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INVESTIGATION OF THE INFLUENCE OF INCIDENT ANGLE AND FREQUENCY DEPENDENCE OF A CEILING ABSORBER ON ROOM ACOUSTIC DESCRIPTORS

ARNHEIDUR BJARNADOTTIR

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MASTER'S DISSERTATION

INVESTIGATION OF THE INFLUENCE OF INCIDENT ANGLE AND FREQUENCY DEPENDENCE OF A CEILING ABSORBER ON ROOM ACOUSTIC DESCRIPTORS

ARNHEIDUR BJARNADOTTIR

Supervisors: **DELPHINE BARD**, Assoc. Professor; Division of Engineering Acoustics, LTH, Lund
and **ERLING NILSSON**, PhD, Saint-Gobain Ecophon AB.

Examiner: **KRISTIAN STÅLNE**, PhD; Division of Structural Mechanics, LTH, Lund.

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For information, address:

Div. of Engineering Acoustics, LTH, Lund University, Box 118, SE-221 00 Lund, Sweden.
Homepage: http://www.akustik.lth.se

Abstract

The aim of this thesis is to investigate the following:

- The influence of incident angle and frequency dependency of a ceiling absorber on room acoustic descriptors
- How ceiling absorber properties influence room acoustic descriptors such as reverberation time and steady state sound pressure level
- Whether steady state sound pressure level is more related to the statistical absorption coefficient (the average of all incidents) than the reverberation time in a room with an absorbent ceiling
- The scattering effect due to furniture in a school classroom

The software package WinFlag was used to simulate acoustics in a typical school classroom. The absorption coefficient was computed for several different angles, frequencies and ceiling absorbers. The WinFlag results were compared with results obtained by measuring reverberation time and sound pressure level in a 1:3 scale model of the classroom.

The conclusion was that it is not enough to use reverberation time to investigate the quality of the ceiling. It is important to use more acoustic parameters to do this like for example sound pressure level, and it is also important to evaluate sound pressure level and reverberation time separately.

Preface

This thesis was done at the Department of Engineering Acoustics, Faculty of Engineering, Lund University, Sweden as an end of my later part of master program, of which the first part was done in University of Iceland.
I would like to thank my instructor Delphine Bard at the Department of Engineering Acoustic and Erling Nilsson at Saint-Gobain Ecophon AB for support and guidance during this project.
I would like to thank my father Bjarni Rúnar Bjarnason and my father in law Kristján Jónasson for proofreading and all the great help.
Last but not least I would like to thank my husband Júlíus Stígur Stephensen for all the support and help and my three wonderful children, Þórdís, Kári and Styrmir for being there.

Lund, December 2013

Arnheiður Bjarnadóttir

Summary

Sound has a great impact on people's life. They can experience sound in a good way or the sound can be disturbing. When sound is disturbing it can be stressful and it can also damage people's health. It can be described as unwanted sound, or simply noise.
Noise is for example sound with very high sound level. Noise can be very disturbing when concentrating.
In a noisy environment it is more difficult to hear or to be heard. It becomes stressful and has a negative effect on people's behavior. One must speak louder in a noisy room, which then becomes even louder. When you are stressed up, your heartbeat becomes irregular, you become anxious and this affects not only your concentration but also your health, if you work or study in an environment like that every day.
The aim of acoustic engineering is to control sound in specific environments. The motivation of this project is to improve sound quality. This can make people feel better both mentally and even physically. It is important that people are comfortable when working, studying or playing.
Here the concern is the classroom. Good studying quality is very important and creating the best possible conditions for the students and the teachers. This requires understanding and researches on the factors that matter in this case.
Good sound quality in a classroom it can improve concentration, memory and speech clarity.

In the beginning of the thesis the theory of acoustic parameters are presented and different standards and regulations that are important in designing good acoustics are listed up.
The study itself can be divided in two parts, the first part, calculations and second part, measurements on sound pressure level and reverberation time.

Calculations were performed by the software package WinFlag. The incidence angle and frequency dependence of the absorption coefficient were calculated for different types of absorbers and then explain the experimental part that follows. Another aim was also to check the hypothesis that steady state sound pressure level is more related to the statistical absorption coefficient(which is average of all incidents) than the reverberation time in a room with an absorbent ceiling. This was supported by these calculations. Results show both frequency dependence and the angle dependence of the sound absorbers. Different types of absorbers, with different frequency absorbing characteristics were tried. Results show that if the surface layer is denser the absorption coefficient is lower, at least for the higher frequencies. For a given density, the thickness of an absorber affects the behavior of the absorption coefficient: if the absorber is thicker than the sound absorption is higher, but if the absorber is thinner it reflects more.

A model of a classroom was made of wood in the scale 1:3 and all the measurements were made for different time of ceiling absorber, which was changed before every measurement. Each ceiling absorber had different sound absorption characteristics. Measurements were made for both classrooms (model) with furniture and in an empty room. This was to investigate the scattering effect of the furniture.

Contents

Chapter 1. Introduction

Sound has a great impact on people's life. They can experience sound in a good way or the sound can be disturbing. When sound is disturbing it can be stressful and it can also damage people's health. It can be described as unwanted sound, or simply noise. Noise is for example sound with very high sound level. Noise can be very disturbing when concentrating.
In a noisy environment it is more difficult to hear or to be heard. It becomes stressful and has a negative effect on people's behavior. One must speak louder in a noisy room, which then becomes even louder. When you are stressed up, your heartbeat becomes irregular, you become anxious and this affects not only your concentration but also your health, if you work or study in an environment like that every day.

The aim of acoustic engineering is to control sound in specific environments. The motivation of this project is to improve sound quality. This can make people feel better both mentally and even physically. It is important that people are comfortable when working, studying or playing. This makes the whole world a better place.

1.1 Background

Most of us spend most of our time indoors. We spend a lot of time in places like offices, classrooms, at home, in factories, workshops and restaurants. The sound in our environment is very important when listening to music, lectures and speech, when attending sports event or just when we are having a cup of coffee in a coffee shop. Even though in some of these cases the sound is not of primal interest it affects how we feel.

The purpose of the room decides how we want to experience the sound around us. Where music is played, we of course want to enjoy the sound, but when we work in an open workspace we want the least attention to what happens around us. Many things affect how we experience sound in our environment, such as speech clarity, sound pressure level, sound propagation and reverberation time. These factors are determined by absorption in the room, furniture, whether there are people in the room and the size of the room.

The purpose of this master thesis is to investigate how properties of ceiling absorbers influence various parameters that measure room acoustics. It will be shown that it is important to look at more than one parameter as well as to investigate the effect of incident angle and sound frequency. It is not enough to look at reverberation time only as often has been done. It is also necessary to look at acoustic descriptors that measure properties such as speech clarity, sound pressure level and sound propagation.

1.2 Objective and method

The aim of this study is to investigate several room acoustic descriptors, and how they depend on parameters such as incidence angle and frequency, for some different types of ceiling absorbers. The final purpose is to improve school classroom acoustics. Good speech intelligibility is extremely important, and school classrooms have to promote intellectual work and concentration.

The first part of this study deals with simulations of acoustics in a school classroom with the computer program WinFlag. The results of the simulations were plotted in Excel and Matlab. The input to WinFlag consisted of different room parameters, including room dimensions and properties of the ceilings. The outcome from the WinFlag computations was absorption coefficients for different angles and frequencies.

The second part of the study involved measurements of sound in a model of a typical classroom in the scale 1:3, using a system called "Norsonic Sound Analyser". The computer program NorXfer was used to process the measurement results and more calculations were made with Excel. Reverberation time, absorption coefficient and sound pressure level were measured for different ceiling configuration.

In the third part of the study, results from the measurements were compared with the theoretical computations from the first part of the study.

The thesis was made under the supervision of Erling Nilsson at Ecophon AB and Dephine Bard at LTH.

1.3 Disposition

- Chapters 2 and 3 discuss the theory of room acoustics, concepts, standards and regulations.
- Chapter 4 contains description WinFlag computations and results.
- Chapter 5 describes the measurement part of the study and discusses the results from the Norsonic measurements and results.
- Chapters 6–8 compare the simulated results with the measurements, and also contain conclusions, discussion and suggestions for further work

Chapter 2. Acoustic concepts

Acoustic concepts discussed in this chapter are of much interest and importance for sound quality studies as the one described in this thesis. Some of these concepts are used in the calculations and conclusion in this work, but others are mentioned here as a reminder what could be considered in acoustical studies.

2.1 Sound propagation

Sound is a sequence of waves of pressure which propagate through compressible media such as air or water. During their propagation, waves can be reflected, refracted, or attenuated by the medium. The behavior of sound propagation is affected by the properties of the medium. These properties include the relationship between density and pressure, the motion of the medium itself and the viscosity of the medium. [6]

The sound pressure level (L_P) in a room depends on the sound power from the sound source (L_W), the directivity of the sound source (Q), the distance (r) between listener and the sound source (the speaker) and the equivalent absorption area (A). The sound pressure level in a room is given by:

$$L_p = L_w + 10log\left(\frac{Q}{4\pi r^2} + \frac{4}{A}\right) \qquad (1)$$

In the near field the direct field dominates the sound pressure level. In the far field the reflections from the room surfaces determine the sound pressure level.

2.2 Reverberation time

The reverberation time, T is defined as the time required for the sound pressure level in a room to decrease by 60 dB. T can be evaluated based on a smaller dynamic range than 60 dB and extrapolated to a decay time of 60 dB. It is then labeled accordingly. Thus, if T is derived from the time at which the decay curve first reaches 5 dB and 25 dB below the initial level, it is labeled T_{20}. If decay values of 5 dB to 35 dB below the initial level are used, it is labeled T_{30}.

The reverberant sound in an auditorium dies away with time as the sound energy is absorbed by multiple interactions with the surfaces of the room. In a more reflective room, it will take longer for the sound to die away and the room is said to be 'live'. In a very absorbent room, the sound will die away quickly and the room will be described as acoustically 'dead'. But the time for reverberation to completely die away will depend upon how loud the sound was to begin with, and will also depend upon the acuity of the hearing of the observer. In order to provide a reproducible parameter, a standard reverberation time has been defined as the time for the sound to die away to a level 60 decibels below its original level. The reverberation time can be modeled to permit an approximate calculation.[5]

Reverberation time is often presented with the Sabine formula, where V is volume and A is the equivalent absorption area:

$T_{60} = 0{,}16 \cdot \frac{V}{A}$

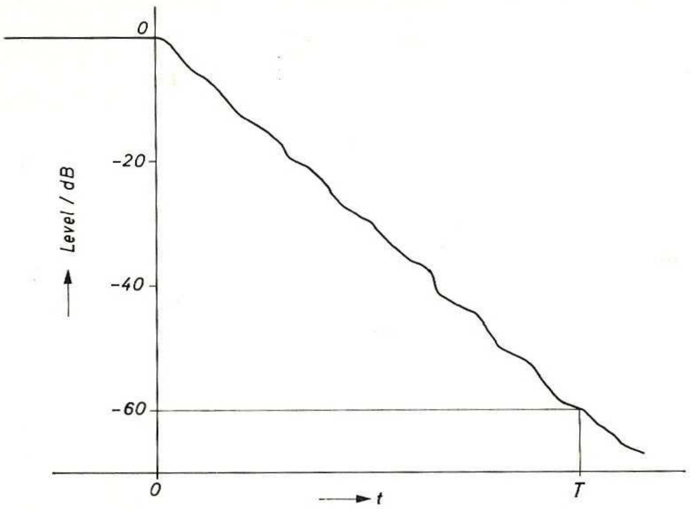

Figure 1– Definition of a reverberation time. [12]

The equivalent absorption area is equal to the absorption coefficient (α) times the surface of the absorber (S). Thus, the equivalent absorption area is given by

$A = \alpha \cdot S$ (2)

The absorption coefficient α is defined as the ratio between the absorbed sound power and the incidence sound power. A totally absorbing surface has an absorption coefficient equal to 1 and a totally reflecting surface has an absorption coefficient equal to 0.

2.3 Speech clarity

Speech clarity measures the quality of speech as heard by a listener. The clarity is good when each spoken word is heard and not blurred and the speaker is loud enough to be heard. The sound that is first heard by the listener is the direct sound, which is then followed by early reflections. Early reflections reach the listener within 50 ms. They are integrated with the direct sound and have a positive effect on speech clarity. The listener does not perceive these early reflections as an echo. Later reflections are likely to be more disturbing. This phenomenon is known as the precedence effect or Haas effect.

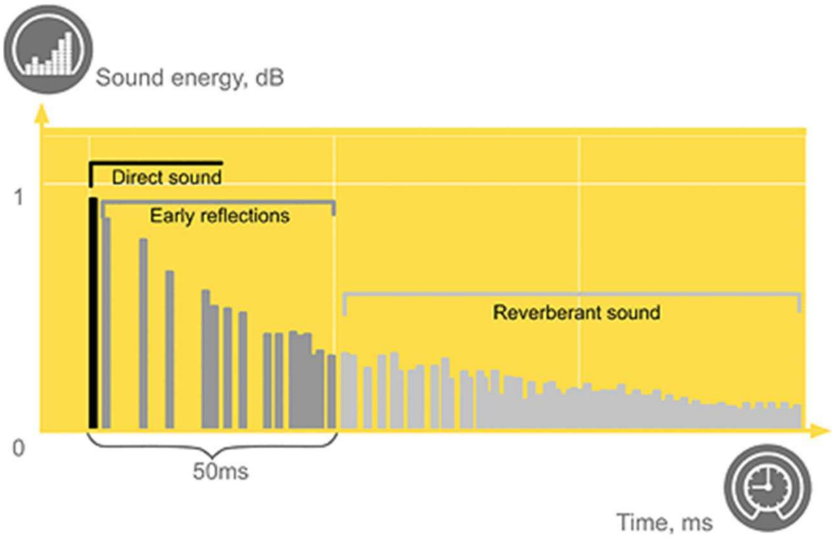

Figure 2– C_{50} measures effect of the room's early reflections. [4]

The clarity descriptor C_{50} compares the sound in early sound reflexes with those that arrive later. A high value is positive for speech clarity. C_{50} is calculated as the ratio of the total sound energy received in the first 50 milliseconds and the rest of the received energy, and similarly for C_{80}. This ratio is called the early-late index, and is defined in general by the formula

$$C_{t_e} = 10 \cdot lg\left(\int_0^{t_e} p^2(t)dt \Big/ \int_{t_e}^{\infty} p^2(t)dt\right) \qquad (3)$$

where t_e is 50 ms for speech and 80 ms for music.[12]

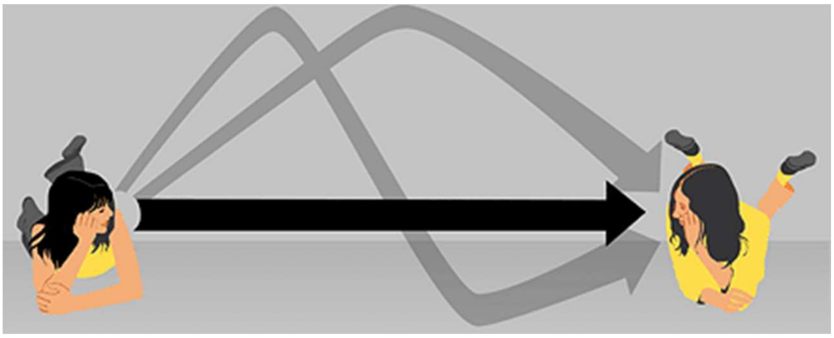

Figure 3 – Direct, early and late reflections [4]

When speech transmission is poor, variations in speech are perceived less well. Factors that impair speech transmission, thus contributing to a lower speech intelligibility are, for instance, background noise, long reverberation time and echoes. Speech intelligibility is measured according to the standard IEC, which defines the so-called "Speech Transmission Index" (STI). When speech transmission is perfect, then STI = 1. In a normal-sized classroom, STI should be greater than 0,75. STI measures quality of speech transfer from speaker to listener.[4]

2.4 Auditory strength

Auditory strength is the level at which we experience sound. A reverberant room gives a higher sound level than a room with added sound absorption. The descriptor “Sound Strength” (G) is defined in the standard ISO 3382-1 with the formula:

$$G = 10lg\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10}^2(t)dt} = L_{pE} - L_{pE,10}dB \qquad (4)$$

where p(t) is the instantaneous sound pressure of the impulse response measured at the measurement point, $p_{10}(t)$ is the instantaneous sound pressure of the impulse response measured at a distance of 10 meters in a free field, L_{pE} is the sound pressure exposure level of p(t) and $L_{pE,10}$ is the sound pressure exposure level of $p_{10}(t)$.

The descriptor “Strength” measures the sound level in the real room in relation to the sound level in an anechoic room with the same sound source and power output, at a reference distance 10 meter. “Strength” describes the room reflections’ effect on the sound level.[4]

2.5 Spatial decay

The sound level decreases as the distance from the sound source increases. The design of the room (shape, furnishing, surface finish etc.) influences the extent to which the sound level decreases along with the distance.

To characterize the propagation of the sound there is a parameter that describes the extent to which the sound decreases when the distance is doubled. This parameter, designated DL_2 and measured in dB, determines the slope of the sound propagation curve. Another parameter, DL_f, also measured in dB, shows how the sound level at a certain distance is related to the sound level at the same distance in a free sound field, i.e. without reflecting objects. A high DL_2 and a low DL_f ensure limited disturbance between work places.

