İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

SOUND TRANSMISSION THROUGH SUSPENDED CEILINGS

Msc. Thesis by

Ercüment BAŞBUĞ, M.Sc.

Department : **ARCHITECTURE**

Programme: **ENVIROMENTAL CONTROL AND BUILDING TECHNOLOGY**

JANUARY 2007

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

SOUND TRANSMISSION THROUGH SUSPENDED CEILINGS

Msc. Thesis by

Ercüment BAŞBUĞ, M.Sc.

(502031706)

Date of submission : **5 March 2007**

Date of defence examination: **30 January 2007**

Supervisor (Chairman): **Prof. Sevtap Yılmaz DEMİRKALE (İ.T.Ü.)**
Prof. Jens Holger RINDEL (D.T.U.)

Members of the Examining Committee **Assoc. Prof. Nurgün Tamer BAYAZIT (İ.T.Ü.)**

Assoc. Prof. Ayşe Erdem AKNESİL (Y.T.Ü.)

JANUARY 2007

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ASMA TAVANLARDAN SES GEÇİŞİ

YÜKSEK LİSANS TEZİ
Y.Müh. Ercüment BAŞBUĞ
(502031706)

Tezin Enstitüye Verildiği Tarih : 5 Mart 2007
Tezin Savunulduğu Tarih : 30 Ocak 2007

Tez Danışmanı : **Prof. Sevtap Yılmaz DEMİRKALE (İ.T.Ü.)**
Prof. Jens Holger RINDEL (D.T.U.)

Diğer Jüri Üyeleri: **Yrd.Doç. Nurgün Tamer BAYAZIT (İ.T.Ü.)**

Doç. Dr. Ayşe Erdem AKNESİL (Y.T.Ü.)

OCAK 2007

Dedicated To My Family…

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

There are a lot of people who contributed so much to this study.

First of all, I would like to thank my thesis supervisor Prof. Jens Holger Rindel for his wisdom, generosity and his patience in helping me throughout the project. I have learnt so much from him and I really am grateful to him for being my thesis supervisor. Jürgen Nickel who is the senior engineer in ROCKWOOL A/S and also my thesis supervisor helped me so much in this project. Without him I would not accomplish this project. I am grateful for his efforts and help for this project. And I would also like to thank Claus Christensen for helping me in the ODEON model.

I would like to thank to Prof. Sevtap Yılmaz Demirkale for trusting on me. She made my dreams come true. I will never forget her contribution on me. Also, Assoc. Prof. Nurgün Tamer Beyazıt helped me throughout my studies. Thousands of thanks to her.

This project was done in cooperation with ROCKWOOL A/S. I would like to thank them for their support during my project. Especially to Lars Hargstorm who accepted me to ROCKWOOL family and Martin Lisa who helped me so much during my project.

Thousands of thanks to all of my friends who never left me alone in Denmark and encouraged me during my studies. Especially, to Gökçe, Selçuk, Jeremy, Cristina. Very special thanks to Kerime Yaşaroğlu.

And finally, I would like to thank my family for always supporting and encouraging me throughout my whole life. They did their best for me. My mother, Hale Başbuğ has always lightened my path in my darkest moments, and has always been 'there' for me. My colleague and my father, Mehmet Bülent Başbuğ always guided me and shared his experiences. I will follow him and try to be a good engineer and person as he is. Thanks for being my family.

This thesis is dedicated to my mother and father and my beloved brother.

ABBREVATIONS

dB	: Decibel
ISO	: International Standard Organiztion
i.e.	: That is

LIST OF TABLES

LIST OF FIGURES

Page No:

LIST OF SYMBOLS

A : Equivalent absorption area

A_0: Reference absorption area

c_0 : Speed of sound in air

C : Adaptation term for pink noise

C_{tr}: Adaptation term for traffic noise

d : Diffuse-reflection coefficient

D: Sound pressure level difference

$D_{n,c}$: Suspended ceiling normalized difference

$D_{nc, w}$: Weighted suspended ceiling normalized level difference

$D_{n,f}$: Flanking normalized difference

$D_{n,s}$: Normalized level difference

D_{nTA} : Total sound transmission

D_{nTw} : Weighted total sound transmission

f_{cr} : Critical frequency

h: Thickness

h_{pl}: Height of the plenum above the ceiling

L_1: Average sound pressure level in the source room

L_2 : Average sound pressure level in the receiver room

m_{hi}: Upper limit of propagating room modes

p_A: Sound fields in the absorber layer

p_H : Sound fields in the plenum

p_e: Incident wave

p_r: Reflected waves

p_s: Backscattered waves

$P_{e\mu}$: Arbitrary amplitude of the incident mode

P_{tn} : Amplitude of the mode n in the formulation of the transmitted wave

Q : Average volume scatter density

R' : Sound transmission loss

R_w : Weighted sound reduction index

R_{FF} : Flanking sound reduction index

S_{cs},: Area of the ceiling in the source room

S_{cr}: Area of the ceiling in the receiving room

ST: Sound Transmission

T: Reverberation time

t_a : Thickness of the absorbing layer in the plenum

$T_{m,n}$: Mutual coupling coefficients.

V: Volume of the Room

α: Absorption coefficient

τ': Sound transmission coefficient

μ : Single incident room mode

η : Loss factor

ρ : Density

ρ_a : Absorber material bulk density

Θ_n : Angle of incidence of the room mode n

Ξ : Air flow resistance

ASMA TAVANLARDAN SES GEÇİŞİ

ÖZET

Bu projede, asma tavan sistemlerinden ses geçisi incelendi. Bu amaçla, odalarda değişik asma tavan malzemeleri ile laboratuvar ölçümleri yapıldı. Tavan arası boşluğunda da bazı ölçümler yapıldı. Ayrıca, tavan arasına eklenen yutuculuk da incelendi. Ölçümlerin yapıldığı odalar ODEON akustik programında modellendi ve simüle edildi. Daha sonra, sonuçlar ODEON programındaki simüle edilmiş değerlerle karşılaştırıldı. Simülasyonlar ayrıca uygulamadaki değişik durumlarda oda boyutları, tavan arası yükseklik gibi oda parametreleri değiştirilerek yapıldı. Tüm laboratuvar ölçümleri ISO standartlarına uygun olarak yapılmıştır. Teori ve bilgisayar simülasyonundan görünen odur ki; tavan arası boşluğu azaldıkça, ses geçiş kaybında artış elde edilmektedir. Tavan arasındaki yutuculuk karakteristikleri çok önemlidir ve ayrıca, tavan arasında yutuculuk kullanımı ses geçiş kaybını arttırmaktadır. Daha fazla ses izolasyonu için diğer ses yolları (yandan geçiş, duvardan doğru geçiş, yerden doğru geçiş, ızgara sisteminden geçiş) daha da düzeltilmelidir. ODEON programından daha iyi sonuçlar alınması için asma tavan malzemesinin yutuculuk özellikleri bilinmelidir aksi takdirde sonuçlar çok memnun edici olmayacaktır.

Sonuç olarak, ODEON modeli odadan odaya asma tavan yoluyula ses geçişinde her ne kadar çok kesin sonuçlar vermese de asma tavan yoluyla ses geçişi hakkında genel bir fikir verebilecek güçlü bir araç olabilir.

Bu proje, Danimarka Teknik Üniversitesi Akustik Departmanı'nda gerçekleştirildi. Akustik ölçümlerde, Danimarka orijinli Rockwool A/S akustik laboratuarlarından yararlanıldı.

SOUND TRANSMISSION THROUGH SUSPENDED CEILINGS

SUMMARY

In this project, sound transmission through suspended ceiling systems has been investigated. For that purpose, laboratory measurements are conducted with different ceiling tile systems in the rooms. Some measurements are done in the plenum. Also, the effect of additional absorption in the plenum has been investigated. The rooms used in the measurements are modelled and simulated in ODEON acoustic programme. Later, some measurement results have been compared with the simulated ones from ODEON. The simulations are also done with changing the room parameters like room dimensions, plenum height to investigate the different conditions in practice. All the laboratory measurements are conducted according to ISO standards. From theory and from the computer simulation it is seen that, as the depth of the plenum reduces more increase in the sound transmission loss is obtained. The absorption characteristics of the plenum are very important and the usage of the absorption in the plenum also increases the transmission loss. To acquire more sound insulation, other transmission paths (flanking, through the wall, through the floor, through the grid system) should be improved. To acquire good results from ODEON programme, the absorption properties of the ceiling tiles should be known, otherwise the results will not be so satisfactory.

In the end it can be said that, although, the ODEON model does not give precise results in room to room sound transmission through suspended ceilings, the results obtained can be used as a powerful tool to give a general idea about the sound transmission via suspended ceilings.

This poject has been carried out in Denmark Technical University Acoustics Department. Danish origin Rockwool A/S acoustics laboratory has been used for the acoustical measurements.

1. INTRODUCTION

In the modern buildings, the requirements for the acoustics are numerous. There are some factors that contribute in the acoustic applications. For example; maximum flexibility, the ability to be able to change the existing construction or layouts quickly should be obtained as well as the economics that is important for reducing building costs and time consumption. Great demand has been placed on the individual building components by these requirements, especially when selecting the ceiling/wall system.

Today, modern office areas are designed in such a way that all services like electricity, air conditioning, plumbing are concealed above a suspended ceiling. To supply the needs of the occupants', the services can be installed through the space above the suspended ceiling, plenum and demountable walls can be built anywhere.

In this project, sound transmission through suspended ceiling systems has been investigated. For that purpose, laboratory measurements are conducted with different ceiling tile systems. Also, the effect of additional absorption in the plenum has been investigated. The rooms used in the measurements are modelled and simulated in ODEON acoustic programme. Later, some measurement results have been compared with the simulated ones from ODEON. The simulations are also done with changing the room parameters like room dimensions, plenum height to investigate the different conditions in practice.

2. SOUND TRANSMISSION

2.1. Sound Transmission Calculation Models

2.1.1. General Principles

When there is a noise generated in the source room, the sound power that is measured in the receiving room is due to the direct and indirect airborne sound transmission and sound radiated by the separating structural elements and the flanking structural elements in that room. In direct and indirect airborne sound transmission, the elements, systems and each element in the receiving room involved form the transmission factors which is a part of total transmission factor (DS- ISO 15186-1, 2000).

$$R' = -10 \log \tau' \text{ dB} \qquad \textbf{(2.1)}$$

$$\tau' = \tau_d + \sum_{f=l}^{n} \tau_f + \sum_{e=l}^{m} \tau_e + \sum_{s=l}^{k} \tau_s \qquad \textbf{(2.2)}$$

In the formula above, d, f, e and s indicate the different contributions to the sound transmission that is shown in Figure 2.1.

