudspeaker was measured with the impulse response method, while the dodecahedron was measured with pink noise while rotating the speaker.

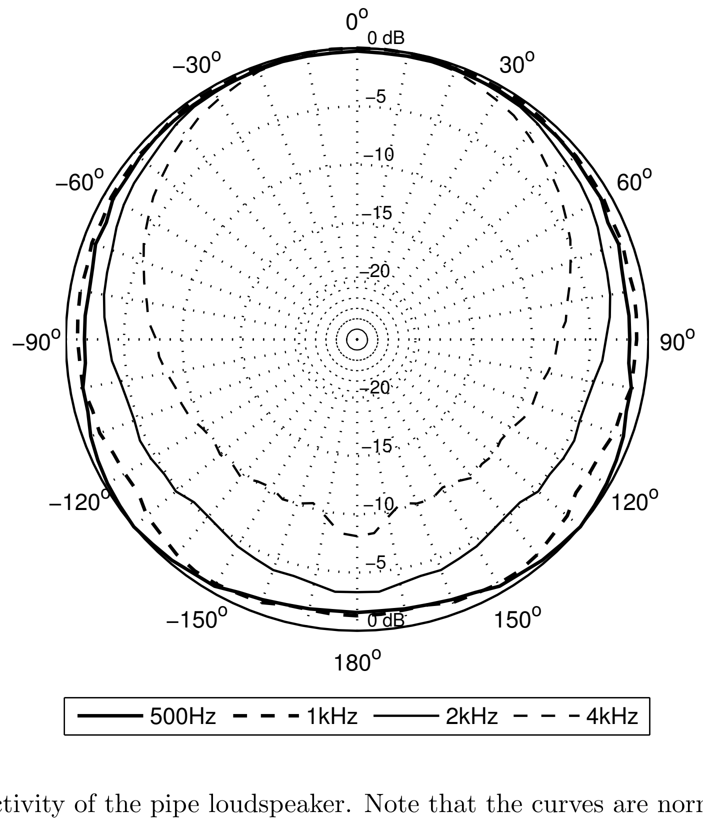

Figure D.1: Directivity of the pipe loudspeaker. Note that the curves are normalized to 0dB.

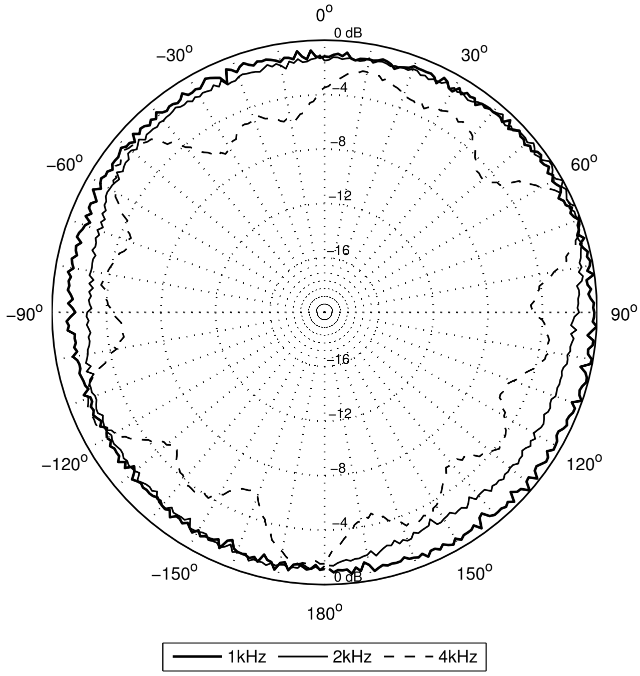

Figure D.2: Directivity of the dodecahedron loudspeaker (1-4kHz). Note that the curves are normalized to 0dB.

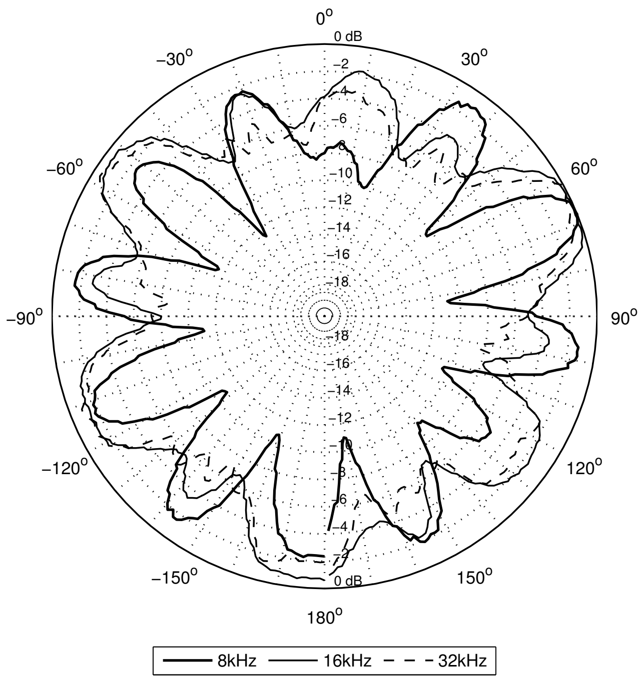

Figure D.3: Directivity of the dodecahedron loudspeaker (8-32kHz). Note that the curves are normalized to 0dB.