Articulation Class (AC) is a classification of suspended ceilings according to their ability to contribute to the acoustic privacy between work stations. AC is defined in ASTM E1110. This method provides measurements of the sound reflective characteristics of ceilings used together with screens.[4]

Figure 4– Sound propagates and sound pressure level decreases [4]

Sound pressure level (SPL) is often measured on a logarithmic decibel scale, because people can hear sounds with a wide range of amplitudes. SPL or L_p is defined with the equation

$$L_p = 10\ log_{10}\left(\frac{p^2}{{p_{ref}}^2}\right) dB, \qquad (5)$$

where p is the root-mean-square sound pressure and $p_{ref} = 2*10^{-5}$ is the reference sound pressure. The reference pressure corresponds to the hearing threshold at 1000 Hz.

2.6 Rooms with absorbent ceilings

Rooms with ceiling absorbers are common. In these rooms the reverberation time is not only dependent on the absorption but also for example on furnishing and the shape of the room. Sound pressure level is dependent on absorption: the more the absorption the less the sound pressure level.

Steady state is obtained when a sound source emits sound continuously to the room, thus giving a constant level of sound everywhere in the room. In a room with absorption in the ceiling the sound is mostly diffuse at steady state.

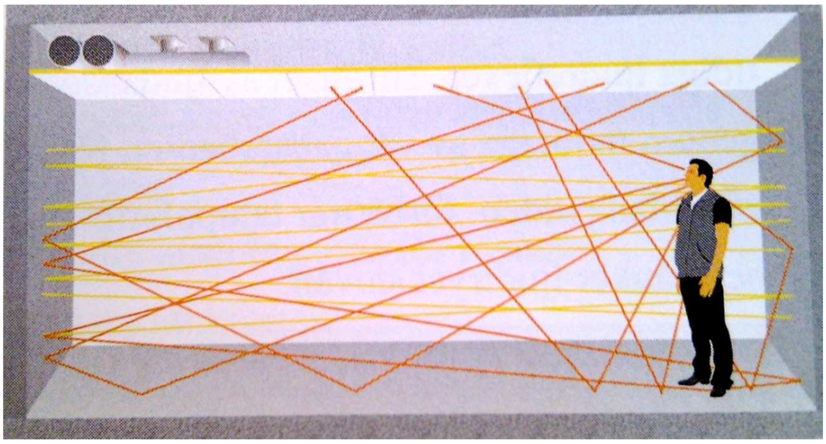

Figure 5 – Red lines show steady state and the yellow lines show reverberation. [4]

In the case of reverberation the situation is more complex. When the sound source is turned off the sound waves that hit the ceiling will be absorbed faster than the ones that propagate parallel to the ceiling and the floor. This is because much of the sound energy is absorbed in the ceiling.

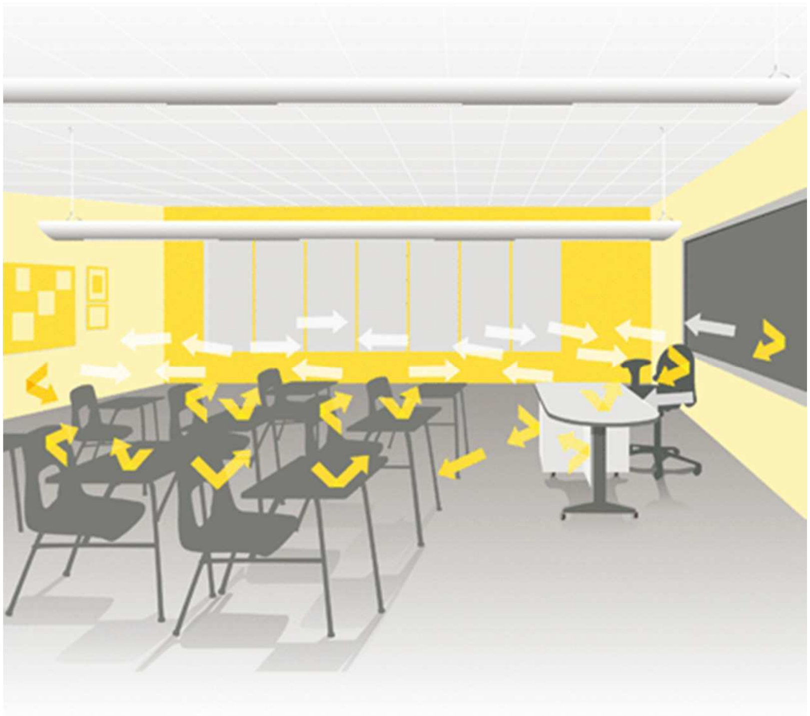

Figure 6 – Reverberation - White arrow: Grazing waves, Yellow arrow: non-grazing waves. [4]

Figure 7 - Steady state [4]

When there is no furniture, and walls and floor have little absorption, then the reverberation time will be determined by the walls' absorption for grazing incidence and the absorption in the ceiling and the floor. Grazing incidence means that the sound waves propagate almost parallel to the floor and the ceiling. The absorption factor of the ceiling for grazing incidence is often a lot less than the statistical absorption coefficient normally stated. The statistical absorption coefficient is measured according to ISO 354.

Reverberation time in rooms with an absorbent ceiling is generally much longer than could be expected from calculations with the Sabine formula. This effect is shown below, in Fig. 8.

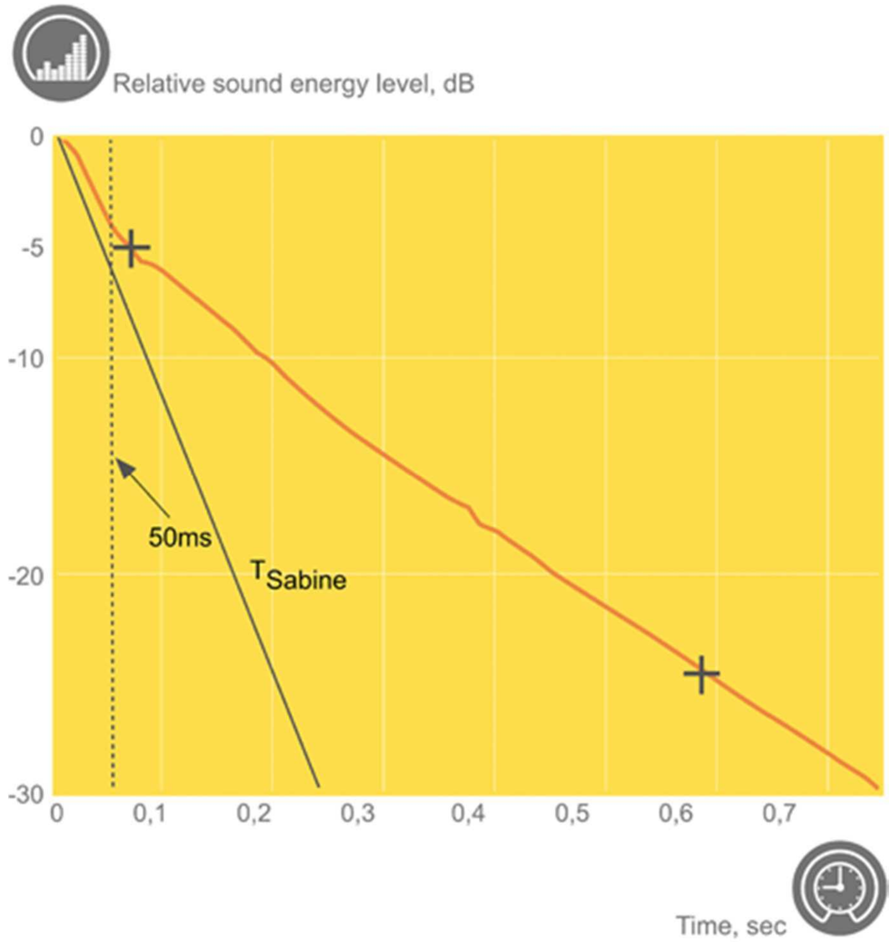

Figure 8 - Reverberation curve in a room with an absorbent ceiling and sound scattering objects. [4]

The early section of the curve in Fig. 5 corresponds quite well to a Sabine reverberation time curve. After the sound source is turned off we have a steady state, where there is a diffuse sound field and sound diminishes quickly. The later part of the curve corresponds to a grazing field.

Early reflections that arrive within 50 ms increase the speech intelligibility. The sound that arrives later can have a negative effect on the speech intelligibility. Since T20 and T30 are not evaluated until after the sound pressure level has decreased by 5 dB the effect of the early reflections is lost. These early reflections are important and therefore it is important to look at more acoustic parameters when investigating speech intelligibility.

Chapter 3. Standards and recommendations

When measuring and calculating acoustic parameters it is important to follow standards and recommendations. This is done to secure the quality of the work and to be able to compare one measurement or calculation to another. The standards and recommendations are also used for increasing the quality of the object which is measured or simulated.

Reverberation time used to be considered as the most important factor to characterize the acoustical properties of a room. Reverberation time still plays an important role but other parameters, such as sound pressure level, speech intelligibility and background noise are now of more interest than before.

3.1 SS-EN ISO 3382

When measuring reverberation time different standards are used for different countries and there are also some international recommendations. The method for obtaining reverberation time is given in SS-EN ISO 3382-1,2,3 and it is used for reverberation time measurements in locals, normal rooms and open office space.

Here are some important points from that standard

- The microphone should be placed where the listener would be.
- When measuring reverberation time it is important to measure in more than one place in the room.
- The microphone should not be placed near the sound source or near reflecting surfaces.
- The microphone in a room for speech or music should be placed in a height of 1,2 m to be in ear height of the listener.
- It should be sufficient to measure in 3 or 4 different spots in the room.
- Measurement should be made in the frequency range 100–5000 Hz when measured in one third octave band.
- It is important to use the same sound power output for all measurements.
  The number of microphone positions used will be determined by the accuracy required.
  The number of measurement spots are different for different room types. [11]

In that standard it is also described how the results should by presented among other guidelines.

3.2 SS 25268

In Sweden SS 25268:2007 is used when measurements are evaluated for schools, offices and hospitals. SS 25267:2004 is used for residences.

For a classroom the reverberation time should be not more than 0,5 or 0,6 seconds, depending on the selected quality level. This applies to normally furnished but unoccupied rooms. The above figure is the highest recommended value for the frequency range 250 – 4000 Hz. At 125 Hz a value 20% higher is permitted.

The quality level is classified with class A, B, C or D where A gives the best quality and D gives the worst. The minimum requirement in Swedish BBR (Boverkets byggregler) is class C.

3.3 More standards and recommendation

More standards for measurements and evaluation of measurements are for example:

- SS-EN ISO 354 Measurement of sound absorption in a reverberant room.
- SS-EN ISO 11654 Sound absorbers for use in buildings -- Rating of sound absorption.
- SS-EN ISO 14257 Acoustics – Measurement and parametric description of spatial sound distribution curves in workrooms for evaluation of their acoustical performance

Other requirements and recommendations are used in different countries. For example UK regulations, Building Bulletin 93 (BB93) says: “Primary school classrooms must achieve an unoccupied mid frequency reverberation time of <0,6 seconds”. In secondary schools it states that an unoccupied mid frequency reverberation time of <0,8 seconds be achieved. If the classroom is designed specifically for the teaching of hearing impaired pupils then an unoccupied mid frequency reverberation time of <0,4 seconds is required.[4]

Chapter 4. Calculation part using WinFlag

In this chapter the incidence angle and frequency dependence of the absorption coefficient are calculated for different types of absorbers. The calculations are performed by the software package WinFlag.

It is difficult to measure absorption as a function of incidence, and that is why we must rely on calculations.

The input for the program consists of the properties of the different types of absorbers and the program output is an absorption coefficient. These result are then discussed, used and compared later in this thesis.

The absorptions coefficient, α is calculated with

$$\alpha = \frac{4Re\left\{\frac{Z_g}{Z_0}\right\}}{\left|\frac{Z_g}{Z_0}\right|^2 + 2Re\left\{\frac{Z_g}{Z_0}\right\} + 1} \qquad (6)$$

Z_g is the input impedance and Z_0 is the characteristic impedance for air.

When „Diffuse“ is chosen, the program calculates the statistical absorption coefficient, α_{stat}. The statistical absorption factor is the mean value obtained when averaging over all angles of incidence.

$$\alpha_{stat} = 2\int_0^{\pi/2} \alpha(\varphi)\, sin\varphi cos\varphi d\varphi = 2\int_0^{\pi/2} \left[1 - \left|R_p\right|^2\right] sin\varphi cos\varphi d\varphi \qquad (7)$$

where α is the absorption coefficient with the incident angle φ and R_p is the pressure reflection factor given by

$$R_p = \frac{Z_g cos\varphi - Z_0}{Z_g cos\varphi + Z_0} = \frac{Z_n cos\varphi - 1}{Z_n cos\varphi + 1} \qquad (8)$$

Z_n is the normalized input impedance of the absorber.[19]

4.1 Ceiling

The cases which were calculated with WinFlag were 8. Table 4.1 shows the different types of ceiling properties.

Table 1 - Ceiling properties

Case	Product	Thickness (mm)	Flow resistance for the glass wool carrier (Pa·s/m)	Flow resistance for the surface layer (Pa·s/m)	Density (kg/m^3)
1	Master A/alpha	40	1300	320	55
2	Master A/beta	40	1300	1650	55
3	Master A/gamma	40	1300	>10000	55
4	Master A/alpha	20	650	320	55
5	Master A/beta	20	650	1650	55
6	Master A/gamma	20	650	>10000	55
7	Focus	20	1300	320	100
8	Wet pressed OWA	11.5	3500	no surface layer	292
9	Wet pressed OWA	2 x 11.5	3500	no surface layer	292

4.2 WinFlag

WinFlag is a program which simulates room acoustics and calculates the absorption coefficient, the impedance and the sound reduction index for constructions with different material layers. Calculations may be performed at single frequencies or as a mean value in one-third octave bands, for free and diffuse field sound incidence. Results can be converted to Excel or ASCII.[8]

In this research the program WinFlag was used to calculate the absorption coefficient for different absorbers according to table 4.1. The ceiling properties were inserted in the program. Then the program processed the data and results were printed out in Excel. Matlab and Excel were used to make figures to be able to see the results more clearly.

The input data to WinFlag were ceiling properties such as density, flow resistance for the core material and the surface layer, thickness and airspace. Results were obtained for absorption coefficients calculated for the incidence angle from 0° to 90° and for the frequencies 400 to 4500 Hz.

4.3 Purpose

The purpose of this study was to investigate the angle and frequency dependence of the different absorbers specified in table 4.1, and furthermore to explain the experimental results for the measurement in the 1:3 scale model.

Another aim was also to check the hypothesis that steady state sound pressure level is more related to the statistical absorption coefficient (which is average of all incidents) than the reverberation time in a room with an absorbent ceiling.

4.4 Calculated results using WinFlag

The input data consists of ceiling properties such as thickness, flow resistance, porosity and air space between absorbers and the hard ceiling. In the calculation the total mounting height has been set to 200 mm for all cases. These data were used as input for the computer program WinFlag. The program calculates the absorptions coefficient for each case, for angles 0° to 89° and frequency from 400 to 4500 Hz. The results are printed out in Excel. Excel is also used to plot the results. Matlab is used to plot the results as a function of angle of incidence and frequencies in three dimensional figures. This is done to be able to compare the results from different cases in a visual way. It would be more difficult to compare the numbers only.
Figures to show the angle dependence and also the frequency dependence were produced.
In the following the absorption coefficient is presented as a function of:

1. frequencies for the region 400-4500 Hz
2. incidence angle for the region 0° to 89°

For each material two curves are presented. In the first figure all the calculated curves are presented for the function of frequencies. In the figures for the function of frequencies the bold line in the curves, shows the frequency dependence of the absorption coefficient refer to the diffuse absorption coefficient, i.e. averaged over all incident angles.

To make it easier to see the angle dependence for different frequencies only three curves are presented. These curves are presented in figure 2 showing the angle dependence for the frequencies 400, 1000 and 4000 Hz.