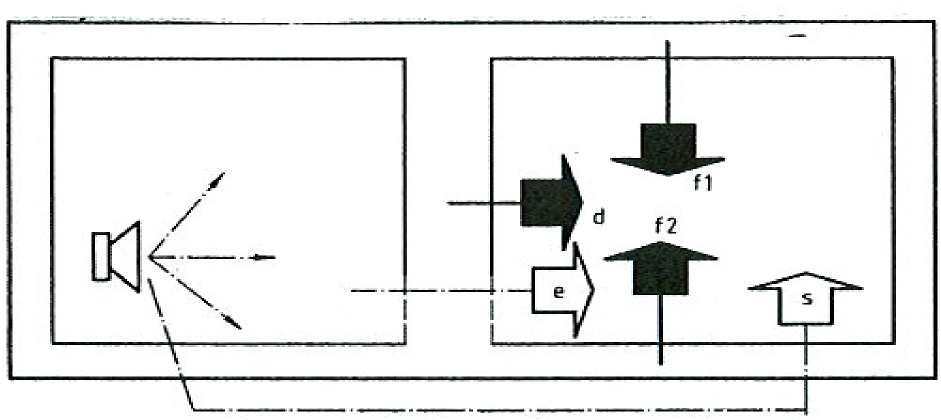

Figure 2.1: Contributions to the total sound transmission from different sound paths (DS- ISO 15186-1, 2000)

In formula 2.2., n is the number of the flanking elements which is normally four. But n can be also smaller or larger than four. Number of elements with direct transmission is denoted as m and number of systems with indirect airborne transmission is denoted as k.

τ' : the sound power ratio of total radiated sound power in the receiving room that is relative to the incident sound power on the common part of the separating element such as a partition wall.

τ_d : the sound power ratio of radiated sound power by the common part of the separating element that is relative to the incident sound power on the common part of the separating element. Paths Dd and Fd are shown in Figure 2.2.

τ_f : the sound power ratio of radiated sound power by a flanking element f in the receiving room that is relative to the incident sound power on the common part of the separating element. Paths Ff and Df are shown in Figure 2.2.

τ_e : the sound power ratio of radiated sound power in the receiving room by an element because of the direct airborne transmission of incident sound on this element that is relative to the incident sound power on the common part of the separating element.

τ_s : the sound power ratio of radiated sound power in the receiving room by a system s because of the indirect airborne transmission of incident sound on the transmission system that is relative to the incident sound power on the common part of the separating element.

Sum of structure-borne sound transmission through several parts form the total structure borne sound transmission. In Figure 2.2., the paths for a flanking element and the separating element can be seen.

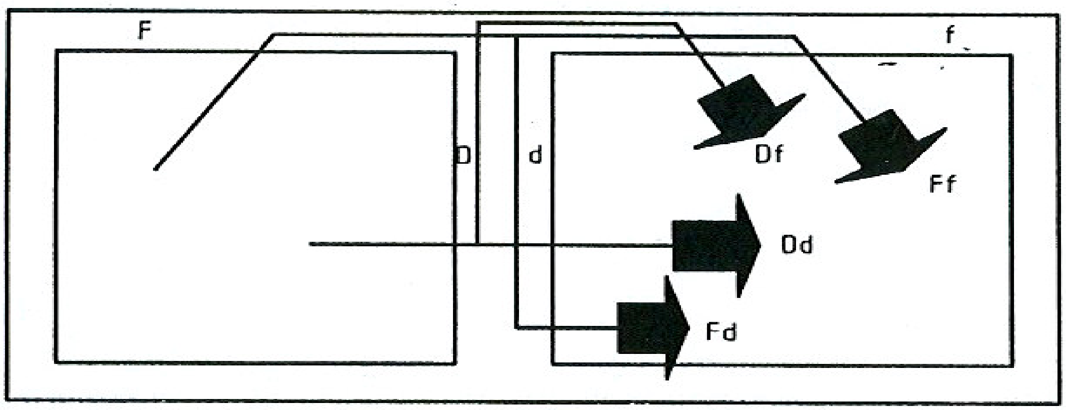

Figure 2.2: Sound transmission paths ij from room to room (DS- ISO 15186-1, 2000).

2.1.2. Indirect Transmission

2.1.2.1. Laboratory Measurement of Total Indirect Transmission: Lightweight elements, suspended ceilings, access floors are a group of flanking structural elements. When the flanking transmission F_f is dominant, it is more convenient to make the distinctive features of the transmission by laboratory measurements. The sound transmission might be primarily structure-borne, primarily air-borne or combination of both (DS- ISO 15186-1, 2000).

By making standardized laboratory measurements of indirect transmission, different products can be compared. The results can be expressed as flanking normalized difference $D_{n,f}$.

$$D_{n,f} = L_1 - L_2 - 10 \log \frac{A}{A_0} \qquad \textbf{(2.3)}$$

Where;

A_0=10 m^2
L_1: Average sound pressure level in the source room, in dB
L_2: Average sound pressure level in the receiver room due only to sound transmitted by the considered flanking construction, in dB

A: Equivalent sound absorption area in the receiving room, in m^2

So, the above formula can be applied for transmission through suspended ceilings. $D_{n,f}$ is denoted as $D_{n,c}$ and the method can be found in ISO 140-10.

2.1.2.2. Indirect Airborne Transmission: If the airborne transmission is dominant over flanking transmission, the relation below can be used to find out the normalized level difference $D_{n,s}$.

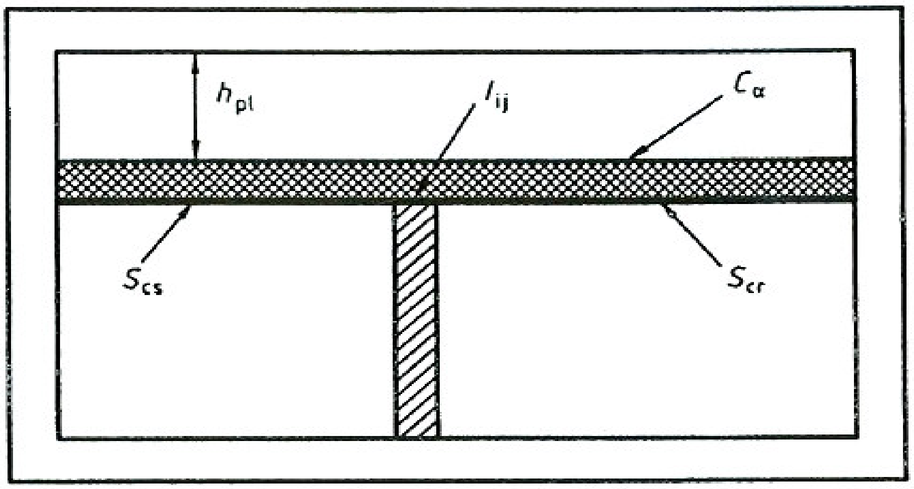

Figure 2.3: Relevant quantities for the prediction of indirect airborne transmission (DS- ISO 15186-1, 2000).

$$D_{n,s} = D_{n,f} + 10\log\frac{h_{pl}l_{ij}}{h_{lab}l_{lab}} + 10\log\frac{S_{cs,lab}S_{cr,lab}}{S_{cs}S_{cr}} + C_\alpha \text{ dB} \quad \textbf{(2.4)}$$

Where;

$C_\alpha = 0$ dB (when there is no absorbing layer)

When there is absorbing layer;

$$C_\alpha = 0 \text{ dB} \qquad f \leq 0{,}015\,\frac{c_0}{t_a} \quad \textbf{(2.5)}$$

$$C_\alpha = 10 \log \sqrt{\frac{S_{cs} S_{cr}}{S_{cr,lab} S_{cr,lab}} \frac{h_{lab}}{h_{pl}}} dB \quad ; \quad 0{,}015 \frac{c_0}{t_a} \le f \le \frac{0{,}3 c_0}{\min(h_{lab}, h_{pl})} \qquad \textbf{(2.6)}$$

$$C_\alpha = 10 \log \sqrt{\frac{S_{cs} S_{cr}}{S_{cr,lab} S_{cr,lab}} \frac{h^2_{lab}}{h^2_{pl}}} dB \quad ; \quad f \ge \frac{0{,}3 c_0}{\min(h_{lab}, h_{pl})} \qquad \textbf{(2.7)}$$

S_{cs}, S_{cr}: Area of the ceiling in the source room and the receiving room, in m^2. For the ISO laboratory $S_{cs,lab}$, $S_{cr,lab}$ =$20m^2$

h_{pl}: height of the plenum above the ceiling. In m. For ISO laboratory h_{lab}=0,7m.

t_a: thickness of the absorbing layer in the plenum, in m.

c_0: speed of sound in air. In m/s.

2.1.2.3.Flanking Transmission: When the structure-borne sound transmission is dominant, the following can be used to determine the flanking sound reduction index R_{FF} .

$$R_{FF} = D_{n,f} + 10 \log \frac{S_s l_{lab}}{A_0, l_{Ff}} + 10 \log \frac{T_{s,F,lab}}{T_{s,F}} + 10 \log \frac{T_{s,f,lab}}{T_{s,f}} \text{ dB} \qquad \textbf{(2.8)}$$

The structural reverberation term might be omitted if the construction has a high internal loss factor (DS- ISO 15186-1, 2000).

2.2. Room to Room Sound Transmission via Suspended Ceiling

Sound pressure level between two rooms is used for calculating the sound transmission loss. In fact, total sound transmission from one room to another which is defined in most of the national requirements for the room to room sound insulation includes all possible transmission paths.

Sound transmission paths can be divided into four groups.

ST_{wall}: direct sound transmission through the wall with sound reduction R

$ST_{flanking,\ wall\text{-}ceiling}$: Flanking sound transmission through ceiling system in the wall connection.

$ST_{flanking,\ floor\ and\ walls}$: Flanking sound transmission through the floor and other walls

$ST_{ceiling}$: Sound transmission through the plenum above the suspended ceiling.

These transmission paths are illustrated in the figure below.

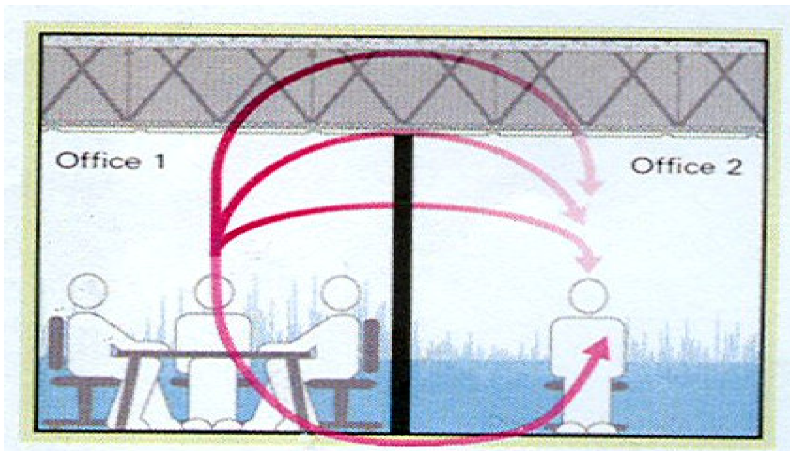

Figure 2.4: Room to room sound transmission paths.

Sum of these four main transmission paths is the total transmitted sound.

The total sound transmission is depended on the following parameters:

- The weighted suspended ceiling normalized difference ($D_{n,\ cw}$) for ceiling which is depended on the ceiling tiles, and grid system
- The geometry of the rooms and the obtained reverberation time values from these rooms
- The properties of the partition wall. The sound transmission loss of the partition wall (R_w value). Type of wall connection.
- The flanking transmission through walls and floor
- Ceiling and partition wall connection. Type and length of the band raster.
- Properties of the plenum. Height and absorption in the plenum.