Figures D.4 - D.5 shows the frequency responses of the two loudspeakers.

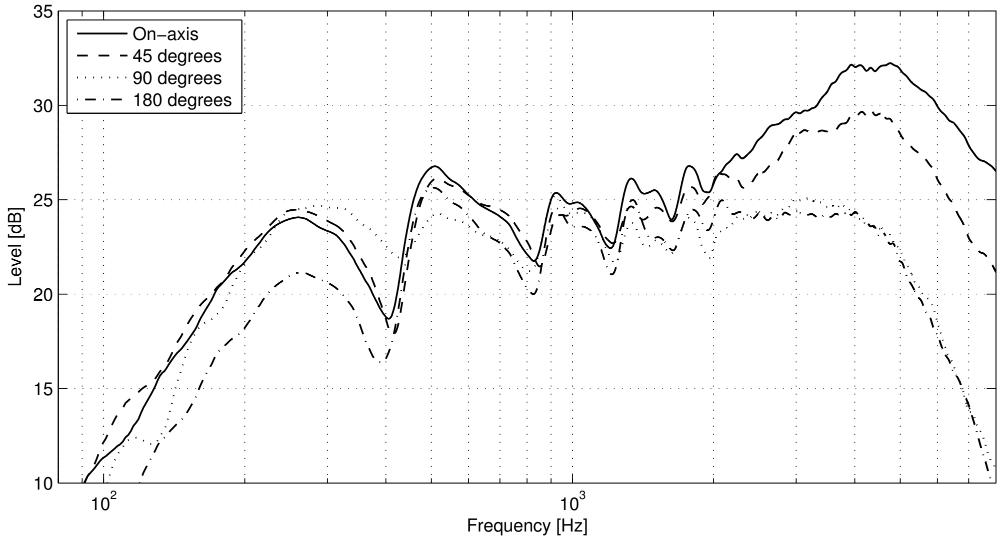

Figure D.4: Frequency response of the pipe loudspeaker, measured at different angles.

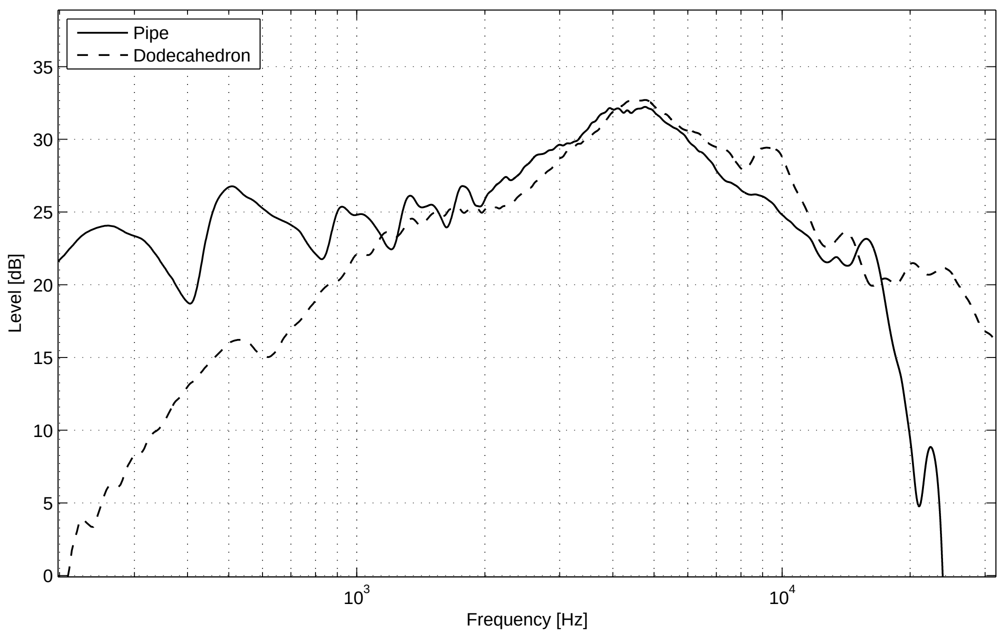

Figure D.5: Frequency response of the pipe and dodecahedron loudspeaker. The loudspeakers work in each their area.

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Articles

Title Index

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