Case 1 – Master A/alpha 40 mm

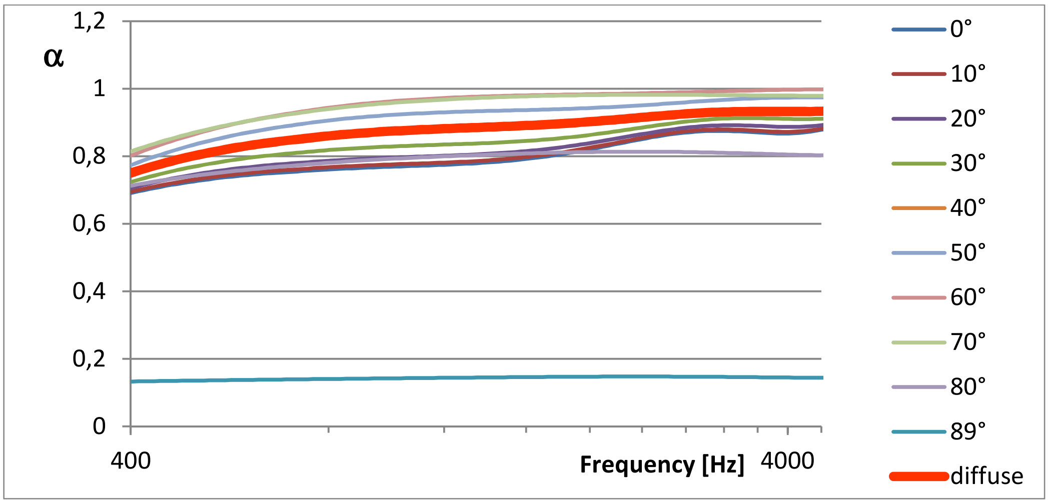

Figure 4.1 – Absorption coefficient for different angle incidents for Master A/alpha 40 mm

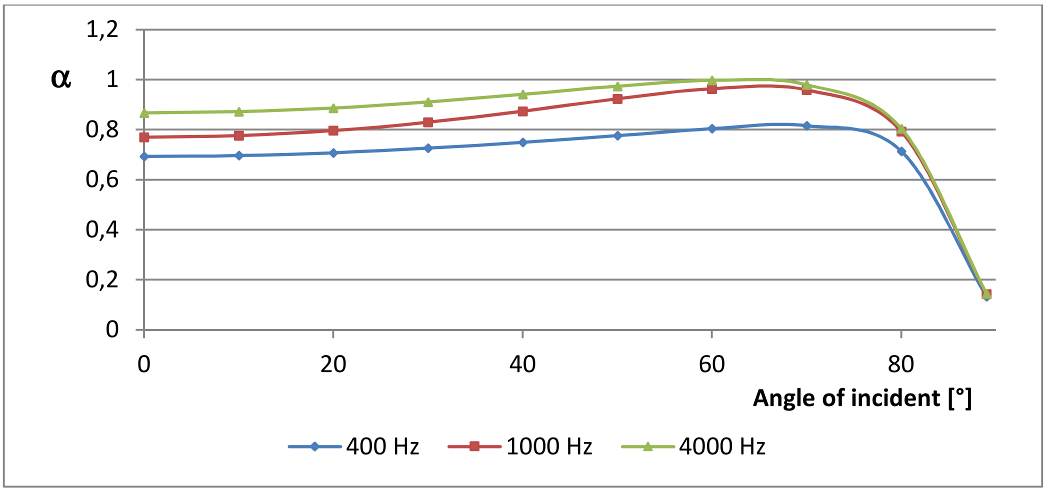

Figure 4.2 – Absorption coefficient for case 1 for the frequency of 400, 1000 and 4000 Hz.

Case 2 – Master A/beta 40 mm

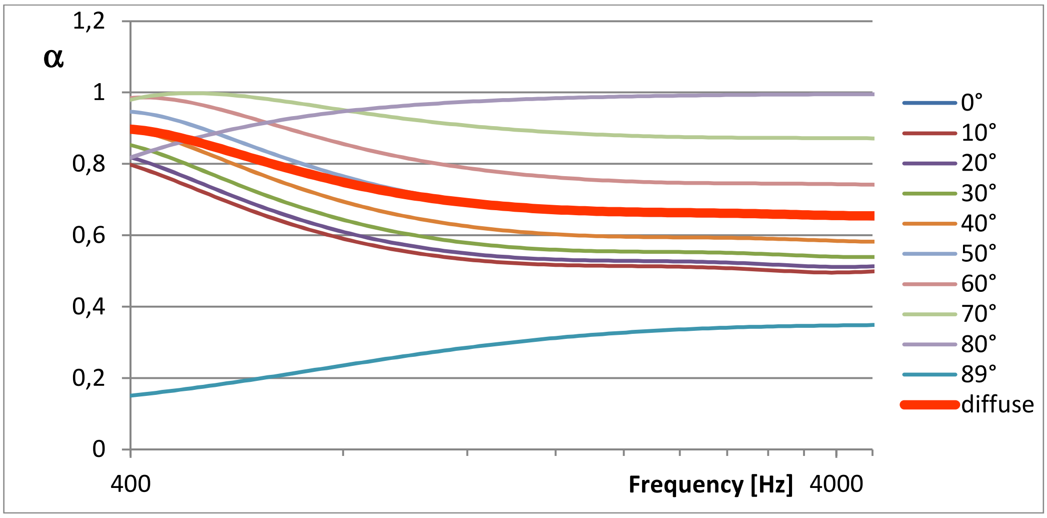

Figure 4.3 – Absorption coefficient for different angle incidents for Master A/beta 40 mm absorber

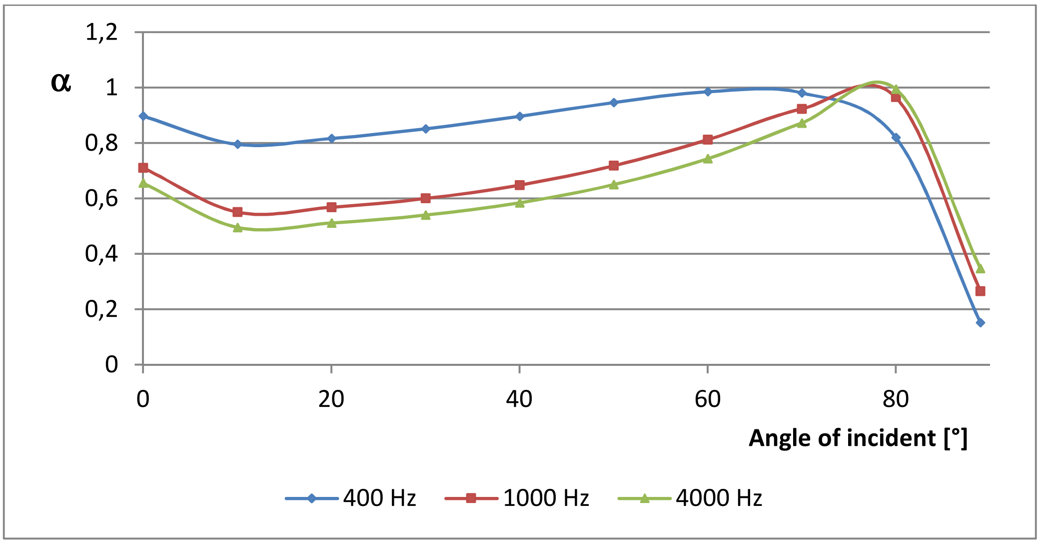

Figure 4.4 – Absorption coefficient for case 2 for the frequency of 400, 1000 and 4000 Hz.

Case 3 – Master A/gamma 40 mm

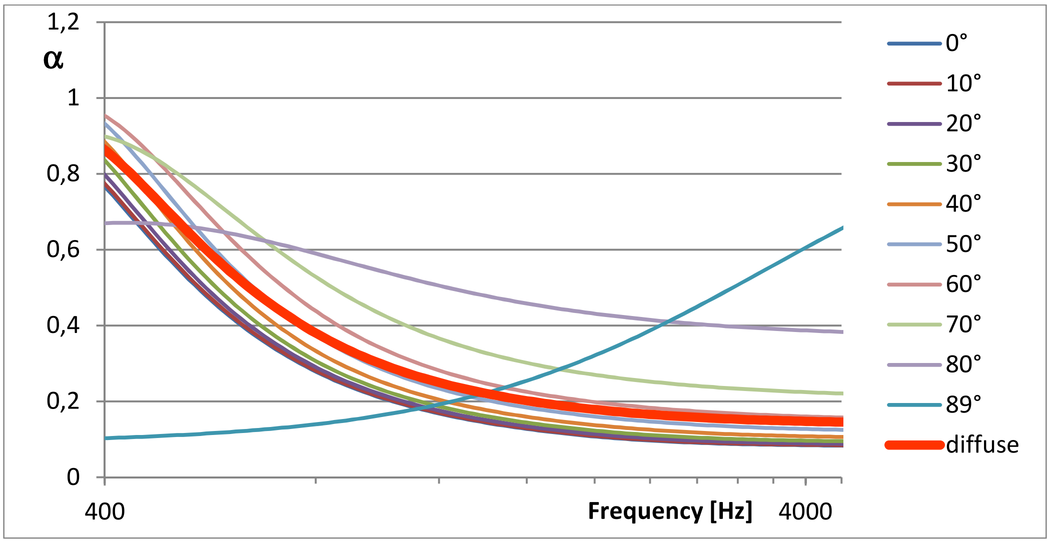

Figure 4.5 – Absorption coefficient for different angle incidents for Master A/gamma 40 mm absorber

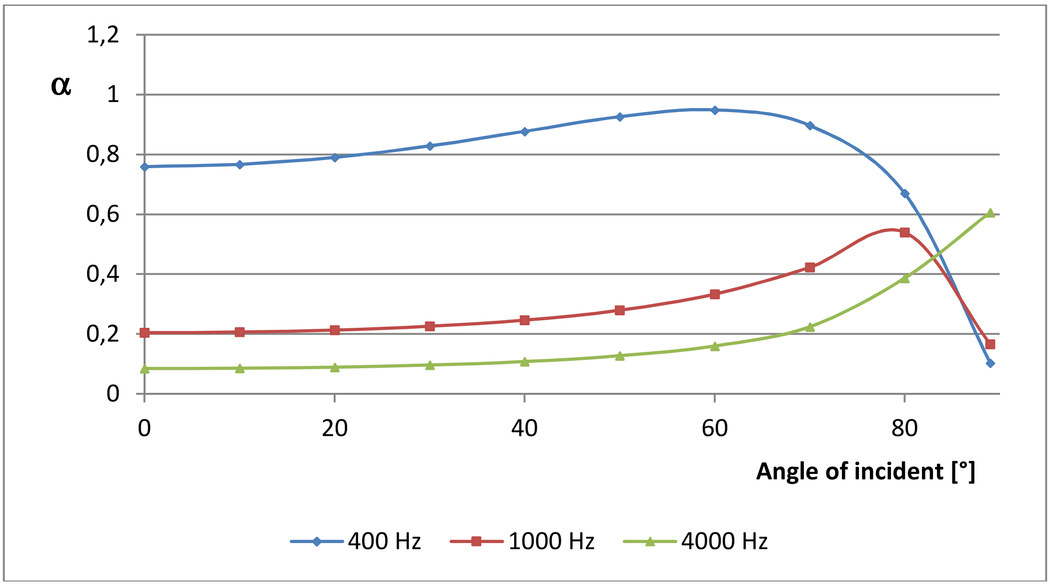

Figure 4.6 - Absorption coefficient for case 3 for the frequency of 400, 1000 and 4000 Hz.

Case 4 – Master A/alpha 20 mm

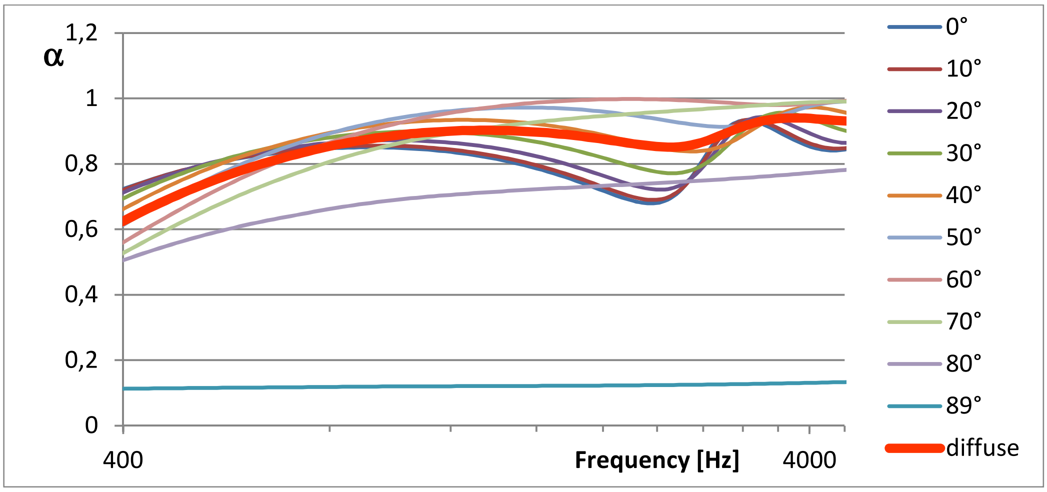

Figure 4.7 – Absorption coefficient for different angle incidents for Master A/alpha 20 mm absorber

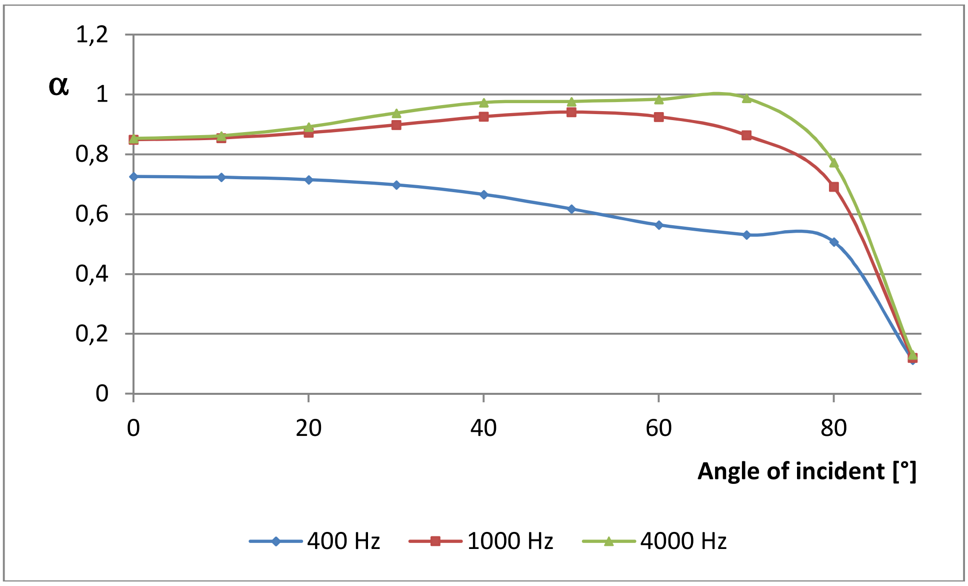

Figure 4.8 – Absorption coefficient for case 4 for the frequency of 400, 1000 and 4000 Hz.

Case 5 – Master A/beta 20 mm

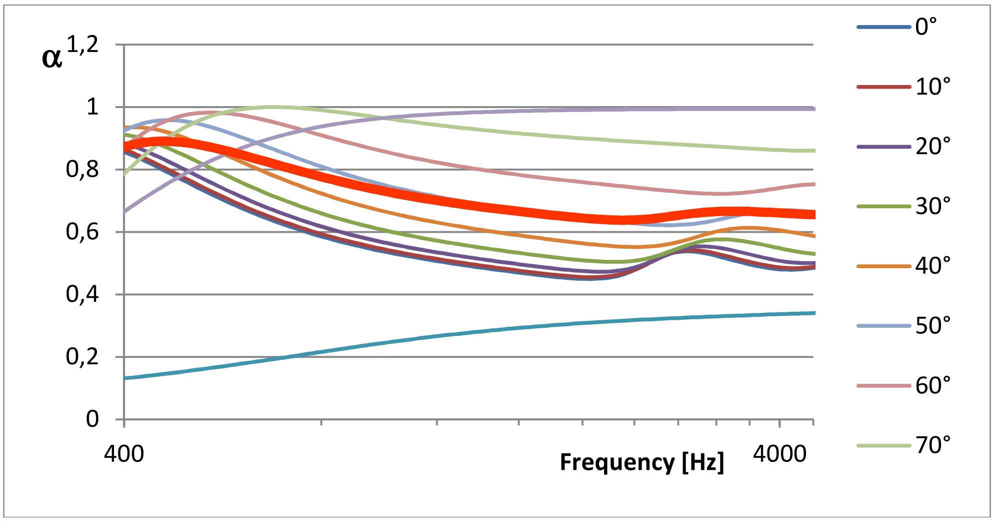

Figure 4.9 – Absorption coefficient for different angle incidents for Master A/beta 20 mm absorber.

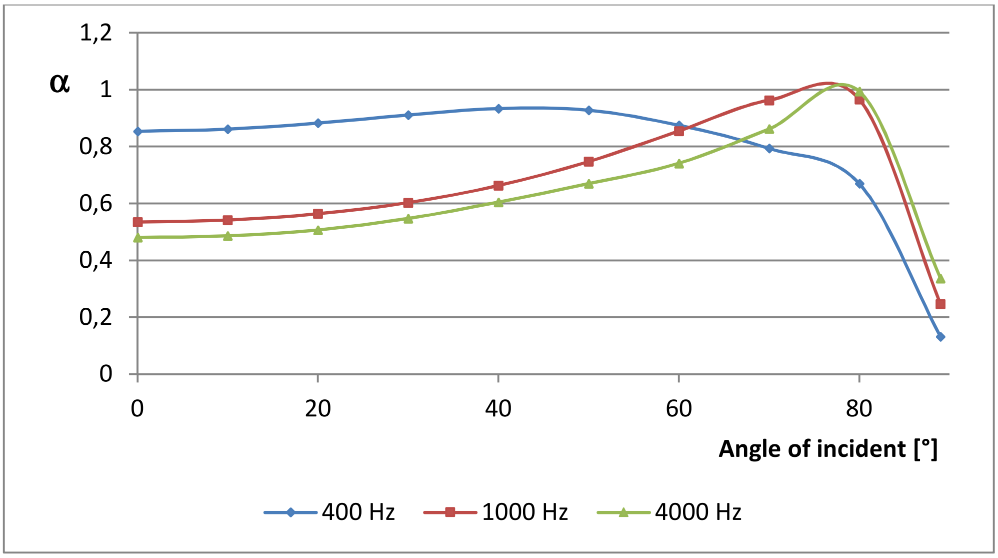

Figure 4.10 – Absorption coefficient for case 5 for the frequency of 400, 1000 and 4000 Hz.