ISO 717 specifies the rating of the sound insulation in buildings and of building elements. According to ISO 717 the single number quantities like weighted sound reduction index, R_W, weighted suspended ceiling normalized level difference, $D_{nc,\ w}$ and etc. are found by shifting the reference curve which is defined in ISO 717 to the measured values curve that is obtained by ISO 140 standards. The value found at 500 Hz is the $R_{w,}$ $D_{nc,\ w}$, etc.

Also, the spectrum adaptation terms C and C_{tr} are defined in ISO 717. C is the adaptation term for pink noise to evaluate the sound insulation for: Living activities, railway traffic for medium and high speed, highway road traffic at high speeds, jet aircraft noise at short distance, factories emitting mainly medium and high frequency noise.

C is the adaptation term for traffic noise. It is used to evaluate the insulation for: urban traffic noise, railway traffic at low speeds, jet aircraft at large distance, disco music, factories emitting low and medium frequency noise.

D_{nc} , $D_{nc,\ w}$, C and C_{tr} values for the ceiling tiles are presented in this project.

According to the external acousticians, the $D_{nc,\ w}$ of the ceiling should be about 7 dB higher as the requirement for the total sound transmission D_{nTA}. To validate this, the following assumption should be made;

- $D_{nTA} \approx D_{nTw}$ – 2dB (2dB is the typical C value)
- $(ST_{flanking,\ floor\ and\ walls} + ST_{flanking,\ wall\text{-}ceiling}) \approx ST_{ceiling} \approx ST_{\ wall}$

Almost equal sound transmission from flanking transmission, direct transmission through the wall and ceiling plenum. So the total sum of these transmissions should be 5dB.

Sound transmission through the ceiling system from room to room can be divided in four different parts:

- Sound transmission through the grid system. $ST_{grid.}$
- Sound transmission through ceiling tiles. $ST_{tiles.}$
- Sound transmission through the leaks in the ceiling-wall connection. $ST_{wall-leaks.}$
- Sound transmission through light fittings and other installations. $ST_{installations.}$

$$ST_{ceiling} = ST_{grid} + ST_{tiles} + ST_{wall-leaks} + ST_{installations} \quad \textbf{(2.9)}$$

2.2.1. Designing of Suspended Ceiling

Usually, when designing the suspended ceiling, the design is optimized for one feature where the other features are compromised. As an example, to obtain flexibility in offices where the suspended ceilings are mostly used, the partition wall commonly extends up to the underside of the suspended ceiling. That is usually the case in many European Countries such as Netherlands, France, etc. In Scandinavia, partition walls are extended above the suspended ceiling up to a limit.

The two types of partition walls that are used under the suspended ceiling can be seen in the Figure 2.5. It should be mentioned that when the sound insulation of these two types are compared, the Scandinavian type of partition wall that extend above the suspended ceiling provides 1dB – 2dB more sound reduction.

While providing some flexibility, the partition wall that extends up to the underside of the suspended ceiling limits acoustical isolation between the rooms (offices). The sound propagates through the suspended ceiling, across the plenum space and back down through the ceiling of the other room. Possibilities arise for flexural wave transmission and lateral propagation through the acoustical material (Hamme, 1961).

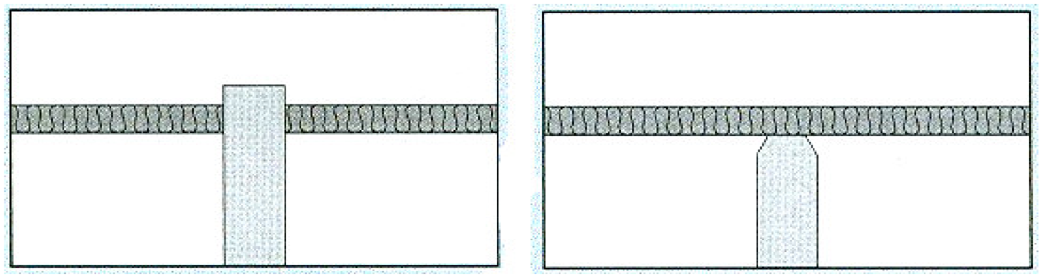

Figure 2.5: Types of partition walls.

In the previous researches that have been made, it has been found out that, only a few dB attenuation is provided in the path through the open plenum space above the suspended ceiling. In this situation, most of the attenuation is provided by the suspended ceiling.

There are many types of ceiling panels that are used for suspended ceiling systems. For example, glass fiber ceiling panels provide little attenuation. And though panels with high transmission loss values are used in some ceiling systems, there are leaks that limit the attenuation.

The main noise leaks in the ceiling occur between the edges of each ceiling panel, the supporting grid system and in the openings for air conditioning or lightning system.

There are two ways to increase the noise reduction. These are either by reducing the sound transmission through the suspended ceiling by using panels with high transmission loss and treating the air-return openings or by blocking the way of the sound propagation over the suspended ceiling by putting a barrier (Halliwell and Quirt, 1991).

There are some factors that effect the acoustical performance of the suspended ceiling constructions. These are:

- Whether there are openings like doors and/or glazing in the partition wall.

- Perimeter finishing of the ceiling against the wall.
- The type, number and location of the services like light fittings.
- Workmanship.

To obtain efficient sound insulation of partitions between the offices, background noise should also be taken into account since that the background noise, either from traffic noise or from the office tools such as typewriter, fax machine, etc., masks the noise coming through the partitions and the insulation required is less than in the presence of a lower background noise.

The spectrum of ceiling attenuation factors are not necessarily controlled by the sound transmission loss of the acoustical material because of the acoustical leakage through the grid and suspension system and the absorptive component of the plenum that is established by back absorption of the ceiling and the termination room absorption that is established by the front absorption of the ceiling (Hamme, 1961)

2.2.2. Theory of Sound Transmission through Suspended Ceilings

Because the dimensions of the plenum space over the adjacent rooms that are divided by a partition wall are no like the dimensions of "regular rooms", the existing theory for room acoustics can not be applied. And, also the dimensions of the plenum are larger than the ducts and so on it is also not suitable to apply the duct acoustics theory for finding out the sound transmission behaviour of the plenum. *Mariner (1950)*, tried to explain a theory for the transmission of sound in the plenum but that fails to represent the experimental data. In Mariner's theory, both parts of a symmetrical suspended ceiling make the same contribution to the total transmission loss. Apparently, the experiment results are not in accordance with the Mariner's theory.

In the figure below, in the source room, p_e is denoted as the incident wave, $p_e + p_s$ are reflected and backscattered waves. In the receiver room, p_t is the transmitted wave. p_A and p_H are the sound fields in the absorber layer and in the plenum.

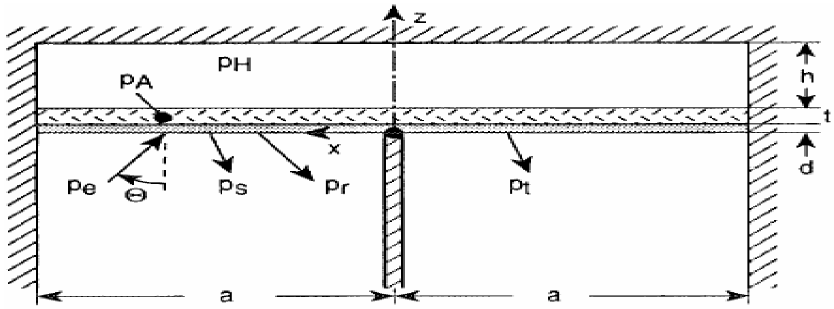

Figure 2.6: Suspended ceiling with ceiling plate, absorber layer and plenum space (Mechel, 2002)

Also, the transmission loss R= -10 log τ is defined from the power ratio $\tau=\Pi_t / \Pi_c$ of the waves p_t and p_e. These waves can be synthesized by room modes.

It is possible to synthesise and make a field theory of the sound fields p_A and p_H with elementary waves (modes) that is in accordance with the wave theory and the boundary conditions in the room limits.

The most significant theory that has been studied lately is the theory of *Mechel*. According to *Mechel (1995),* two different field theories can be conceived for suspended ceilings. One of them use the principle of superposition, which minimizes the problem of sound transmission to two tasks of reflection by using boundary conditions. In the other theory, the fields p_A and p_H are composed with plenum modes.

2.2.2.1.Theory with principle of superposition: For all sound transmitting objects that have a plane of symmetry (x=0 in that case) and for the incident waves that have all the shapes, the principle of superposition can be applied. The solution is made of two parts. In one part (β)=(h), the sound transmitting area of the plane of symmetry which is the area of the absorber and of the plenum between the rooms, is assumed to be rigid. In the other part of the solution, (β)=(w), the area is theorized to be soft. In these solutions, p_r is the rigid reflection of p_e at the lower ceiling surface (Mechel, 1995)

Transmitted wave p_t is:

$$p_t(x,z) = \frac{1}{2}\left(p_s^{(h)}(-x,z) - p_s^{(w)}(-x,z)\right) \quad \textbf{(2.10)}$$

(β)=(h) case is easy to solve because of the all fields having the shape of incident room mode with lateral profile

$$q_m(x) = \cos(m\pi x / a) \quad \textbf{(2.11)}$$

where m = 0,1,2,…

In (β)=(w) case, p_e p_r $p_s^{(w)}$ are combined with room modes $q_m(x)$. On the other hand, the p_A and p_H fields are synthesized with shelf modes that appear in underwater acoustics.

Shelf mode:

$$s_n(x) = \sin((2n+1)\pi x / a) \quad \textbf{(2.12)}$$

where n= 0,1,2,…

Both room modes and shelf modes are orthogonal over $0 \le x \le a$.

$$T_{m,n} = \frac{1}{a}\int_0^a q_m(x).s_n(x)dx = -\frac{2}{\pi}\frac{2n+1}{(2m)^2-(2n+1)^2} \quad \textbf{(2.13)}$$

Where;

$T_{m,n}$ are the mutual coupling coefficients.

It is possible to solve the boundary conditions at the layer interfaces of the multilayer system of the suspended ceiling for the mode amplitudes by standard methods of modal analysis.

The sound transmission coefficient τ_μ for a single incident room mode μ is:

$$\tau_\mu = \frac{\delta_\mu}{\cos\Theta_\mu} \sum_{m=0}^{m_{hi}} \frac{\cos\Theta_m}{\delta_m} \left| \frac{P_{tm}}{P_{c\mu}} \right|^2$$

(2.14)

$$\delta_n = \left\langle \begin{matrix} 1; n = 0 \\ 2; n > 0 \end{matrix} \right. ; \cos\Theta_n = \sqrt{1 - (n\pi / k_0 a)^2} \, ; m_{hi} \leq k_0 a / \pi$$

Where;

Θ_n: angle of incidence of the room mode n

m_{hi}: upper limit of propagating room modes

$P_{e\mu}$: arbitrary amplitude of the incident mode

P_{tn} : amplitude of the mode n in the formulation of the transmitted wave

The total transmission coefficient is computed when the incident wave is a superposition of all propagating room modes with equal energy density. This is shown in the formula below.

$$\tau = \sum_{\mu=0}^{\mu_{hi}} \tau_\mu \cos\Theta_\mu \Big/ \sum_{\mu=0}^{\mu_{hi}} \cos\Theta_\mu \qquad \textbf{(2.15)}$$

Because of the increasing number of propagating modes and the corresponding number and size of the systems, the numerical solution increases with frequency f and room width a and it is time consuming to solve these equations.