Case 6 – Master A/gamma 20 mm

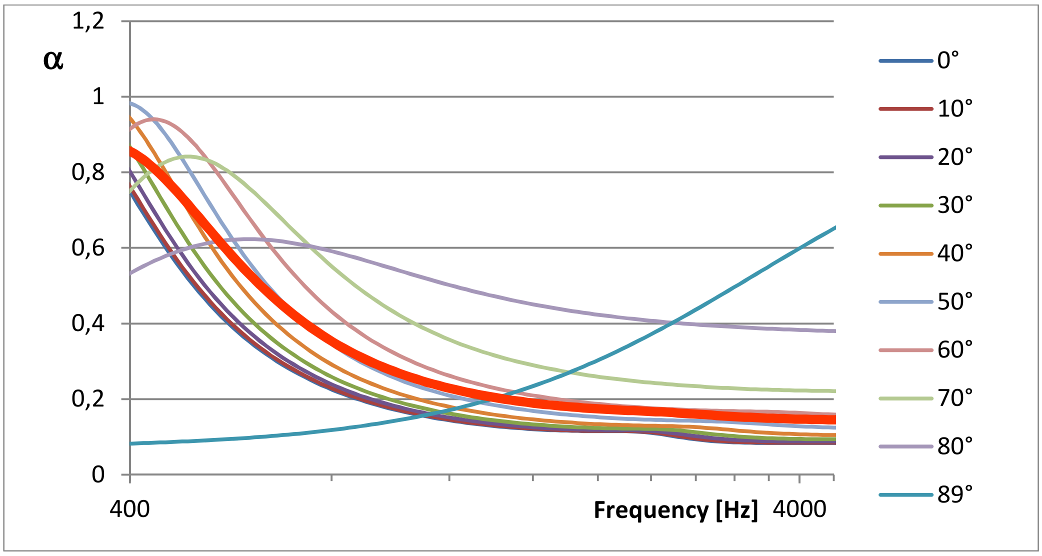

Figure 4.11 – Absorption coefficient for different angle incidents for Master A/gamma 20 mm absorber.

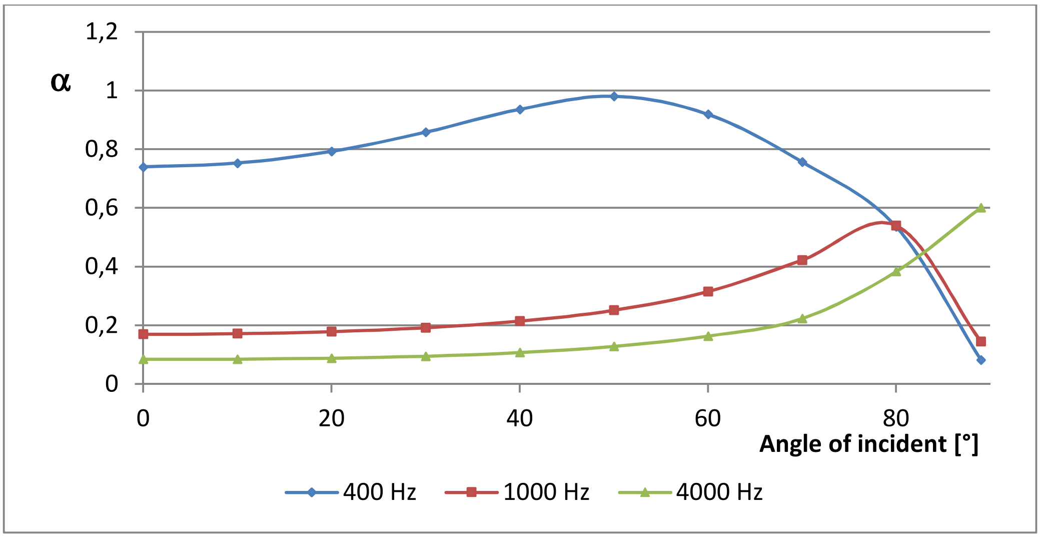

Figure 4.12 – Absorption coefficient for case 6 for the frequency of 400, 1000 and 4000 Hz.

Case 7 – Focus 20 mm

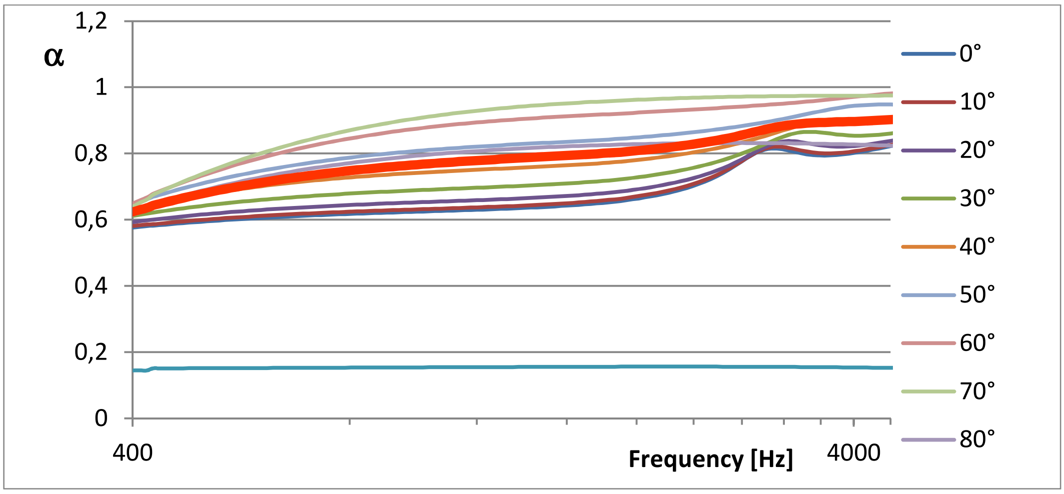

Figure 4.13 – Absorptions coefficient for different angle incidents for Focus absorber.

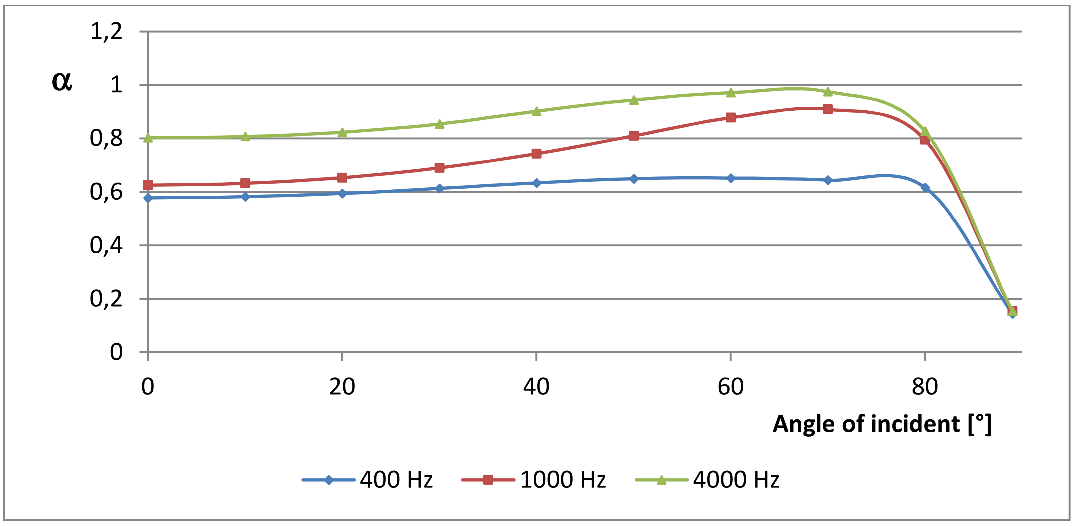

Figure 4.14 – Absorption coefficient for case 7 for the frequency of 400, 1000 and 4000 Hz.

Case 8 – Wet pressed OWA 11,5 mm

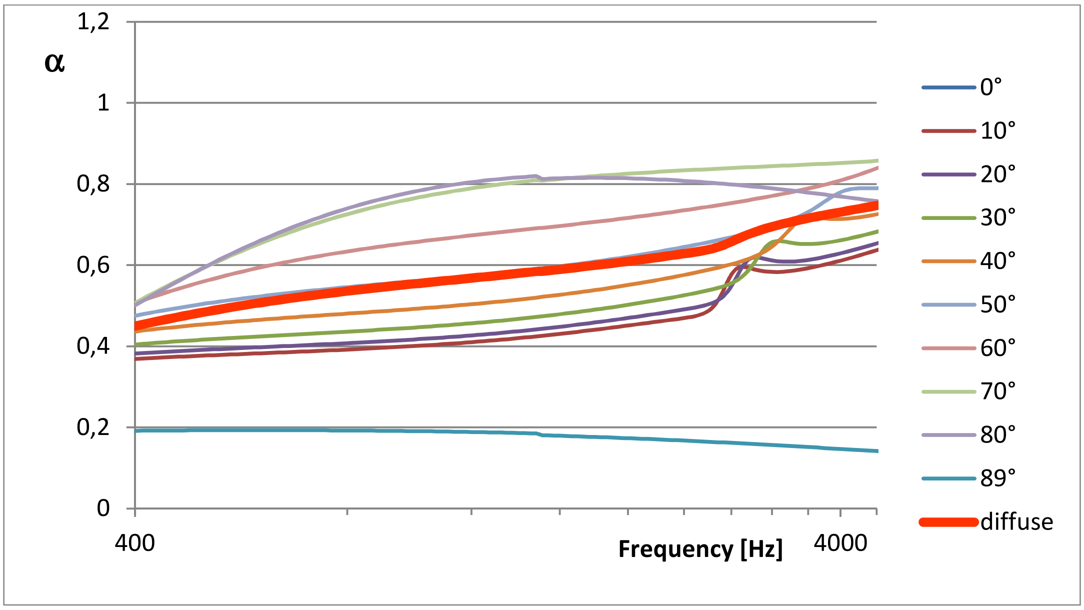

Figure 4.15 – Absorption coefficient for different angle incidents for Wet pressed OWA 11, 5 mm absorber.

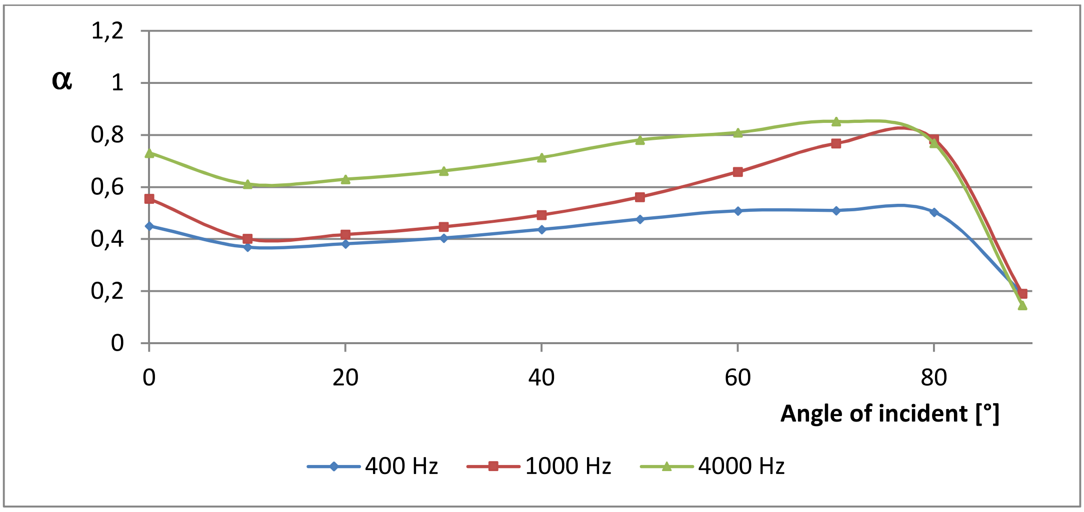

Figure 4.16 - Absorption coefficient for case 8 for the frequency of 400, 1000 and 4000 Hz.

Case 9 – Wet pressed OWA 23 mm

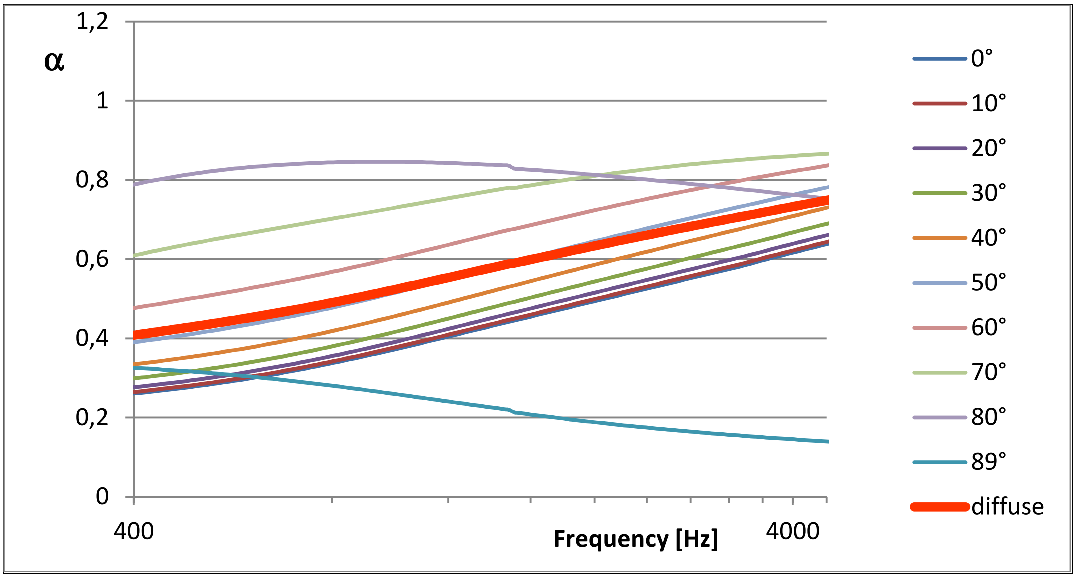

Figure 4.17 – Absorption coefficient for different angle incidents for Wet pressed OWA 23 mm absorber.

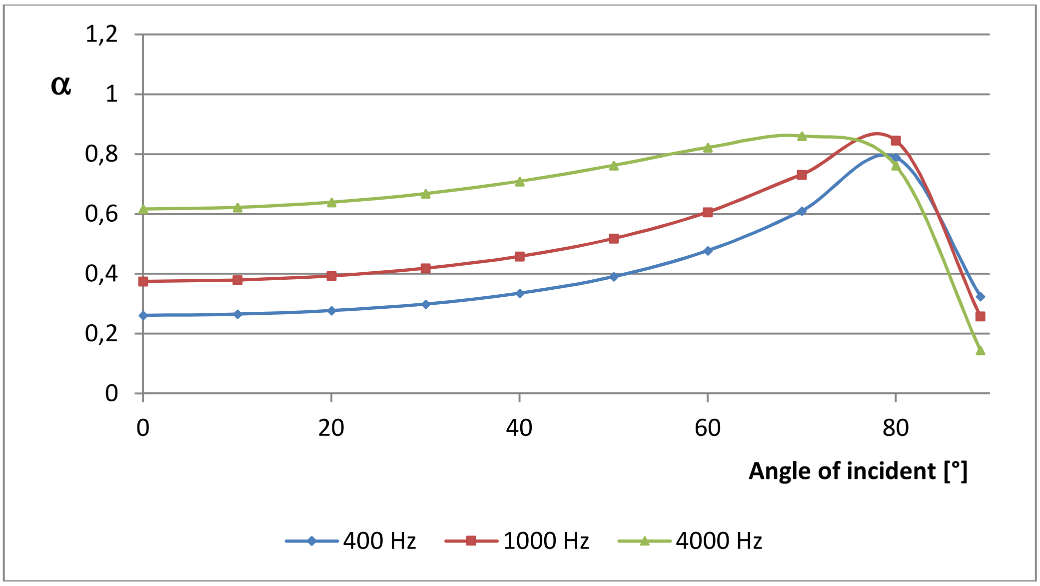

Figure 4.18 – Absorption coefficient for case 9 for the frequency of 400, 1000 and 4000 Hz.

4.5 Discussion of calculated absorption coefficient

For the ceiling absorber denoted *Master* three different surface layers have been tested. The alpha layer is acoustically transparent, the beta and the gamma layers are denser whereas the gamma layer is more reflecting than the beta layer. Both the beta and the gamma layers act a little bit like resonance due to the heavy surface layer which acts like a mass layer. (figure 4.3, figure 4.4, figure 4.5, figure 4.6, figure 4.9, figure 4.10, figure 4.11 and figure 4.12) This is clearly seen in the figures, with a typical resonance top at lower frequencies. This resonance behavior does not appear for the transparent alpha layer.

A typical behavior for the absorption coefficient as a function of incidence angle is that the absorption coefficient increases for higher incidence angles, until a maximum is reached. After the maximum the absorption coefficient decreases rapidly and normally reach the lowest value close to 90°.

The statistical absorption coefficient is measured according to ISO 354. Manufacturers usually present these absorption coefficients for their products. The statistical absorption coefficient is approximately given by the absorption coefficient at 45° incidence.

Generally in our figures we can see that close to 90° incidence (grazing incidence) the absorption coefficient is lower than the corresponding statistical absorption coefficient estimated at 45°.

The thickness of an absorber affects the behavior of the absorption coefficient. The absorption factor for thick absorbers is the highest. When the surface layer is denser and not that transparent, we get lower values for the absorption coefficient at higher frequencies and increased absorption at certain low frequencies where the absorber acts like resonance absorber.