Below, there can be seen three figures with the computed and measured values of the transmission loss for the suspended ceiling of d=9,5 mm plaster board with and without absorber layer and suspended ceiling with a ceiling board of compressed mineral fibres, covered with a felt of mineral fibre absorber, respectively (Mechel, 1995)

Where;

f_{cr} d : product of critical frequency of the board and its thickness

η : loss factor including the losses by mounting

Ξ : absorber material resistivity

ρ_a: absorber material bulk density

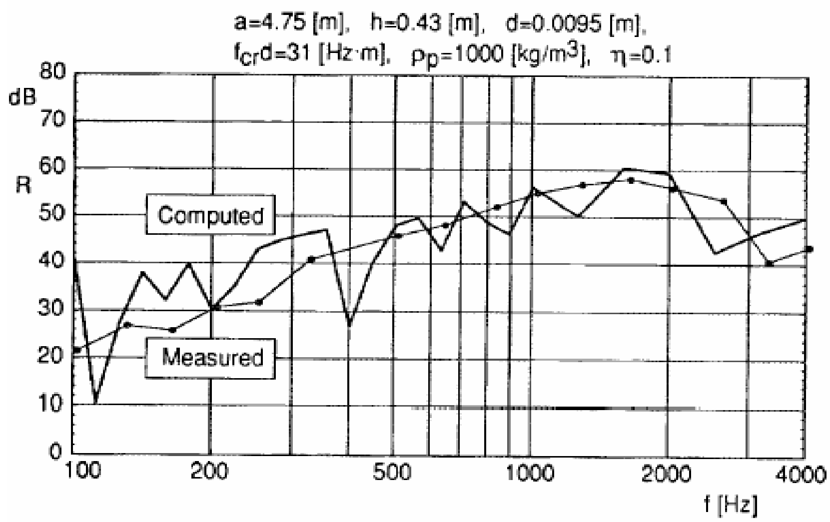

Figure 2.7: Measured and computed transmission loss for a suspended ceiling d=9,5 mm plaster board without absorber layer (Mechel, 1995)

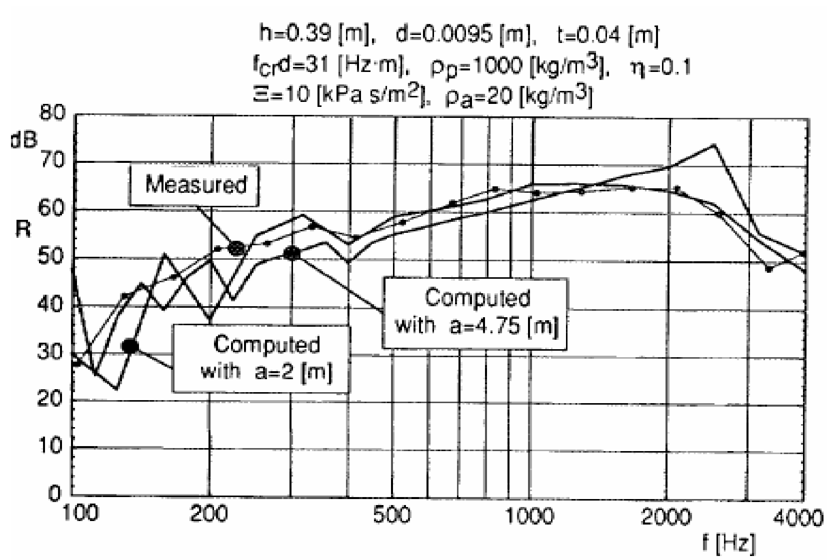

Figure 2.8: Measured and computed transmission loss for a suspended ceiling d=9,5 mm plaster board with absorber layer (Mechel, 1995)

Also in the figure below, the measured and computed values for the ceiling plate consisting of boards of compressed mineral fibres can be seen.

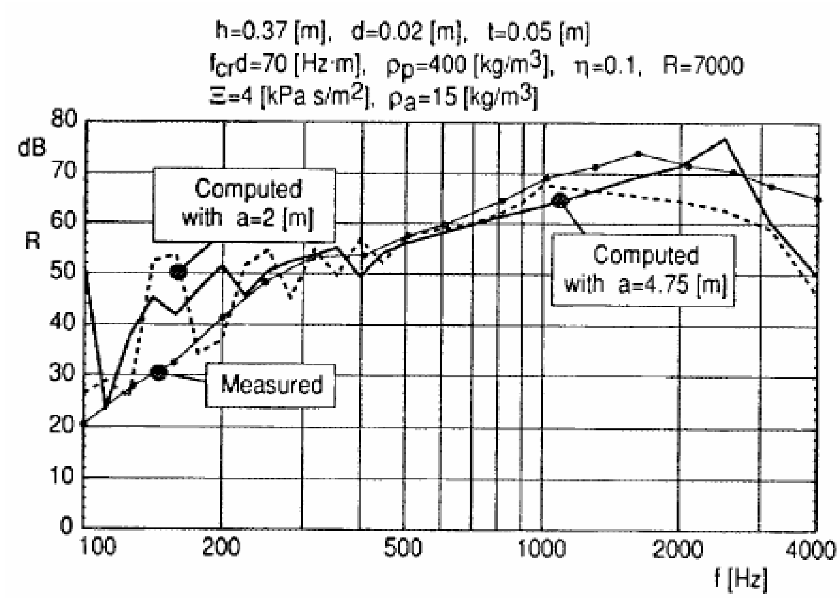

Figure 2.9: Measured and computed transmission loss for a suspended ceiling with a ceiling board of compressed mineral fibres (Mechel, 1995)

It can be seen from the figures that the measured and computed transmission loss values for different ceiling systems are well agreement with each other. And also, Mechel claims that no experimental data is used in the computed results.

The disadvantage of the theory is to solve very big systems of equations. On the other hand, it is possible to calculate the sound field distribution in the plenum, the absorber layer and in the receiving room according to Mechel´s theory. In application it is tedious to apply all the equations to obtain the results for the plenum characteristics.

<u>2.2.2.2. Theory with plenum modes:</u> If the central plane x=0 becomes permeable to sound, the solution for (β)=(h) becomes distorted due to the fact that the change of the boundary conditions at x=0. It is possible to compensate this error and satisfy all the boundary conditions by additional waves at x=0. These waves that compensates are the plenum modes which are like silencer modes except the radiation and

oscillation on the wall of the plenum. Numerical solutions and formulation can be applied to the plenum modes.

In the figure below, sound pressure level for the first room mode μ=1 incident on a suspended ceiling of 9.5 mm plasterboard covered with a 8 cm thick mineral fibre felt under a plenum of 35 cm height at 500 Hz can be seen. The room sizes are 4 meters and the plenum back walls are hard. Left behind is the emission room, right behind is the receiving room, left front is the plenum above absorption and right front is the plenum above receiving room.

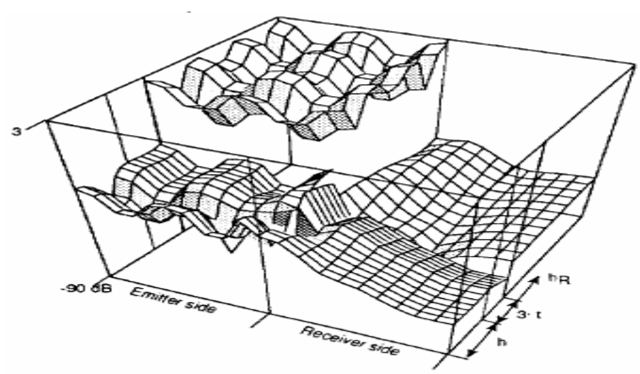

Figure 2.10: Sound pressure level for the first room mode incident on a suspended ceiling (Mechel, 2002)

Mechel claims that from the source room to the plenum the level difference is higher than the plenum to the receiver room. The sound field on the source room side has the lateral profile of the incident wave where the receiver side is an exponential decay of the plenum modes that are created at the central plane. It is seen that the behaviour and the roles of the two part of the plenum are different.

3. SOUND DIFFUSIVITY AND ABSORPTION

3.1. Diffuse Sound Field

Diffuse sound field is defined as one in which, at any point in the room, reverberant sound waves are incident from all directions with equal intensity and random phase. Also, the reverberant sound energy density must be same at all points in the room (Kutruff H., 1991)

Kutruff (1991) says that there are two ways to increase the room sound field diffuseness. These involve increasing the extent to which the room surfaces are diffusely reflecting. And the other method is to introduce scattering or diffusing obstacles into the room volume which is referred as volume scatterers. Reflecting panels are commonly used as a volume scatterer in the reverberation rooms for diffuseness. Both methods tend to increase the randomization of the sound incidence on the surfaces and thus that results a more diffuse field. There are some exceptions like, when the density of the volume scatterers becomes high, the sound becomes trapped and can not reach the surfaces that results the decrease in diffuseness.

For a room that has the dimensions of 30m x 15m x 5m, Figure 3.1 shows the sound decay for various degrees of uniform diffuse surface reflection, as quantified by the diffuse-reflection coefficient d. When sound energy strikes a surface, a proportion d is diffusely reflected according to Lambert's law, while the remaining proportion (1-d) is reflected. Figure 3.1 also shows the sound decay for various amounts of isotropically distributed volume scatterers, as quantified by their average volume density Q; the range of Q values is below that at which sound is "trapped" between the scatterers. Q is equal to the inverse of the mean free distance between scatterer.

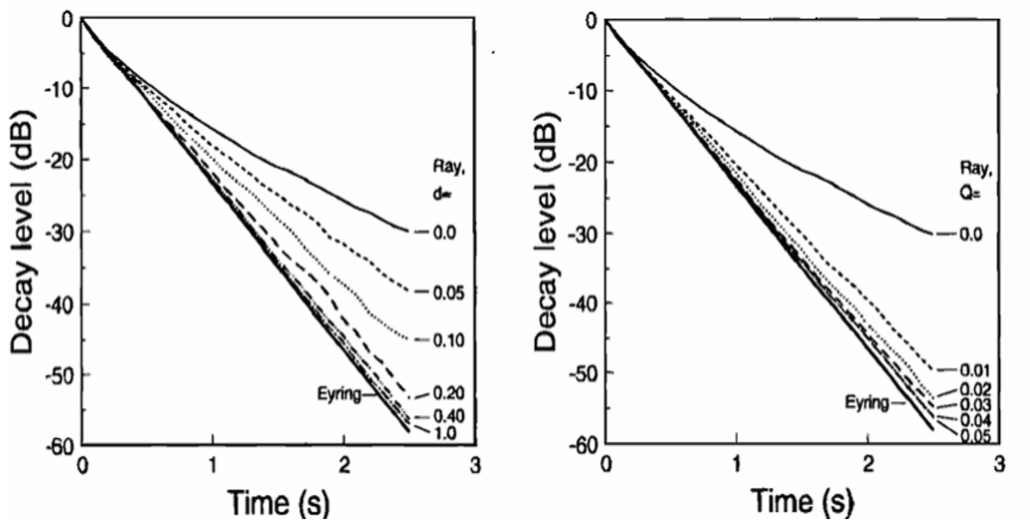

Figure 3.1: Room sound decays predicted by the Eyring formula and by ray tracing for the indicated values of the diffuse-reflection coefficient d (left figure) and average volume scatter density Q in m (right figure) (Hodgson, 1994)

Clearly, it can be seen from the figures that by increasing d or Q, gives a more linear slope. The curves tend toward that predicted by the Eyring equation, and the reverberation time tends toward that predicted by the Eyring reverberation-time formula, T_{60}=0.163 V/ α S.