Comparing Master A/alpha 20 and 40 mm shows that a thicker absorber is more efficient at lower frequencies. At higher frequencies the behavior is quite similar. The thicker absorber gives a little flatter absorption curve at higher frequencies. This is an effect of the actual peak height. (figure 4.1, figure 4.2, figure 4.7 and figure 4.8)

For the Master A/gamma 20 and 40 mm surface there is an odd behavior for 4000 Hz. The absorption coefficient increases monotonically towards grazing incidence. This has to be further investigated.

The curve for Focus looks a lot like Master A/alpha 20 mm. The Focus absorber has higher absorption at lower frequencies than Master A/alpha 20 mm. This is due to the higher flow resistance of the Focus absorber.(figure 4.13 and figure 4.14)

Wet pressed OWA is a high density product with no surface layer. The absorbing efficiency is a little bit lower compared to Master A/alpha and the Focus products.

Chapter 5. Experimental part

This chapter presents the method and results of measurements of acoustics in a 1:3 scale model of a school classroom. The sound pressure level was measured in a steady state condition. Investigating early reflections is important and when measuring reverberation time these factors are not included. In this experimental part both reverberation time and sound pressure level were measured and then compared. The purpose was to show that it is important to investigate more acoustic descriptors than only reverberation time. Measurements were made in a room with and without furniture and with different ceiling absorbers, to be able to see how the different situations affect different parameters. Investigating sound pressure level in a steady state condition is important to be able to analyze the effects of furniture, and to compare to early reflections and scattering.

5.1 Description of room

Measurements were made in a model built with plywood and placed in a reverberant room. The reverberant room was supplied with glass wool on the walls to minimize the influence of the room. Measurements were made in three places in the model, in the back, in the center and in the front. Mean values were used when result were shown. The model is a rectangular box 1,8 x 3 x 1 m^3 and has an opening at the top to allow change of ceilings. The model is a typical classroom in the scale 1:3 with chairs, tables and bookshelves. Reverberation time and sound pressure level measurements were made with Norsonic Sound Analyser, nor 140. The microphone was placed inside the model on a tripod and the measurement unit was placed on a tripod outside the model for more convenience.

The ceiling tiles where rectangular plates of size 0,6 x 0,6 $m^{2.}$ The plates were placed on a T profile grid which was described in the chapter above (figure 5.1). The number of plates in the ceiling was 15. In total 11 different ceiling types were measured according to table 5.1. The absorption coefficient for the different ceiling absorbers has been calculated in chapter 4.

Table 5.1 – List of measurement cases

Nr	Cases
1	Master A/alpha 40 mm
2	Master A/beta 40 mm
3	Master A/gamma 40 mm
4	Master A/alpha 20 mm
5	Master A beta 20 mm
6	Master A/gamma 20 mm
7	Focus 20 mm
8	Wet pressed OWA 11,5 mm
9	Wet pressed OWA 23 mm
10	Wet pressed OWA 11,5 mm / with Master A/alpha 20 mm in corners
11	Wet pressed OWA 11,5 mm without furniture
12	No ceiling absorber with furniture
13	No ceiling absorber without furniture (empty room)

5.2 Ceiling

The ceiling was placed on a T-profile frames that were exactly the right size for the ceiling plates to fit in. Inside the box the ceiling plates make a ceiling with no gaps.

Figure 5.1 – Picture taken inside the model.

5.3 Measurements method.

Reverberation time and steady state sound pressure level were measured for the 13 cases according to table 5.1. A loudspeaker was placed in one corner near the teacher's desk. Five microphone positions were used for each measurement. Measurements were made at the height of 40 cm from the floor which corresponds to a height of 120 cm because of the scale of 1:3, corresponding to a sitting person.

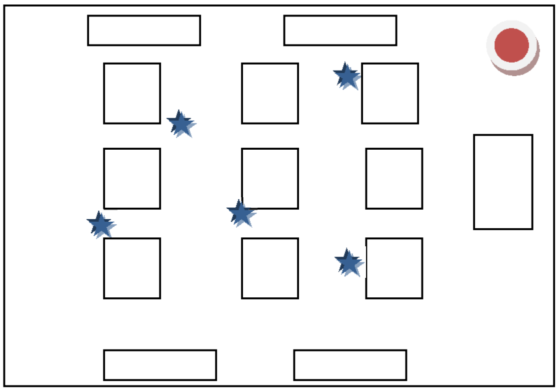

Figure 5.2 – The model from above. The stars mark the measurement points. The red mark in the corner shows where the loudspeaker was placed.

A Norsonic microphone was placed on a stand and moved from one marked spot to another on the floor of the model. The different cases are shown in table 5.1.

Figure 5.3 – Norsonic Sound Analyser

Before every measurement the ceiling was changed. The top was opened, the current ceiling was removed and a new ceiling put in. The top was then closed again.

For the cases of 20 mm, the 40 mm plates were cut in half, before being placed in the model. The output from the loudspeaker was the same for all the measurements.

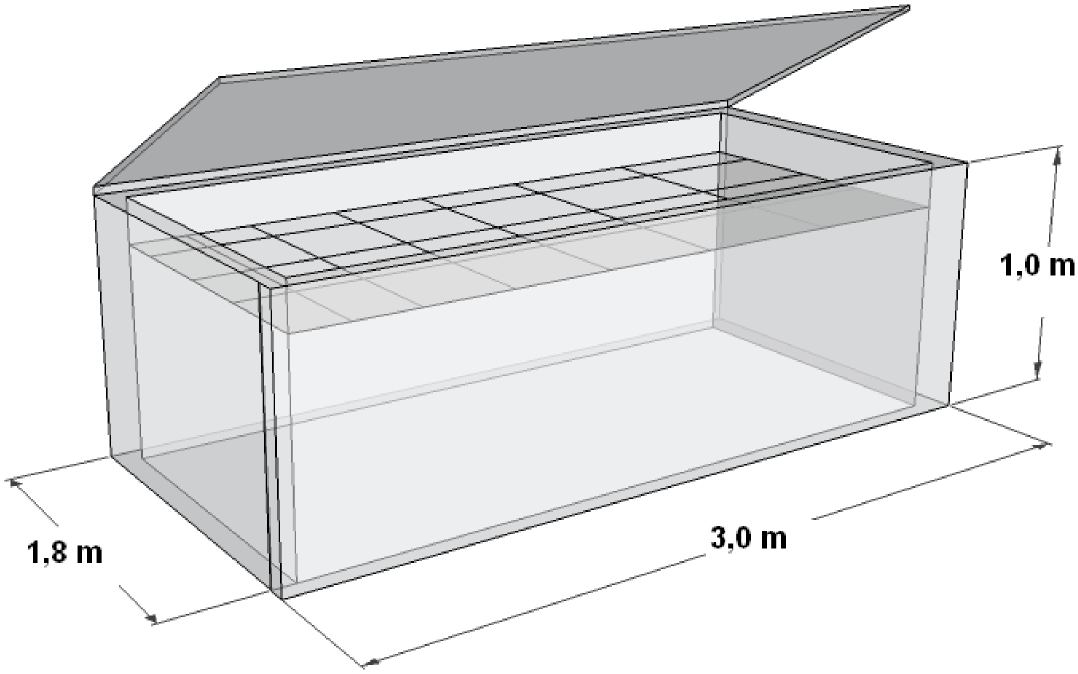

Figure 5.4 – The classroom model

The model has an opening at the front, at the side and at the top. The top is opened to change ceilings and the other openings to move the microphone.

Figure 5.5 – Picture of the model

The absorber ceilings were placed on the steel frames and then made a nice looking ceiling from the inside. Then top of the box was closed again before starting the measurements.


Figure 5.6 – Picture inside the model.

Inside the model was model sized furniture typical for a classroom, i.e. teacher’s desk, tables and bookshelves. The loudspeaker was placed in the corner of the model as shown in figure 5.2. The microphone was moved between different spots in the model.

5.4 Measurements with Norsonic

Measurements were made for total of 13 cases, with Master A/alpha 20 and 40 mm, Master A/beta 20 and 40 mm, Master A/gamma 20 and 40 mm, Focus 20 mm, Wet pressed OWA 11,5 and 23 mm and combination with Wet pressed OWA 11,5 mm with Master A/alpha 20 mm in the corners. The purpose of the corner absorber was to increase the lower frequency absorption. This measurement is used in practice.

The measurements were also made without ceiling and without furniture. It is also of interest to see how the furniture effect reverberation time and sound pressure level. The different cases are listed in table 5.1.

Table 5.1 – List of the cases

Nr	Cases
1	Master A/alpha 40 mm
2	Master A/beta 40 mm
3	Master A/gamma 40 mm
4	Master A/alpha 20 mm
5	Master A beta 20 mm
6	Master A/gamma 20 mm
7	Focus 20 mm
8	Wet pressed OWA 11,5 mm
9	Wet pressed OWA 23 mm
10	Wet pressed OWA 11,5 mm / with Master A/alpha 20 mm in corners
11	Wet pressed OWA 11,5 mm without furniture
12	No ceiling absorber with furniture
13	No ceiling absorber without furniture (empty room)

Measurements were made for the frequency region 100 to 8000 Hz. Room acoustic measurements are normally performed for the frequency region 125 to 4000 Hz. Since the model scale is 1:3 this means that 125 Hz corresponds to 375 Hz in our case. The lowest frequency was therefore chosen to be 400 Hz.

Using a model the physical dimensions are scaled. However the absorbing properties of the ceiling material are not scaled. The principal behavior of the absorbers effect on the sound field is not affected.

5.5 Sound pressure level measurements

At first sound pressure measurements were made. The results are presented in figures below. The different cases are all presented in one graph and then compared fewer at a time. Figure 5.7 shows the sound pressure level for all the cases of table 5.1.

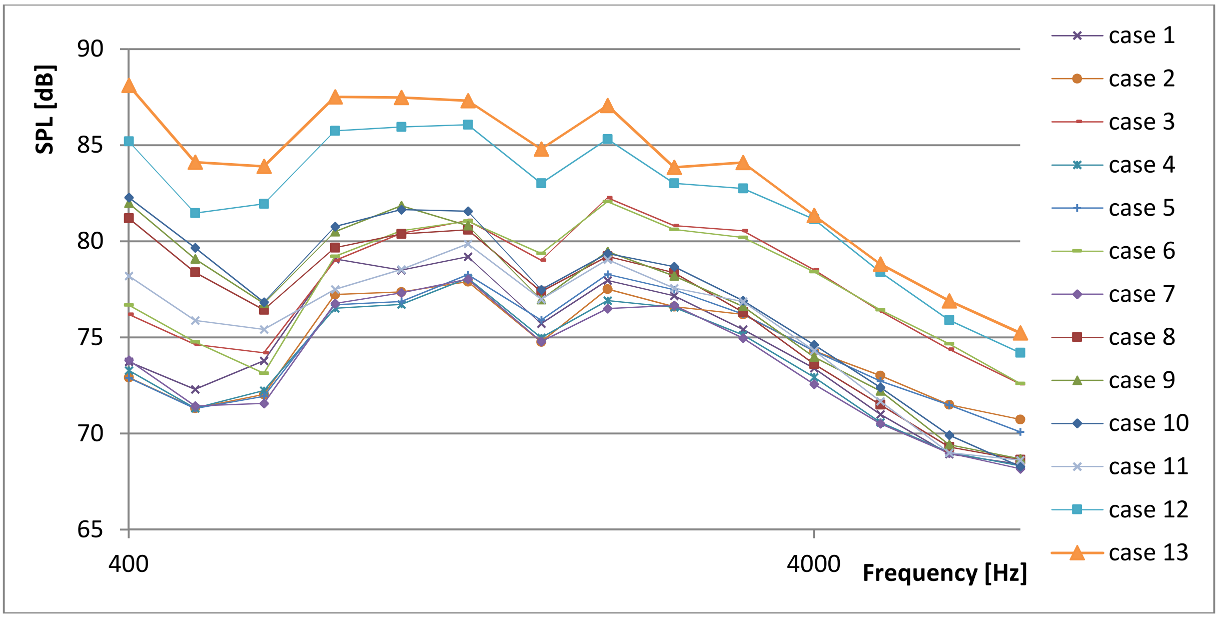

Figure 5.7 – Sound pressure level[dB] measured with Norsonic. All 13 cases shown. (table 5.1)

To be able to see the results more clearly the normalized values are plotted, where the reference value is the case without ceiling and furniture. Normalized SPL value is the difference $\Delta L = L_0 - L_i$, where i gives the cases, from 1 to 12. L_0 is the case for no ceiling absorbers and no furniture, and with only the wood fiber ceiling on top.
Normalized values are shown in figure 5.8. Higher values of the sound pressure level difference mean a higher noise reduction.

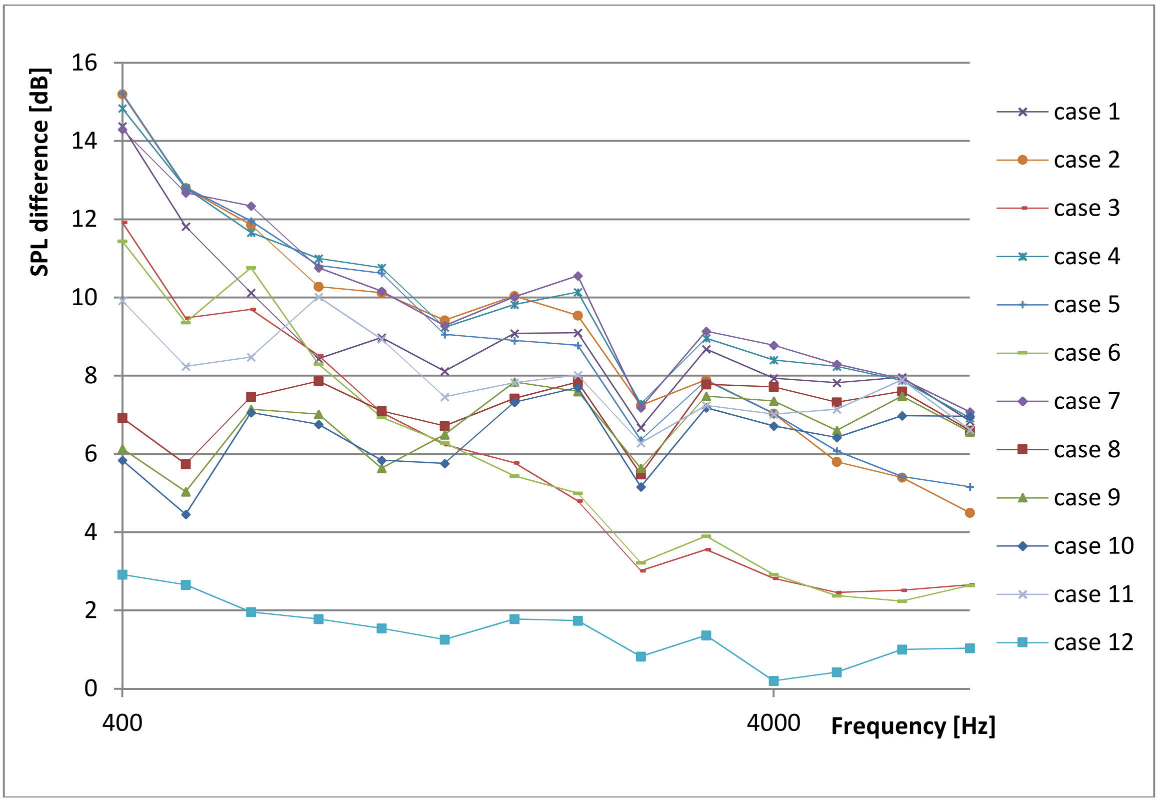

Figure 5.8 – Sound pressure level difference [dB] measured with Norsonic. All 13 cases shown. (table 5.1)

It is obvious from figure 5.8 how much the ceiling absorbers influence the sound pressure level. Generally the porous products with transparent surface layer (alpha, beta) give the highest noise reduction especially at lower frequencies. The wet pressed materials are less efficient at lower frequencies. The porous products with the reflecting surfaces (gamma) give low sound reduction at higher frequencies but are quite good at low frequencies.

To see the results more clearly it may be easier to compare the different ceilings for only few cases at a time. Values for Wet pressed OWA cases, and also where there is no furniture and/or no ceiling absorber, were compared (fig 5.9).

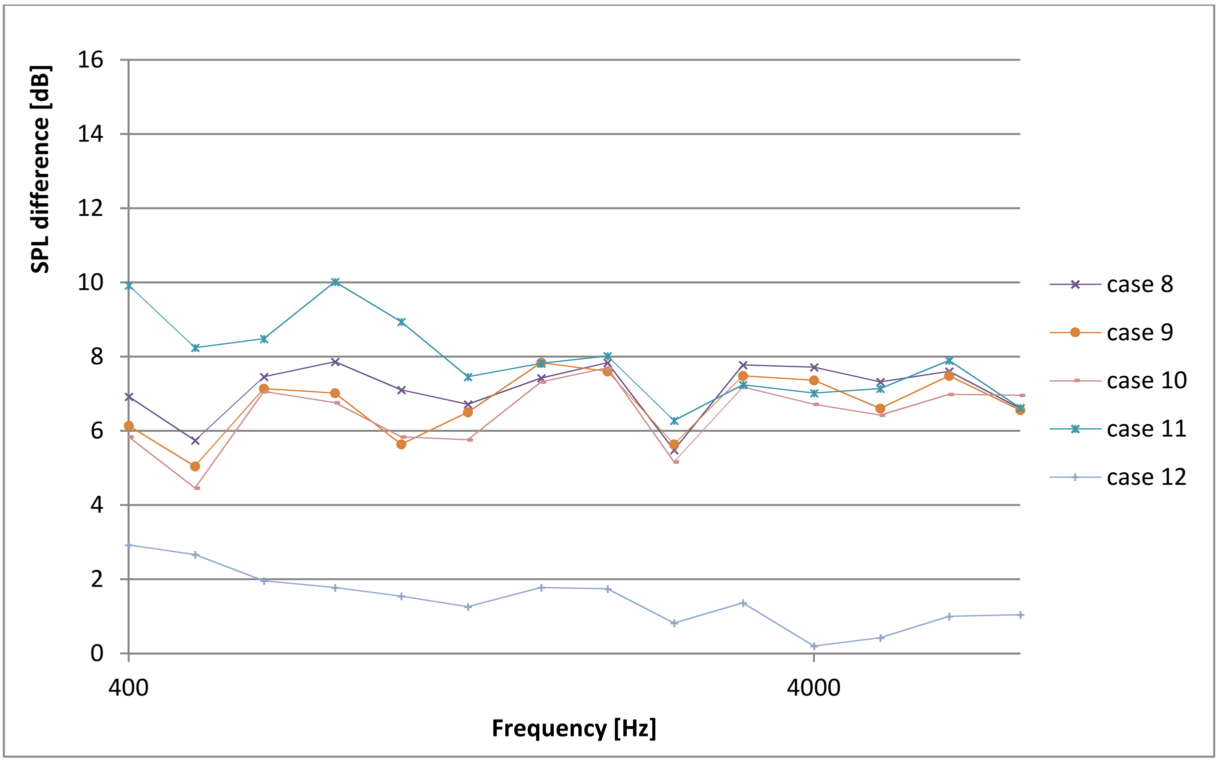

Figure 5.9 – Sound pressure level measurements. Comparison. Case 8: Wet pressed OWA 11,5 mm, case 9: Wet pressed OWA 23 mm, case 10: Wet pressed OWA 11,5 mm with Master A/alpha in the corners, case 11: Wet pressed OWA 11,5 mm without furniture. Case 12: no ceiling absorber and no furniture.

It is clear that the case with no ceiling absorber has the highest sound pressure level. Adding a ceiling absorber has a big effect, or about 7 dB noise reduction for the whole frequency range.

It is interesting to see the effect of furniture when comparing cases 11 and 8, that is comparing sound pressure level for the wet pressed ceiling with and without furniture. The case with furniture gives about 3dB lower sound reduction at 400 Hz than the case without furniture. As will be shown later on, the reverberation time for case 11, i.e. without furniture is 0,65 sec. The case with furniture gives a reverberation time of 0,30 sec.

It is also interesting to see from figure 5.9 that the sound pressure level reduction is opposite what you might expect from the reverberation time measurement. In fact, inserting the furniture increases the sound pressure level instead of lowering it, which you can expect from the reverberation time. This has to be further investigated.

There is a small difference in changing the thickness of the wet pressed material. The effect of the corner absorber is not shown in the figure. The reason could be that the wet pressed material has a high flow resistance and therefore blocks the low frequency absorber behind.

The next comparison is between Master A/alpha, A/beta and A/gamma 20 mm. (fig 5.10)

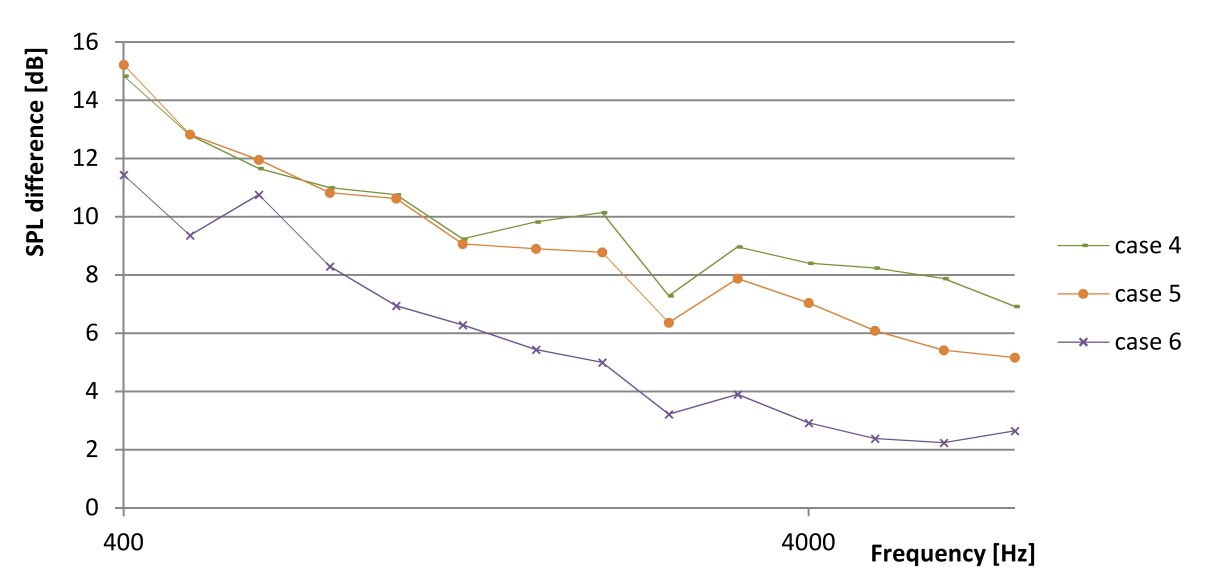

Figure 5.10 – Sound pressure level measurements. Comparison. Case 4: Master A/alpha 20 mm, case 5: Master A/beta 20 mm, case 6: Master A/gamma 20 mm.

Figure 5.10 shows that the reflecting surfaces (gamma) give higher sound pressure level than the more transparent surfaces (alpha, beta). Alpha and beta follow each other in lower frequencies but at higher frequencies the alpha layer gives a little bit higher noise reduction than the beta layer. The gamma absorber has more paint that closes the pores in the surface layer which changes the absorption properties and increases the reflection. The alpha and beta absorbers have more open surfaces and are therefore more absorbing.

The porous master products are significantly better at lower frequencies then the wet pressed material. There are no large differences between the 20 and 40 mm absorbents relating to sound pressure level reduction. The results for the 40 mm absorbents are shown in figure 5.11.

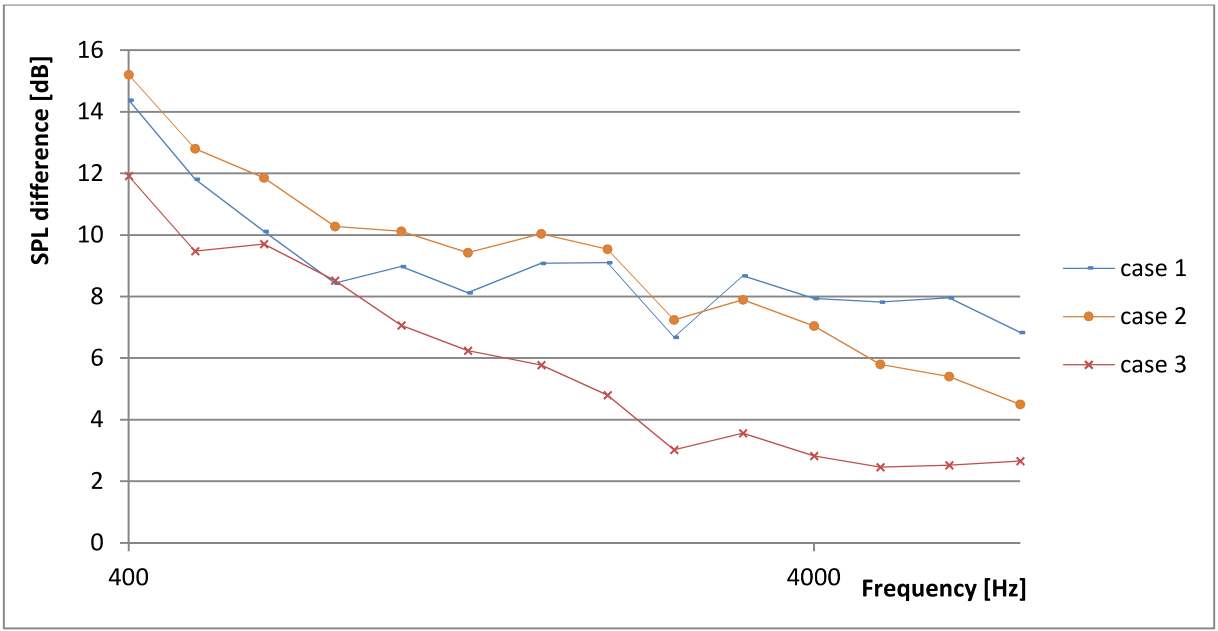

Figure 5.11 – Sound pressure level measurements. Comparison. Case 1: Master A/alpha 40 mm, case 2: Master A/beta 40 mm, case 3: Master A/gamma 40 mm.

Three different products Focus, wet pressed OWA 11,5mm and Master A/alpha 20 mm were compared. Results are shown in figure 5.12.

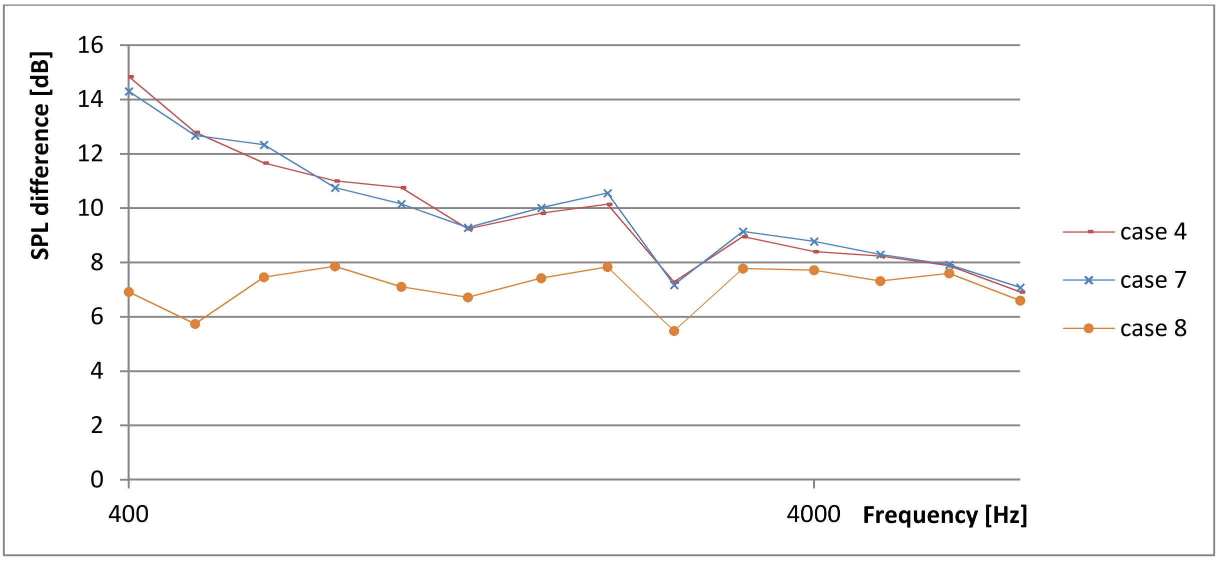

Figure 5.12 - Sound pressure level measurements. Comparison. Case 4: Master A/alpha 20 mm, case 7: Focus 20 mm, case 8: Wet pressed OWA 11,5 mm.

Focus and Master A/alpha 20 mm have a very similar sound pressure level reduction in spite of the difference in density. The Focus absorber has a density of 100 kg/m^3 and master A/alpha has a density of 55 kg/m^3. However differences exist for the wet pressed material which has a density of 292 kg/m^3. The less efficient noise reduction for the wet pressed material compared to the master products appear at low frequencies.

5.6 Reverberation time measurements

The next measurement was for reverberation time. The reverberation time is measured in seconds. It is interesting to see how the furniture affects the reverberation time. Figure 5.14 shows reverberation time for all 13 cases.

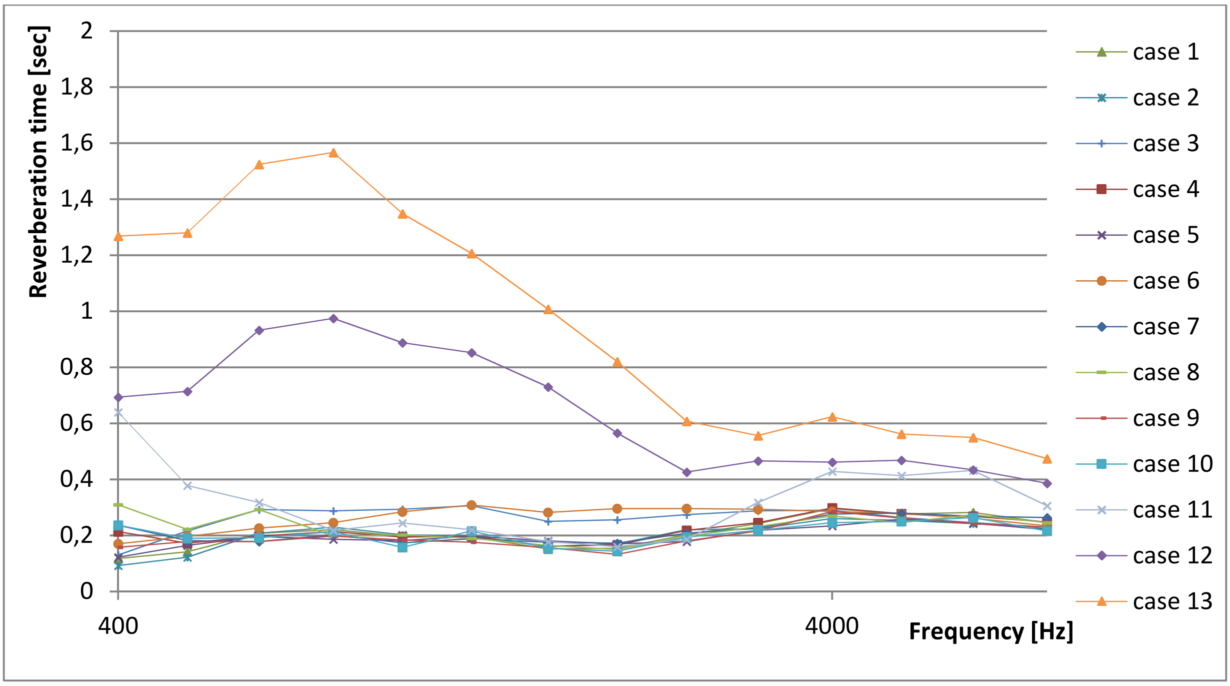

Figure 5.14 – Reverberation for all 13 cases.

To be able to see better how the cases differ, it is better to look at fewer cases at a time. In figure 5.15 we have excluded the case without ceiling absorber. The scale must also be changed to be able to look at the curves in more detail.

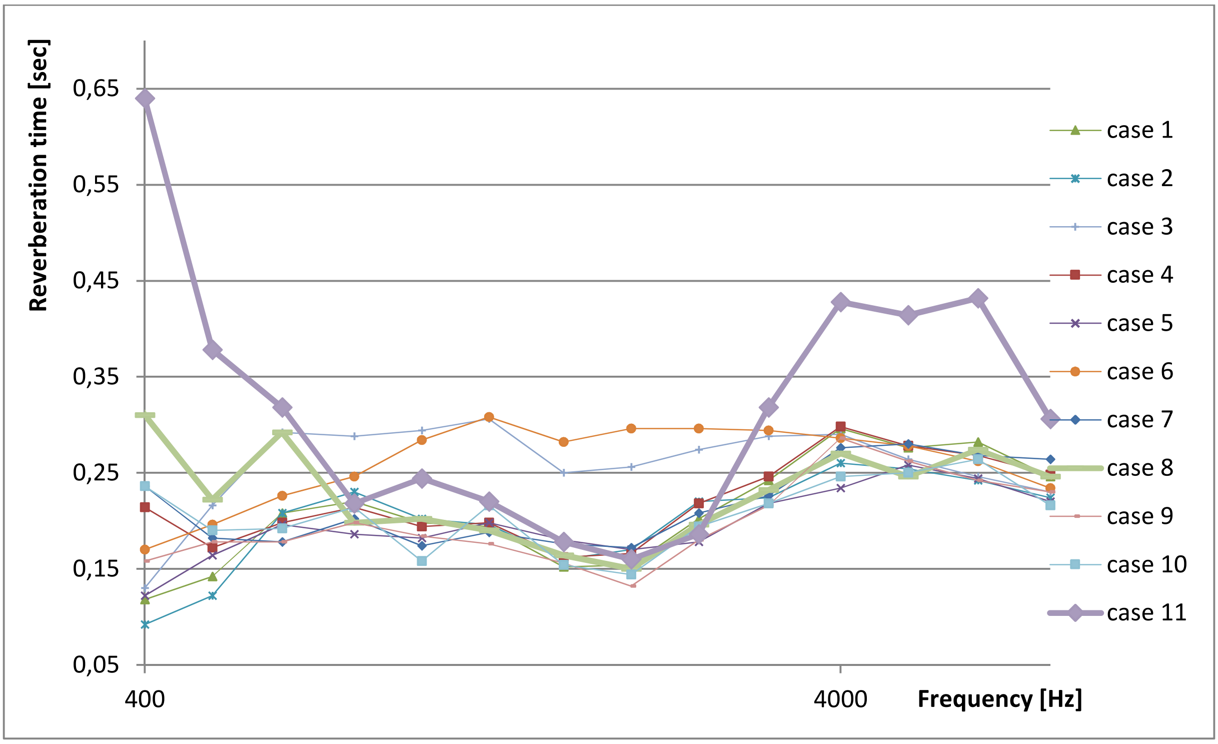

Figure 5.15 – Reverberation time for all cases with ceiling.