The effect of the use of diffusers in the laboratory rooms can be seen in the laboratory measurements. This has been explained in the measurement results.

3.2. Sound Absorption and Sound Absorbers

Since three side walls (and later more absorption material is added above the ceiling tiles) of the plenum was covered by absorption material (mineral wool), when the sound propagates through the plenum to the adjacent room, it is also important to understand the absorption in the plenum.

Mineral wool products are example of porous sound absorbers. Three different catagories can be made for the porous materials in an acoustical point of view:

i. A porous layer mounted directly on a hard surface

ii. A porous layer at a certain distance from a hard backing
iii. Porous boards positioned freely in the room

An example of the first situation is the mineral wool product that is put in the plenum sidewalls.

The absorption coefficient with the change of frequency can be seen in Figure 3.2 for different materials with two different thicknesses and four different values for flow resistances in the figures below. Flow resistance plays a crucial role in the absorption. The values for the flow resistance should not be so large or small to have a high value of absorption over a wide frequency range. The reason for this is, when the flow resistance is small, the sound wave will have no obstacle on its way and be reflected from the hard surface back into the room. When the flow resistance is large, the sound wave will be reflected from the surface of the material itself.

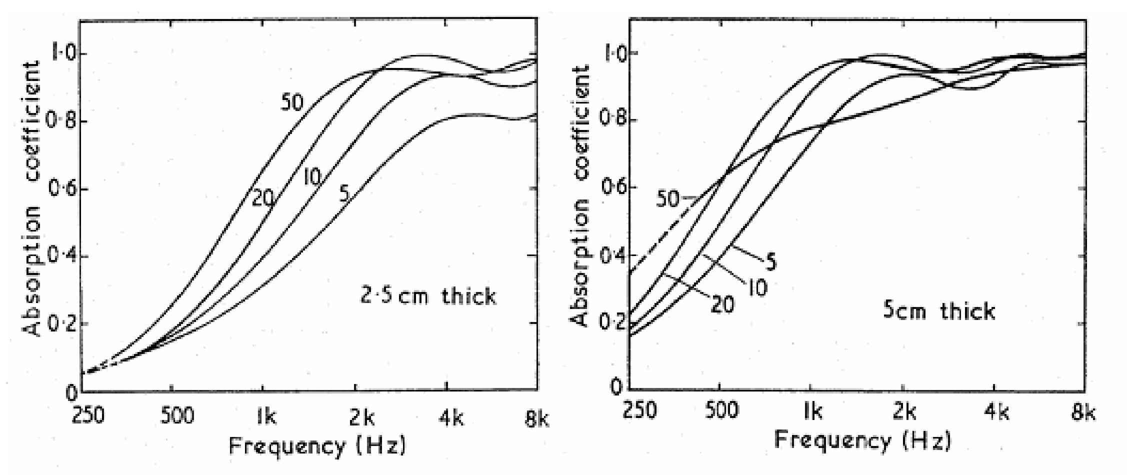

Figure 3.2: Absorption coefficients calculated from theory for normal incidence of sound against 2.5 cm. and 5 cm. thick layers of porous materials flush mounted on a hard surface. (Delany&Bazley, 1970)

So the optimum values for the air flow resistance for porous materials are:

$$1000\ Nsm^3 \leq \ h\Xi \leq 3000\ Nsm^3 \qquad \textbf{(2.16)}$$

When the flow resistance is in that region, the absorption coefficient will fall in the hatched area in Figure 3.3.

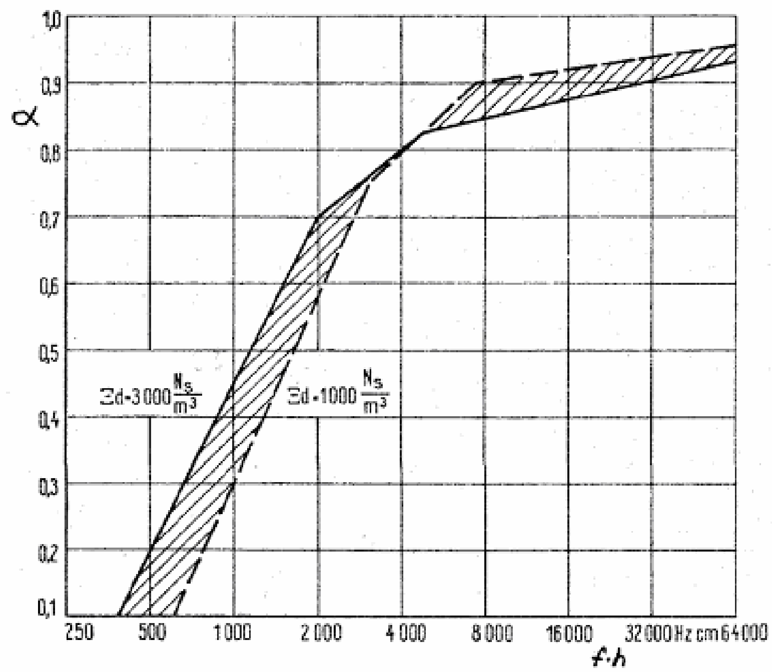

Figure 3.3: Idealized absorption coefficient or diffuse sound field incidence on a porous material mounted directly on a hard surface. (Fasold&Sonntag,1976)

Rindel (1982) states that to be efficiently absorbing, a porous absorber mounted directly on a hard surface should have a thickness of about 8 cm. And also, the values for the specific flow resistance of the material Ξ should be between 12500and 37500 Nsm^{-4}.

If more absorption is needed for the low frequencies, the thickness of the material can be increased but in that case the specific flow resistance should have low values.

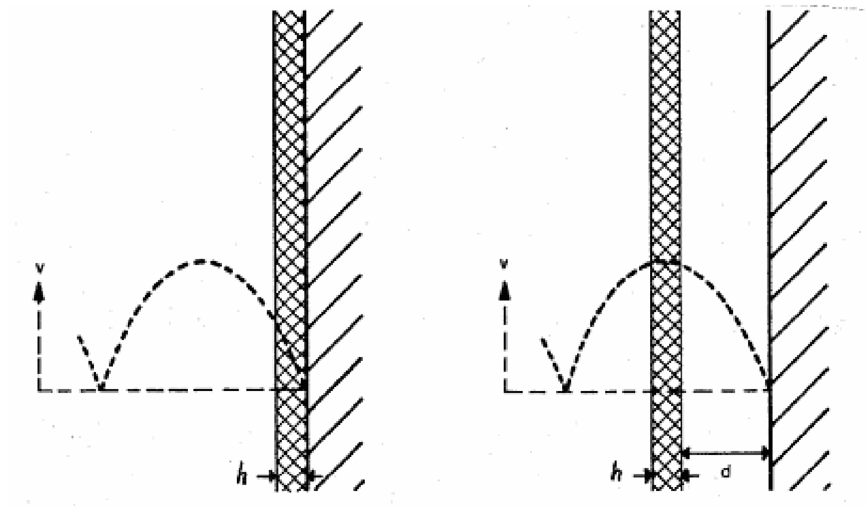

Figure 3.4: The particle velocity of the standing wave for unfavourable and favaourable (left and right respectively) positioning of a porous layer in front of a hard surface (Rindel, 1982)

As seen in figure above it has more advantages in acoustical way to place the porous absorbers a distance from the hard backing. The optimal values for the flow resistance turn into:

$$500\ Nsm^3 \leq h\Xi \leq 1000\ Nsm^3$$

These values for flow resistance are almost three times lower than the values for the porous layer that is placed on the hard surface. The difference in the absorption values are represented in the Figure 3.5 below.

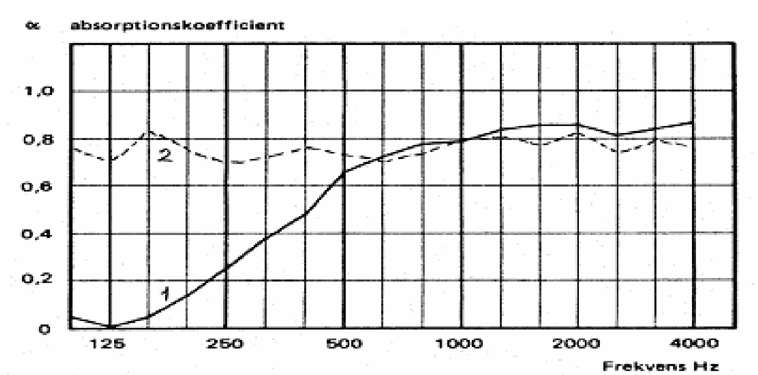

Figure 3.5: Example of measured absorption coefficients for a 25 mm thick panel (Rindel, 1982)

The hard line in the figure represents the Rockfon Fibral a compressed mineral wool with glass vies and a paint that does not cover the surface with a density of 70 kg/m^3 directly mounted on hard surface. The dashed line represents the absorption for the material which is suspended 30 cm.

In Figure 3.5., it can be seen that the same max absorption value is obtained at $r_m=1/4\ \rho\ c$ and $r_m=4\ \rho\ c$.

Depending on the direction of incidence, when the sound hits the absorber from many different angles of incidence at the same time, the minimum absorption values occur at different frequencies (Rindel,1982).

The absorption characteristics change as the distance from the hard backing to the material changes. The distance between the floor and the ceiling tile is different from the distance between the back-side of the ceiling tile and plenum top ceiling. So, this also proves that the absorption characteristics should be different for the different sides of the material.

Of course, it should be stated that the sound absorption of suspended ceiling elements are measured according to the ISO 354. It is frequently unviable to install, in a reverberation room, a suspended ceiling system with a plenum in its normal orientation, hence, the type E mounting, as defined in ISO 354, proposes a system to simulate the ceiling, but placed on the floor of the reverberation room instead. This consists of a horizontal support into which the test specimen is placed with the test surface visible, i.e., in an upside down position. This support is raised a given distance off the floor and the sides closed with heavy material. The whole support structure delimits a volume of air, simulating a plenum.

3.3. Additional Absorption Layer in Plenum

The ISO 140/9 states that the one sidewall and two end walls of the plenum of the measurement laboratory should have absorption. The effect of absorption has been investigated by many projects.

Lately, increase in the sound transmission loss in the plenum has been investigated by the EURIMA project by putting additional absorption in the plenum on 1:10 scale models. Some of the results obtained from their measurements with two different plenum heights are presented below. Situation 1 represents no absorption on the plenum, situation 2 represents 50 mm. mineral wool and situation 3 represents 100 mm. mineral wool.

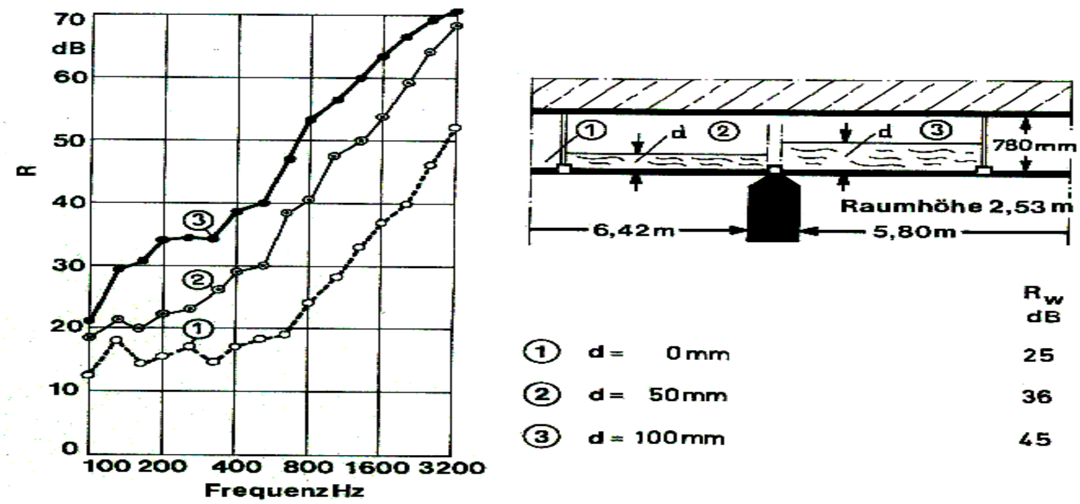

Figure 3.6: Increase in sound transmission loss by using absorption in 780 mm plenum height (Eurima, 2005).

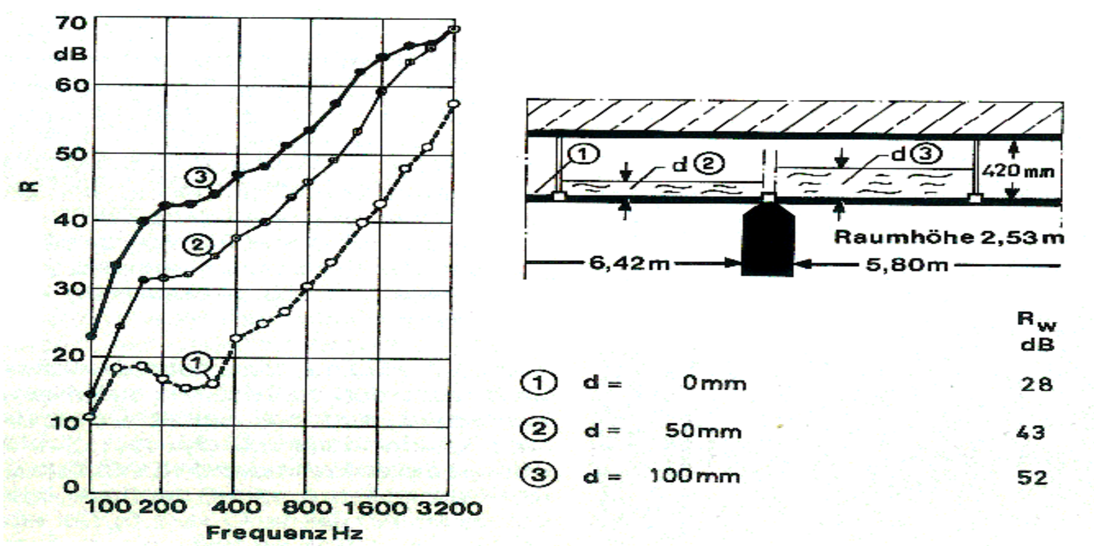

Figure 3.7: Increase in sound transmission loss by using absorption in 420 mm plenum height (Eurima 2005).

It is seen that by using a thicker absorption material (100 mm in EURIMA investigation) the transmission loss increased by 10-14 dB. When the plenum height is reduced to 420 mm, it has been shown that more increase in the sound transmission loss is obtained when compared to the plenum height of 780 mm.

Since, the ceiling tiles possess little back-absorption, without absorption in the sidewalls of the plenum, the sound propagates through plenum and hits the plenum sidewalls and then reflected back toward the receiver room and that enhances the sound levels developed there by directly transmitted sound. On the other hand, using sidewall absorption in the plenum increase the attenuation factors 2.5 to 10 dB dependent on the frequency. But of course that also depends on the back absorption of the ceiling material since with a more back absorber material the effect of plenum sidewall absorption reduces (Hamme, 1961).

4. LABORATORY MEASUREMENTS

4.1. Rooms and Measurement Equipment

4.1.1. Laboratory Rooms

In order to measure the room to room sound transmission through suspended ceiling ROCKWOOL testing facilities are used. The plans and dimensions of the test rooms can be seen in the drawings below.

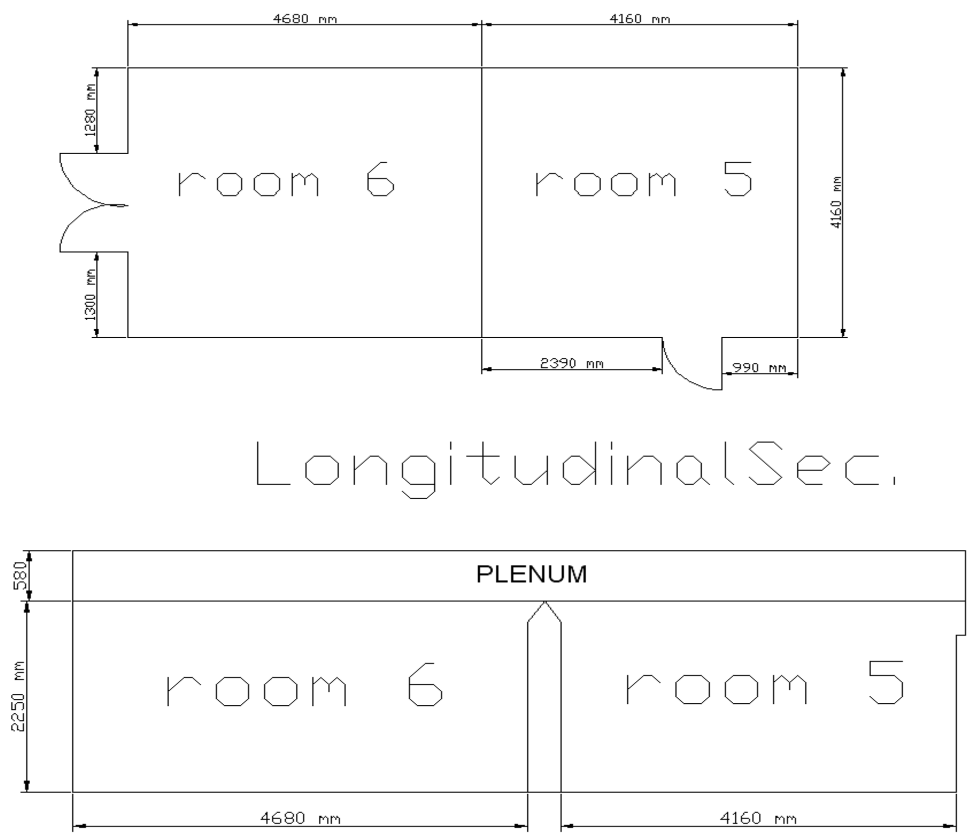

Figure 4.1: Plan and side view of the test rooms

ISO 140/9 specifies the laboratory method of measuring the airborne sound insulation of a suspended ceiling with a plenum of defined height mounted above an acoustical barrier (partition wall) that separates two rooms of the test facility.

In ISO 140/9 the dimensions of the test facility specified as 4,5 ± 0,5 m of width and 2,8 ± 0,2 m of height from the ground to the underside of the suspended ceiling. Also, the volume of each room should be at least 50 m^3 and the volume of the rooms should differ at least 10%. The plenum depth is specified between 650 and 760 mm in the standard. In Rockwool test laboratory it is measured as 580 mm.

Both endwalls and one sidewall of the plenum are lined with suitable sound-absorbing material in accordance with ISO 140/9 and ISO 354. The absorption material was 5 cm thick with density of 80kg/m^3. The top ceiling is gypsum and the other sidewall of the plenum are hard surfaces and have low sound absorption coefficients that are used in ODEON simulation.

The floor is concrete and the walls (except the partition wall) are constructed as painted brick. The top ceiling is made of gypsum panels. In the plenum there are some wooden beams that can effect the sound propagation through the plenum.

The partition wall is extended up till the ceiling tiles. Dividing wall is according to the ISO 140/9 standards. Its sound insulation is at least 10 dB more than the ceilings that are tested.

To obtain a more diffuse sound field in the rooms, 3 diffusers with dimensions of 50cm x 110cm are installed in each room. The reason for this is due to the hard surfaces of such small rooms. Without diffusers the reverberation times are measured much longer because of the sound waves that hit the hard surfaces several times back and forward.

Although, the test facility in Rockwool do not fulfill the requirements perfectly the dimensions are close to the standard and represents the ‘real world’ conditions better than the standard.

Figure 4.2: The ceiling of the laboratory before installing the suspended ceiling

4.1.2. Measurement Equipment

The equipment used in the measurements are:

- The sound level meter is B&K 2260 Investigator.
- Noise Generator B&K 1405 model.
- Loudspeakers' brand is Etronic (the power or impedance is unknown)
- 1/2" B&K microphone.

The equipment used were calibrated before the measurements according to the supplier's spefications.

4.2.Ceiling System and Details

The ceiling tiles used in the measurements can be seen in the table 4.1. The weight mentioned is the density of the mineral wool. In product 3, 6 mm. additional gypsum panel is used at the back of the ceiling tile.

Table 4.1: Materials used in the measurement

PRODUCT	MODULE SIZE (mm)	WEIGHT OF THE MINERAL WOOL (kg/m^3)	THICKNESS (mm)
Product 1 (Alumunium foil at the back side)	600 x 1200	90	50
Product 2 (Alumunium foil at the back side)	600 x 1200	150	30
Product 3 (6 mm gypsum panel at the back side)	600 x 1200	150	20

The absorption values for the product 1, product 3 and for the additional absorption material ($80kg/m^3$ weight) that has been used over the ceiling tiles are given in the table below. These values are used in the ODEON simulation.

Table 4.2: Absorption values used in the ODEON simulation

Product/Frequency	63	125	250	500	1000	2000	4000
Product 1 (Alumunium foil at the back side)	0.45	0.45	0.75	0.85	0.95	0.9	0.8
Product 3 (6 mm gypsum panel at the back side)	0.45	0.22	0.35	0.5	0.7	0.5	0.5
Additional absorption material (80 kg/m^3)	0.11	0.15	0.72	0.9	0.89	0.92	0.91

Details and application method of the ceiling tiles are shown in the figure below.

Figure 4.3: Installation of ceiling tiles and grid system.

4.3. Measurements

4.3.1. Reverberation Time Measurements

4.3.1.1. Reverberation Time Measurements in Rooms**:** In ISO 354, reverberation time which is denoted by T is defined as the time that is required for the sound pressure level to drop 60 dB after the sound source has stopped.

Sound absorbing characteristics of the surfaces are needed to make the connection of the reverberation time of an office, workshop, theatre, etc. with the noise reduction that would be effected by an absorbing treatment. The reverberation time measurements are necessary to determine the sound absorption of the discrete objects and equivalent absorption area of the rooms in this project.