In figure 5.15 the curves for case 11 and 8 are compared. These lines are made bold in the figure. Case 11 is with wet pressed material without furniture and case 8 is for the same ceiling but with furniture. It is clearly seen that the furniture has a large effect on the reverberation time at lower and higher frequencies. The mid frequencies are less affected. The effect is partly due to the absorbing and the scattering effect of the furniture, where the scattering effect is dominant. The quantification of the scattering will be further investigated in chapter 6.2.

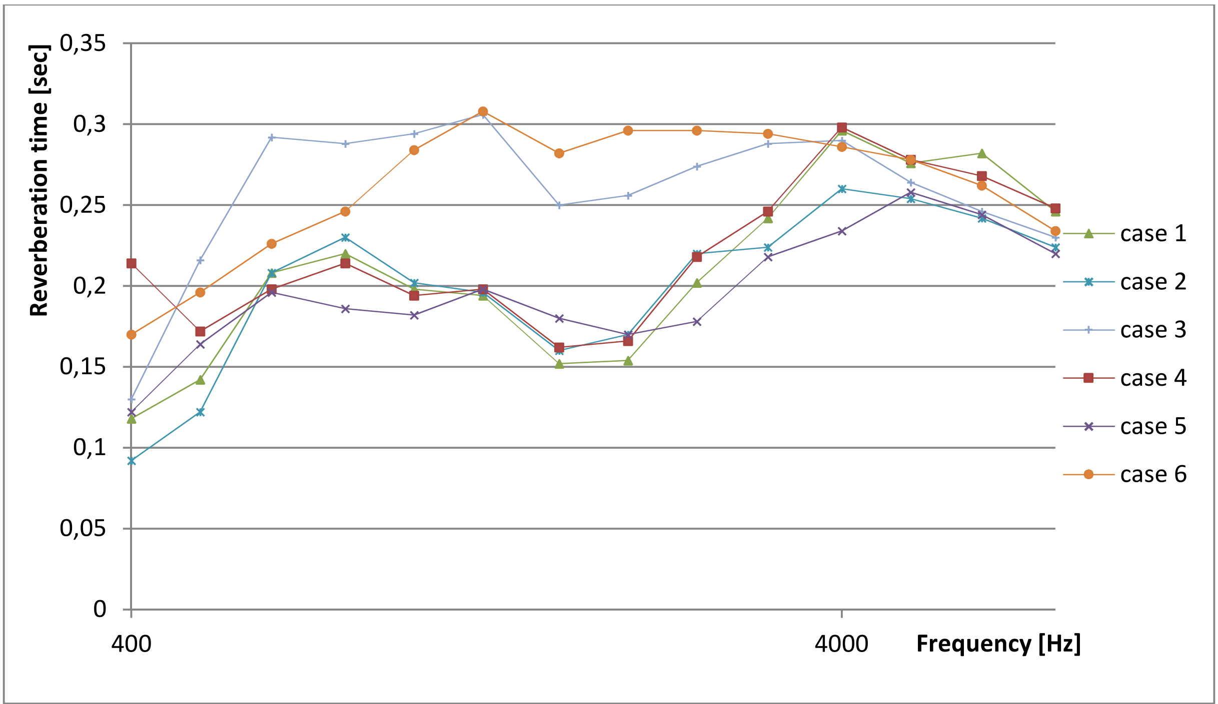

Figure 5.16 – Comparison of reverberation time. Case 1: Master A/alpha 40 mm, case 2: Master A/beta 40 mm, case 3: Master A/gamma 40 mm, case 4: Master A/alpha 20 mm, case 5: Master A/beta 20 mm, case 6:Master A/gamma 20 mm.

In figure 5.16 we compare all master products with different surface layers. In spite of the fact that the different products have different absorbing properties at high frequencies according calculation results in chapter 4.4 the reverberation time at high frequencies is similar in the results for the measurements. The explanation for this behavior is that the sound field during the decay process is non-diffuse. The reverberation time is more determined by the absorption for grazing sound incidence than diffuse sound incidence.

Looking at figure 4.1 to 4.12 we see that there are large differences in the diffused absorption coefficient for the different absorber types. However looking at the angle dependent absorption coefficient we can see that for grazing incidence in the region of 85° the absorption coefficients for the different products are quite similar. This is partly the explanation of the results in figure 5.16. This effect is more pronounced at high frequencies where the sound waves behave like rays. At lower frequencies the wave character of the sound field is more pronounced and there we have larger differences between the products.

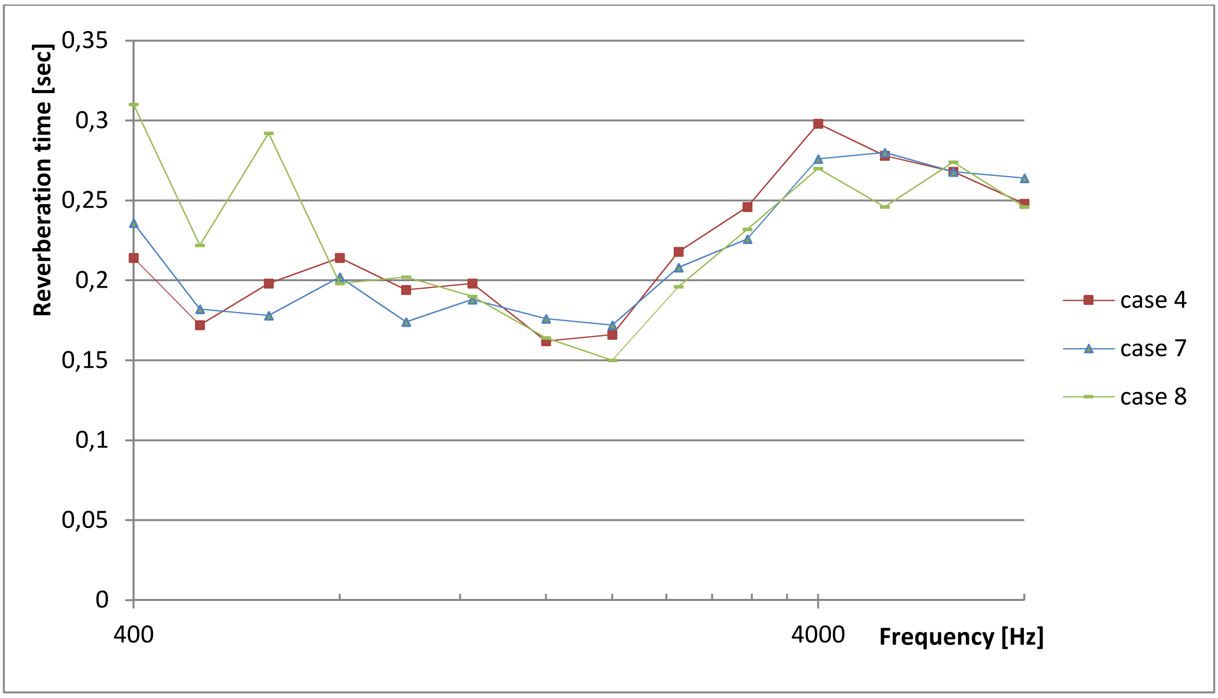

Figure 5.17 – Comparison of reverberation time. Case 4: Master A/alpha 20 mm, case 7: Focus 20 mm, case 8: Wet pressed OWA 11,5 mm.

Comparing absorption coefficient in figure 4.7, 4.13 and 4.15 with the reverberation time in figure 5.17, there is a quite large difference. The corresponding absorption coefficient for the absorbers in cases 4, 7 and 8 are shown in figure 5.18.

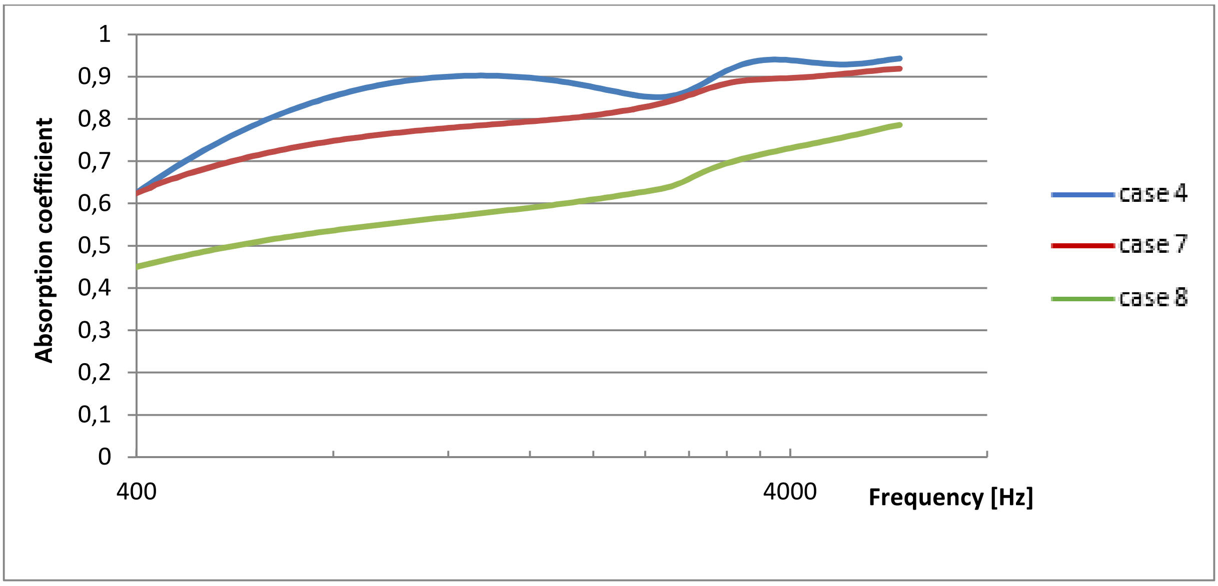

Figure 5.18 - The corresponding absorption coefficient for the absorbers in case 4: Master A/alpha 20 mm, case 7: Focus 20 mm, case 8: Wet pressed OWA 11,5 mm.

The figure shows low correspondence between the diffuse absorption coefficient and the measured reverberation time. Based on the absorption coefficient we had expected a larger difference of the reverberation time in higher frequencies. At grazing incidence the absorption coefficient is quite similar for these three absorbers. This will partly explain the results in figure 5.17.

Chapter 6. Comparison of calculated and experimental values

In this chapter the calculated (simulated) results of chapter 4 are compared with the measurement results described in chapter 5, for sound pressure level and reverberation time. The purpose is to see if the different parameters correlate and correspond. The scattering and absorption of furniture were also investigated.

6.1 Comparison of sound reduction

The sound pressure level has been calculated based on the reverberation time and the equivalent absorption area, respectively. The calculations are compared with measured sound pressure level differences, for cases 11 and 13. The sound pressure levels for the two cases are given by:

$$L_{P_1} = L_W - 10\, log \frac{0{,}16V}{4\, T_1} \qquad (9)$$

$$L_{P_2} = L_W - 10\, log \frac{0{,}16V}{4\, T_2} \qquad (10)$$

where Lp1 and Lp2 are the sound pressure levels for the two cases, Lw is the sound power level which is the same in both cases, V is the volume, and T_1 and T_2 are the reverberation times for the two cases.

The sound pressure level difference is given by:

$$\Delta L = L_{P_1} - L_{P_2} \qquad (11)$$

Using equations 9 - 11 the sound pressure level could be expressed by:

$$\Delta L_p(T_1/T_2) = 10\log(T_1/T_2) \qquad (12)$$

or using the Sabine formula, A=0,16V/T, we get:

$$\Delta L_p(A_2/A_1) = 10 \cdot log\left(\frac{A_0+A}{A_0}\right) \qquad (13)$$

where A is the equivalent absorption area and A_0 the equivalent absorption area of an empty room.

If the ceiling absorber dominates the absorption in the room, then the equivalent absorption area is A = α x S, where α is the absorption coefficient and S is the area of the absorber. The unit of the equivalent absorption area is commonly notated as m^2 Sabine.

In figures 6.1 and 6.2 measured sound pressure level and reverberation time for cases 11 and 13 are compared, i.e. the sound pressure level in a room with and without a ceiling absorber, both without furniture.

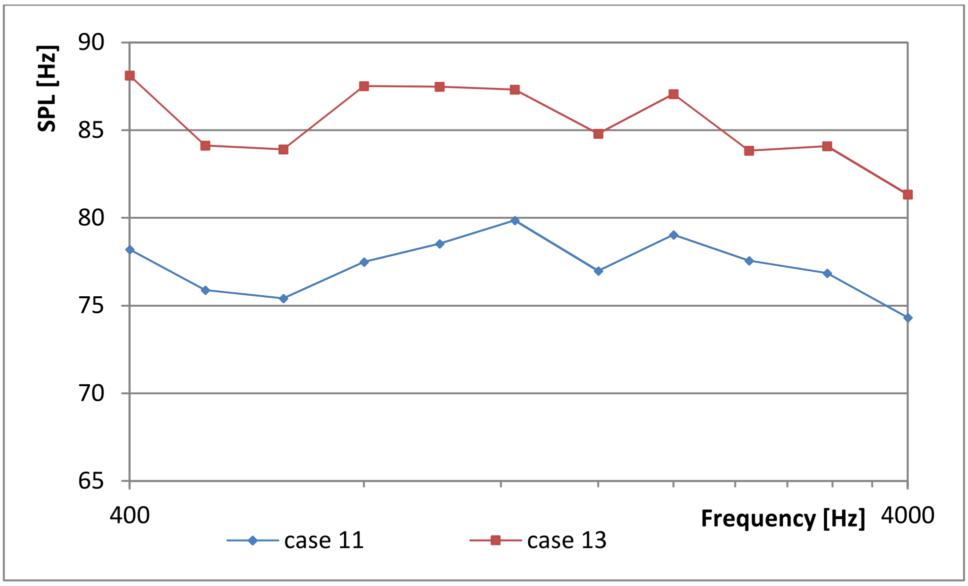

Figure 6.1 – SPL for the cases Wet pressed OWA without furniture, case 11 and empty room, case 13.

In figure 6.2 case 11 (T_C) is with ceiling absorbers but without furniture and case 13 (T_0) is without furniture and ceiling absorbers.

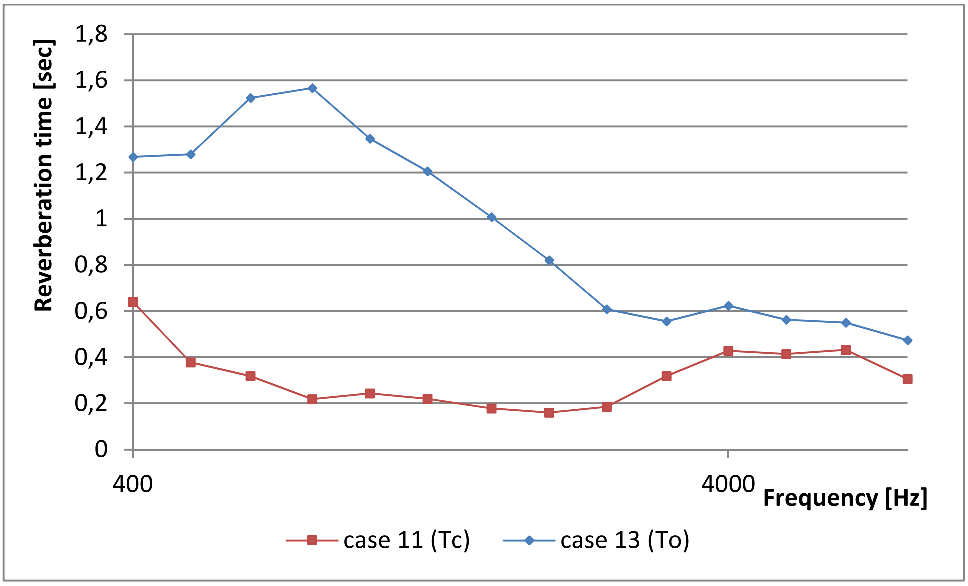

Figure 6.2 – Measured reverberation time for the cases Wet pressed OWA without furniture and no ceiling absorber without furniture.

Measured and calculated values according to equation 12 and 13 are presented in table 6.1 and figure 6.3. The measured values are from case 8, wet pressed OWA 11,5mm and case 13, without ceiling absorber.

Table 6.1 - ΔL_p for measured values, ΔL_p for equivalent absorptions area and ΔL_p for reverberation time.