The equivalent absorption area A, in square meters is calculated as using the formula:

$$A=\frac{55,3V}{cT_1} \quad \textbf{(4.1)}$$

Where;

V: Volume of the room in cubic meters
c: Velocity of sound in air, in meters per second
T_1: Reverberation time of the room in seconds

The equivalent absorption area of the each room is obtained from decay curves measured with at least three microphone positions and two speaker positions. The microphone is at least 1 m from room surfaces or diffusers and 1 m from the sound source. Special care was taken for the background noise not to interfere the results.

4.3.1.2. Reverberation Time Measurements in Plenum: In order to get a general idea of the reverberation time and to be able to use and compare the measured data with the ODEON, reverberation time measurements are conducted in the plenum that has a height of 580 mm. The measurements are done with loudspeakers (with subwoofer) and two different microphone positions in the plenum. The measurements are conducted with product 1 which has an aluminum foil back side. So, the surface can be regarded as a reflective surface.

4.3.2. Sound Pressure Level Measurements and Suspended Ceiling Normalized Difference

Laboratory method of measuring the airborne sound insulation of a suspended ceiling with a ceiling space (plenum) of defined height installed above a partition wall (acoustical barrier) that separates the two rooms is specified in ISO 140/9.

This method is used so that it can simulate typical offices, horizontally adjacent rooms or rooms which have a common partition wall, suspended ceiling and plenum space.

In the measurements conducted in the ROCKWOOL laboratories, the dividing wall was extending to the underside of the ceiling system.

The quantity that is measured is called suspended ceiling normalized difference which is denoted by $D_{n,c}$. Although there are other paths that the sound propagates while measuring the airborne sound insulation of suspended ceiling with a plenum, these paths are negligible. Actually, $D_{n,s}$ is defined as normalized level difference for indirect airborne transmission in EN 12354-1 (2000). That includes the sound transmission only through specified path like suspended ceilings ($D_{n,c}$) or ventilation duct, corridors, etc.

$$Dn,c = D - 10 \log \frac{A}{A_0} \quad \textbf{(4.2)}$$

Where;

D: the sound pressure level difference (dB)

A: the equivalent absorption area in the receiving room

A_0: Reference absorption area. (For the laboratory A_0=10 m^2)

Sound pressure level difference which is denoted by D is obtained by measuring the sound pressure levels produced in two rooms by a sound source in one of the rooms.

$$D = L_1 - L_2 \quad \textbf{(4.3)}$$

Where;

L_1: Average sound pressure level in source room

L_2: Average sound pressure level in receiving room

The sound pressure level measurements are carried out for each room in both directions with 2 different speaker and 6 randomly distributed microphone positions. Sound pressure level readings are taken at averaging time of at least 5 seconds for each microphone position. Then, the arithmetic average of the obtained two sound pressure level difference values are taken to get the $D_{n,c}$ values. For each direction of the test, the suspended ceiling normalized difference is measured.

Also, the sound pressure level measurements are conducted by putting a loudspeaker system that generates noise and a microphone system in the plenum The measurements are done with moving the microphone from the source step by step (like 1meter, 2meter……5,7 meter away from the source).

4.3.3 Sound Intensity Measurements

The single way sound reduction values R of the ceiling tiles that is used in the measurements are obtained by using a sound intensity probe and scanning it throughout the ceiling tiles. All these measurements are conducted according to the ISO 15186-1.

One of the most important parts in the test is the installation of the suspended ceiling and joining the ceiling to the top of the partition wall. This has done in accordance with the actual field conditions. The suspended ceiling has been mounted with the recommended practice of the manufacturer.

One-third octave band filters is used throughout the measurements. Special care has been taken for the sound in the source room to be steady and have an uninterrupted spectrum in the frequencies that are measured.

4.4. Measurement Results

4.4.1. R_w Values of the Ceiling Tiles

The R_w, C and C_{tr} values for single way sound reduction for the ceiling tiles are presented at Table 4.3.

Table 4.3: R_w, C and C_{tr} values for the ceiling tiles that are used in the measurements

PRODUCT	R_W (C, C_{tr})
Product 1 **(Alumunium foil at the back side)**	23 (-2.1, -3.9)
Product 2 **(Alumunium foil at the back side)**	25 (-2.3, -2.9)
Product 3 **(6 mm gypsum panel at the back side)**	28 (-0.4, -3.3)

As can be seen from the values the product 3 has the highest sound reduction values among the others because of the high density of the mineral wool (150kg/m^3) that is used and the 6mm gypsum at the back.

4.4.2. Suspended Ceiling Normalized Difference and $D_{nc,w}$ Values

$D_{nc,w}$ values are obtained from the D_{nc} values. That has been explained in the previous sections. Below in the table are given the average values of $D_{nc,w}$ for different situations since the measurements are conducted in both ways in the rooms. The first three of the $D_{nc,w}$ values are obtained from the three different products that have been used in the measurements.

Extra measurements are conducted with product 2 by using band raster in the partition wall and suspended ceiling joint.

For the product 3, the band raster was also installed at the joint of the partition wall and ceiling tiles. The extra measurements are done with putting 80kg/m^3 density 50 mm thick extra absorption over the ceiling tiles in the plenum. First, the extra absorption has been put on the source room (the receiver room had no extra absorption), later the measurements are conducted with extra absorption on both rooms.

Below, the compared results of $D_{nc,w}$ values of the different ceiling tiles and grids can be seen in the figure below. The individual test results for each of the ceiling tiles are given in the appendex.

Table 4.4: $D_{nc, w}$ values for different test products and conditions

TEST SERIES	PRODUCT / Condition	$D_{nc, w}$ (C, C_{tr})
Test 1	Product 1 (Alumunium foil at the back side)	35 (-2.1, -5.7)
Test 2	Product 2 (Alumunium foil at the back side)	39 (-2.3, -6.6)
Test 3	Product 2 / band raster in the partition wall and ceiling tile joint	37 (-1, -5)
Test 4	Product 3 / band raster in the partition wall and ceiling tile joint	43 (-1.4, -6.7)
Test 5	Product 3 / band raster in the partition wall and ceiling tile joint and extra absorption over the ceiling tiles only on the source room)	47 (-1.9, -7.1)
Test 6	Product 3 / band raster in the partition wall and ceiling tile joint and extra absorption over the ceiling tiles on both rooms)	51 (-2, -7.8)

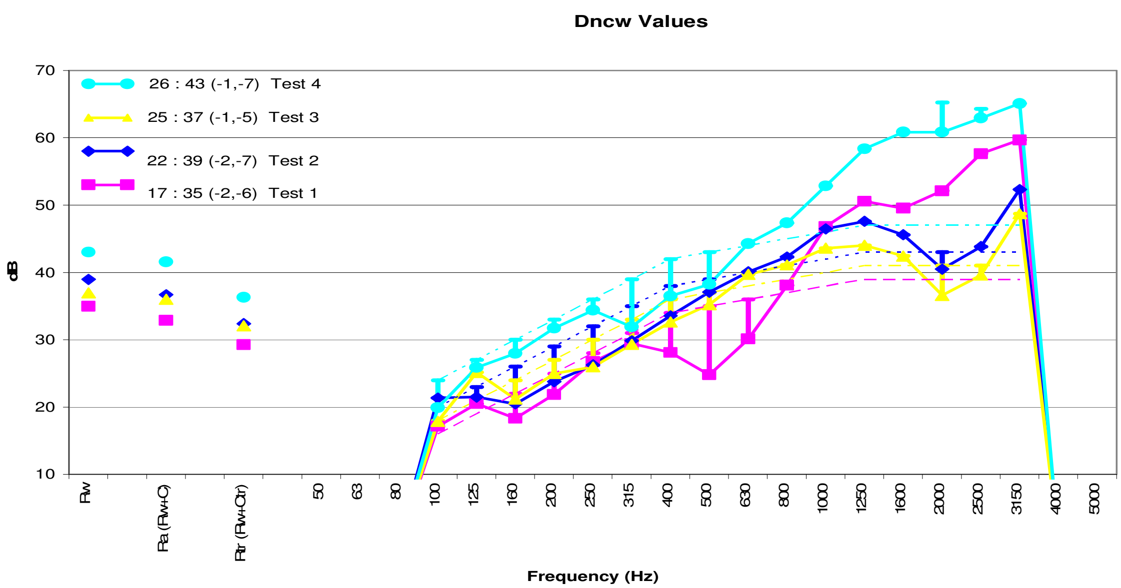

Figure 4.4: Compared $D_{nc, w}$ values for test 1, test 2, test 3 and test 4

The coincidence effect (coincidence dip) in the high frequencies is not at all uncommon in the acoustical performance of the acoustical ceiling materials. It is seen that for the test 1 there is a dip in the 500 Hz. The reason for this might be that the mineral wool inside the ceiling tile is thicker than the other products so, that could effect the performance at that frequency . As expected, as the product 3 with gypsum panel back shows a better performance, especially in the high frequencies although it has lower thickness than the two other materials. But the density of the material is higher than the 1st product and the 6mm gypsum layer provides good sound attenuation. What is interesting in these results is that, although it was expected to give higher $D_{nc,\ w}$ values by using band raster, it can be seen by comparing test 2 and test 3 that actually it is not the case. Surprisingly, the tests conducted with the same ceiling tile without band raster and with band raster (test 2 and test 3 respectively), shows that the $D_{nc,w}$ value for the test 2 is higher than test 3. The difference is especially in the high frequencies. Maybe that might be due to some mechanical vibrations at the junction of the ceiling and partition wall.

And it should be also remembered that workmanship in installing the ceiling tiles effect the sound transmission. The small holes between the ceiling tiles and grid system while mounting the system might also effect the overall transmission loss.

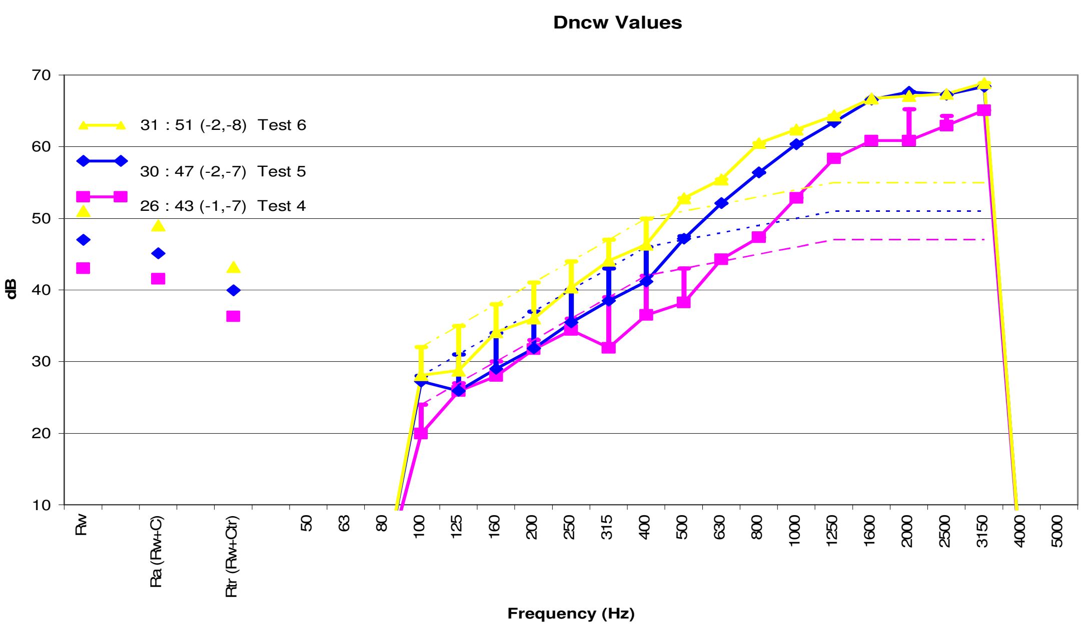

Figure 4.5: Compared $D_{nc,\ w}$ values for test 4, test 5 and test 6

By putting extra absorption over the ceiling tiles on one side increases $D_{nc, w}$ by 4dB where if extra absorption is put on both sides the $D_{nc, w}$ increases by 8dB. It is seen that, the ceiling with high back absorption, the vertical reflections in the plenum has been decreased resulting lower sound transmission values. The lateral reflections in the plenum had already been taken care of by the absorption in the sidewalls of the plenum. Above 1000 Hz, the $D_{nc, w}$ values are improved the same for both situations of the absorption usage in the plenum probably due to acoustical leakage. So it might be said that, the improvement in the absorption characteristics above a point is useless. The leakage through the grid or suspension system should be improved to have more sound reduction through the ceiling.