Frequency	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
$\Delta L_{p,meas}$	9,9	8,2	8,5	10,0	8,9	7,5	7,8	8,0	6,3	7,2	7,0
$\Delta L_p(A_2/A_1)$	7,0	7,0	8,3	8,4	7,8	7,4	6,8	6,6	5,6	5,4	6,1
$\Delta L_p(T_1/T_2)$	3,0	5,3	6,8	8,6	7,4	7,4	7,5	7,1	5,1	2,4	1,6

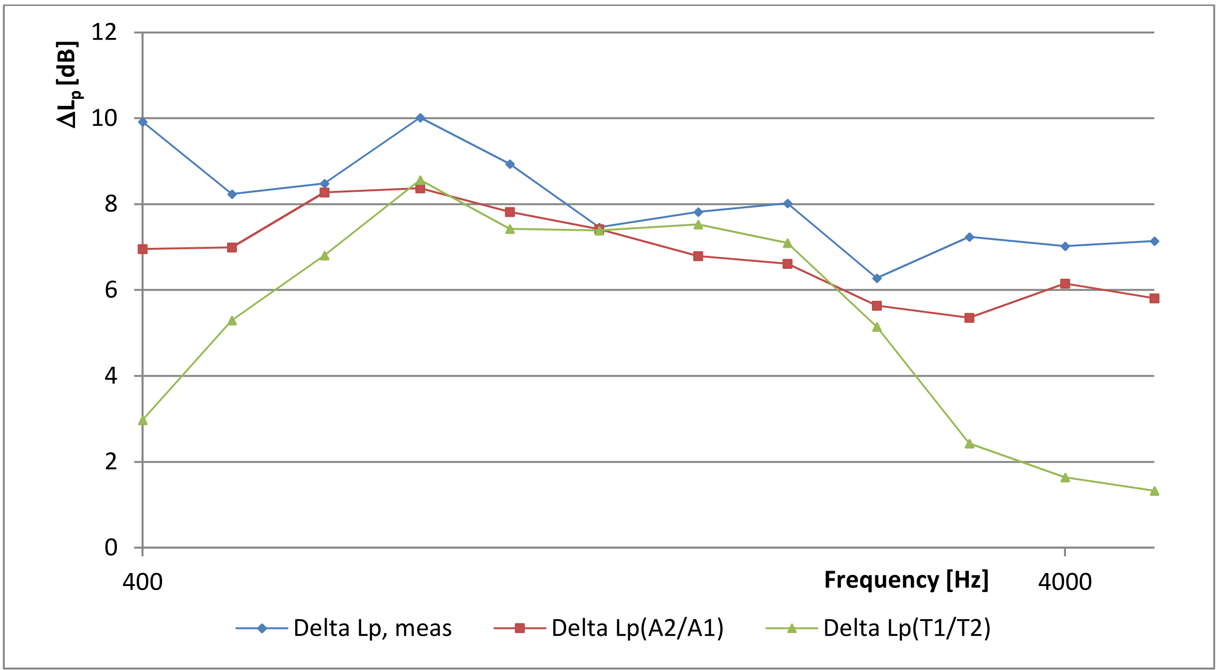

Figure 6.3 – ΔL_p for measured values, ΔL_p for equivalent absorptions area and ΔL_p for reverberation time.

Looking at mid to higher frequencies we see a large difference between calculated values of ΔL based on the reverberation time and measured values. If we instead use calculated values of ΔL based on the equivalent absorption area the correspondence is much better. The equivalent absorption area for the empty room A_0 has been estimated from the reverberation time measurement and the equivalent absorptions area A_1 for the ceiling absorber is given by $A_1 = \alpha \times 5{,}4$, where 5,4 is the area of the ceiling.

The conclusion is that when estimating noise level in a room with ceiling treatment the reverberation time will generally underestimate the sound pressure level decrease. This is because the reverberation time represents the decay of the grazing sound field which is weakly related to the steady state situation and the diffuse absorption coefficient.
Using the equivalent absorption area and the diffuse sound absorption coefficient instead of reverberation time this is better related to the steady state conditions, because at steady state the sound field conditions are quite close to diffuse conditions, even though we have an absorbing ceiling.

6.2 More comparison

In figure 6.4 and 6.5 the sound pressure level difference and reverberation time are shown for cases 1-6. The behavior above is also shown here. For 4000 Hz and higher the reverberation time is quite similar for these different ceilings, but for the sound pressure level there is a 4-5 dB difference. 4000Hz corresponds to about 1300Hz in a normalized room.

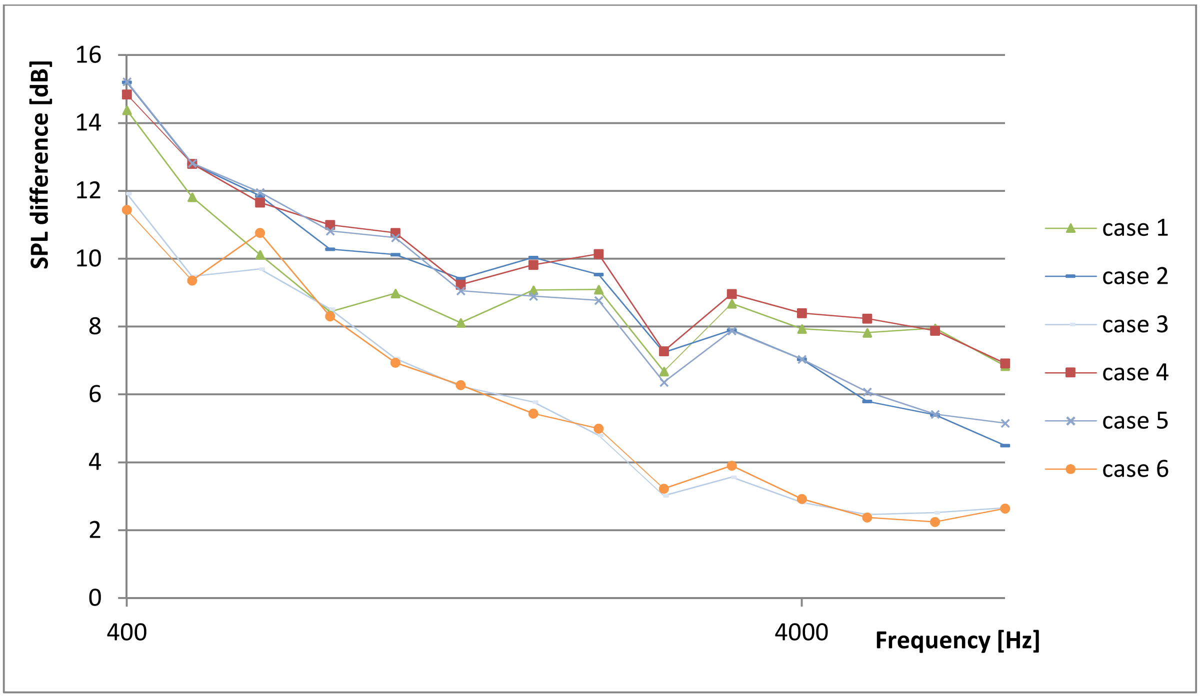

Figure 6.4 – Sound pressure level difference for cases 1-6.

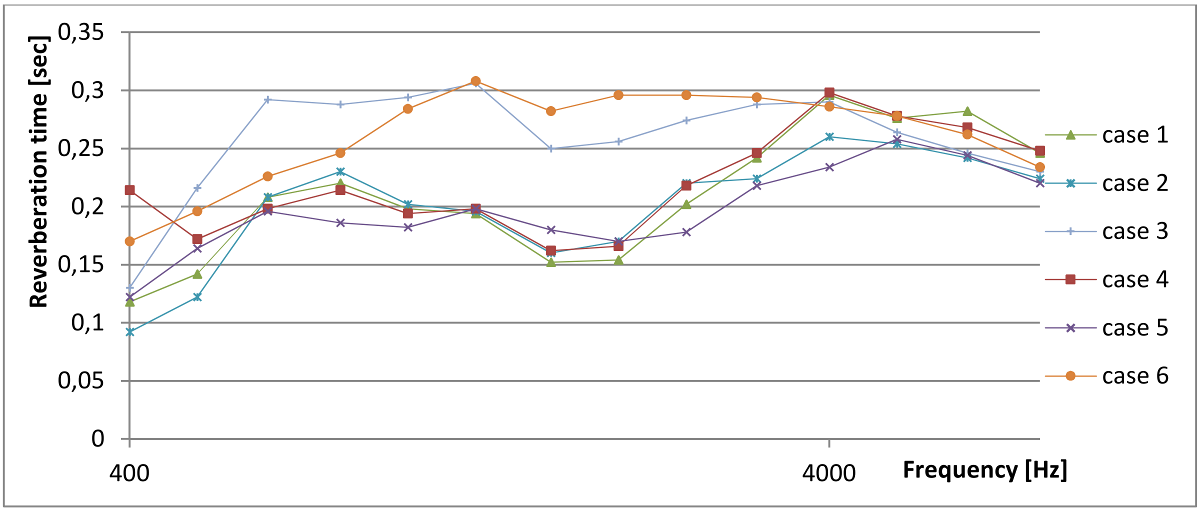

Figure 6.5 - Reverberation time for cases 1-6.

The two figures show clearly the importance of evaluating sound pressure level and reverberation time separately. This also shows that it is normally important to use several acoustic parameters.

6.3 Scattering

The effect of furniture is to absorb and scatter the sound energy. Scattering means that the sound is redirected randomly. In this chapter the scattering and the absorbing properties of furniture are quantified. The scattering is quantified as an equivalent scattering absorption area. In figure 6.6 the reverberation time for case 12, without ceiling but with furniture and case 13, an empty room, are shown.

Table 6.2 – Reverberation time for cases no ceiling absorber with furniture and without furniture.

Frequency	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
No ceiling absorber with furniture	0,69	0,71	0,93	0,97	0,89	0,85	0,73	0,57	0,43	0,47	0,46
No ceiling absorber and no furniture	1,27	1,28	1,52	1,57	1,35	1,21	1,01	0,82	0,61	0,56	0,62

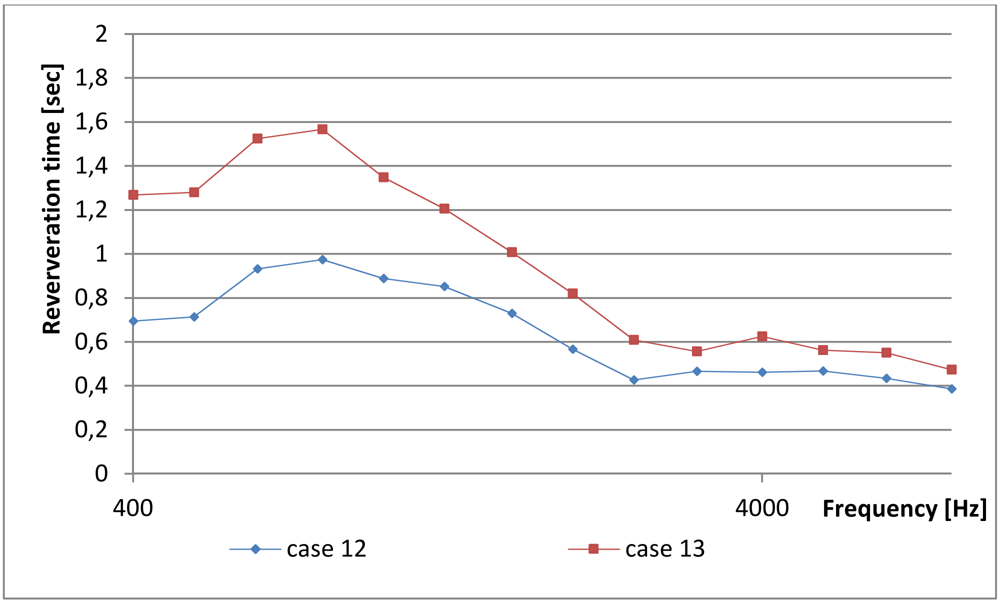

Figure 6.6 – Reverberation time for cases without ceiling absorber with (case 12) and without furniture (case 13).

To calculate the equivalent scattering area the following procedure is used.

Calculation of the equivalent absorption area A_F and scattering absorption area $A_{SC,F}$ for the furniture:

1. Measured T_E for empty room i.e. without absorbent ceiling and furniture.

   $A_E = 0{,}16\, V / T_E$ (14)

2. Measured $T_{F,E}$ for the room with furniture but without absorbent ceiling.

   $A_{F,E} = 0{,}16\, V / T_{F,E}$ (15)

   Equivalent absorption area for the furniture is given by:

   $A_F = A_{F,E} - A_E$ (16)

3. Measured T_C i.e. in a room with absorbent ceiling but without furniture gives.

   $A_C = 0{,}16\, V / T_C$ (17)

4. Measured $T_{C,F}$ i.e. in a room with absorbent ceiling and furniture gives.

   $A_{C,F} = 0{,}16\, V / T_{C,F}$ (18)

5. Scattering effect of furniture is then given by:

   $A_{SC,F} = A_{C,F} - A_C - A_F$ (19)

The calculations are based on the Sabine formula.

A_{SC} will to some degree depend on the absorbing properties of the ceiling. For ceiling absorbers with α_w >0,7 the A_{SC} will be quite similar at medium and high frequencies.

Figure 6.7 shows the equivalent scattering absorption area and the absorption area for the furniture.

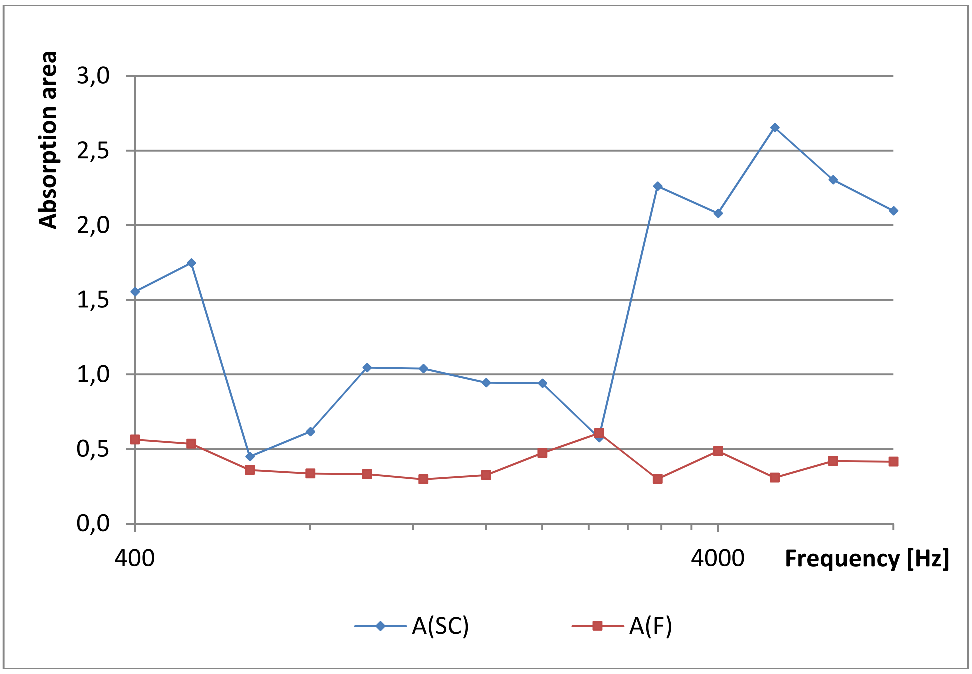

Figure 6.7 – Scattering absorption and furniture absorption area.

Figure 6.7 also shows that the scattering effect is more pronounced at higher frequencies. It is also interesting to see that the scattering effect of the furniture is larger than the absorbing effect.

Chapter 7. Discussion and conclusions

The hypothesis was that reverberation time is weakly related to the sound pressure level at a steady state condition in room with absorbent ceiling. Further on that reverberant and steady state condition has to be evaluated separately. Our findings show that this is the case.

Evaluating the acoustics in rooms with absorbent ceilings generally requires the use of several room acoustic parameters, related to acoustical qualities such as sound strengths, speech clarity and reverberance.

It has been clearly shown that using the reverberation time to estimate the decrease in sound pressure level in rooms with absorbent ceilings generally underestimates the sound pressure level achieved.

Calculations were made in WinFlag for different ceiling absorbers for different angle and frequencies. The results were plotted in figures and compared.

Measurements were made in a model in the scale 1:3. Reverberation time and sound pressure level were measured and the results were plotted and compared.

The difference in using the reverberation time and equivalent absorption area was examined. The influence of the furniture on the reverberation time and sound pressure level was investigated. The scattering effect was investigated.

The results were as follows:

- When estimating noise level in a room, with an absorbent ceiling, the reverberation time cannot be used. Instead it is necessary to use equivalent absorption area. This is obvious when the results are compared. Figure 6.3 on page 48 shows how the equivalent absorption area correlates to the measured values, while reverberation time does not, except in low or middle frequency.
- Influence of furniture is clear. The reverberation time changes when the furniture is taken out of the room. In a room without furniture the reverberation time is a lot longer for lower frequencies. The difference is not as big in higher frequencies, but still there is a difference. The sound pressure level is also higher at low frequencies with furniture.
- By comparing the scattering absorption and the absorption area of the furniture it is clear that the scattering effect is much greater in the higher frequencies than the lower frequencies.
- There is difference between using sound pressure level and reverberation time.
- It is very important to use several parameters to find out the quality of the classroom, such as sound pressure level and reverberation time.

- For a given density, the thickness of an absorber affects the behavior of the absorption coefficient: if the absorber is thicker than the sound absorption is higher, but if the absorber is thinner it reflects more.
- Not only do the results show the frequency dependence but also the angle dependence
- If the surface layer is denser and not as transparent then the absorption coefficient is lower, at least for the higher frequencies.
- The angle dependence and the frequency dependence of the absorbent material were shown.

Chapter 8. Suggestions for further work

The next thing to look at could be to do more combinations of the ceilings. An interesting case is to investigate ceiling absorbers in combination with wall panels on one or several of the room walls.

It could also be interesting to investigate the theoretical explanation of the results, and investigate suitable models for steady state conditions for sound pressure level and transient conditions for reverberant situations. It could be good to compare experimental findings in this report with theoretical models. Especially of interest is to study the influence of the angle dependent properties of the ceiling absorber on the room acoustic parameters.

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