4.4.3. Reverberation Time Results in the Rooms

For three different ceiling tile products the reverberation time measurements are conducted. The results obtained from each test can be seen in the appendix. The reverberation times obtained for four different situations of the room can be seen in the figures below: With no diffuser, with one, two and three diffusers respectively. The results obtained are very well in accordance with the theory. By increasing the number of diffusers, a more diffuse sound field in the laboratory cubic rooms has been achieved, the peaks over the frequency range between 500-1000 Hz has disappeared. So, all the measurements in the project are conducted with three diffusers in each room.

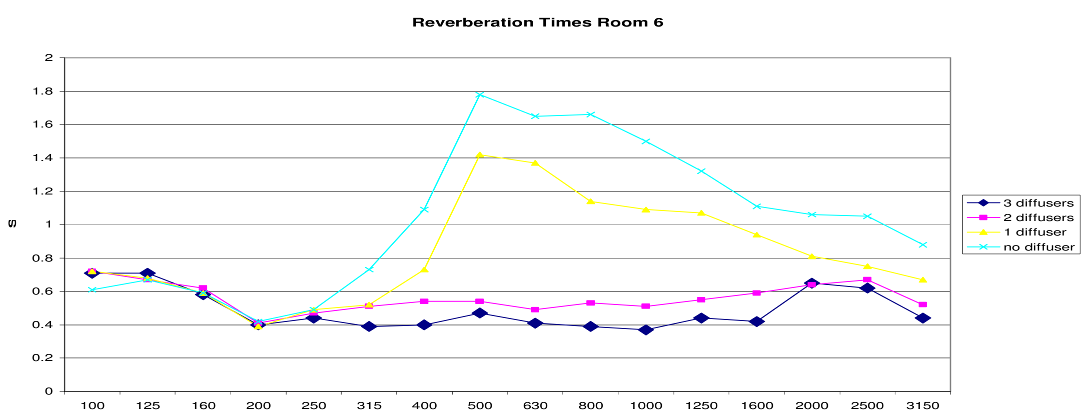

Figure 4.6: Change of reverberation times by using diffusers in room 6

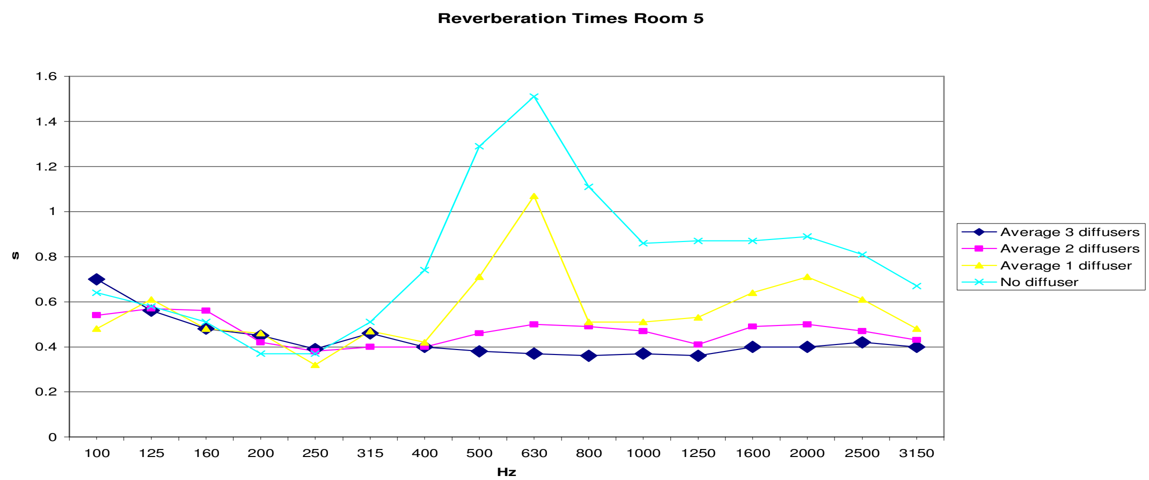

Figure 4.7: Change of reverberation times by using diffusers in room 5

4.4.4. Reverberation Time Results in the Plenum

The reverberation time results obtained from the measurement can be seen in the figure below.

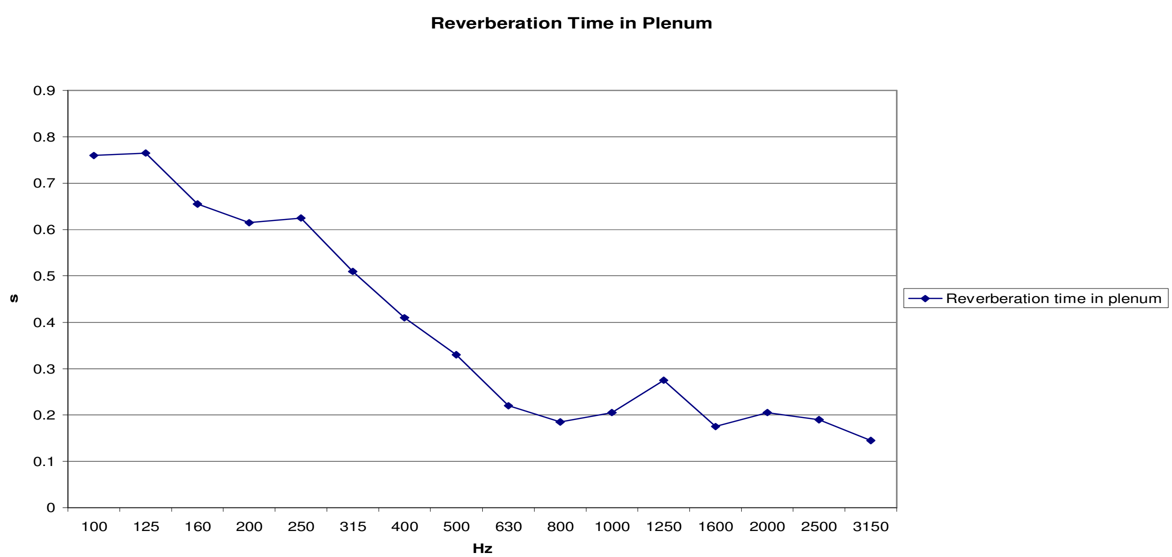

Figure 4.8: Reverberation time in plenum

Above 500 Hz, the reverberation times are quite low probably due to the sound absorption in the sidewalls of the plenum. And also, the dimensions of the plenum are different from regular rooms. That also effects the reverberation time.

The reverberation time measurements are conducted only on one ceiling tile system due to the practical difficulties of installing the microphone and the loudspeaker system. The results are used to compare the values that are obtained from ODEON programme.

4.4.5. Sound Pressure Level Measurement Results in Plenum

Below can be seen the results of the sound pressure level measurements when the microphone is placed 1 m., 2 m., 3 m., 4 m., 5 m., 5.7 m. away from the source. The back of the ceiling tiles were aluminum in these measurements.

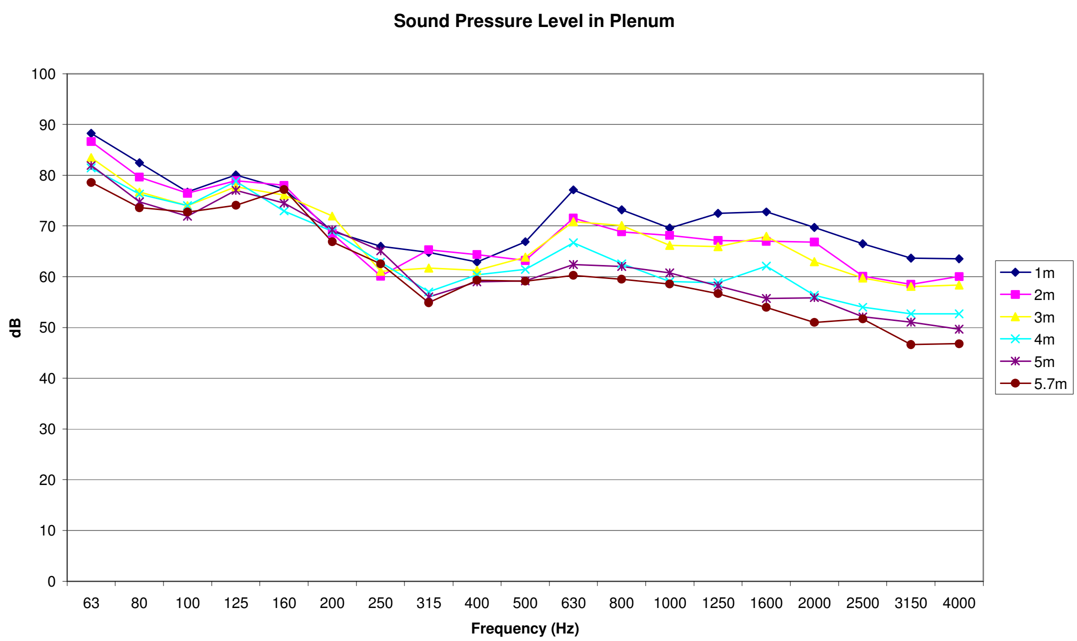

Figure 4.9: Sound pressure level in plenum

As the receiver gets far away from the source, the attenuation of the sound increases. Actually, what is interesting in the results is that, in mid and high frequency range (above 500) the difference between the closest and furthest position of the receiver to the source has a sound pressure level difference of almost 20 dB. The more attenuation in the high frequencies can be explained by the absorption material usage in the 3 sides of the plenum side walls. And, because the plenum has different room dimensions than a regular room, that might also be the reason of this deviation in the mid and high frequencies.

It should be kept in mind that, because of the applicability reasons and the facility conditions, not many measurements in the plenum are taken.

5. COMPUTER SIMULATION

The main purpose of this project is to understand how close can the computer based simulation results get to the measurement results in the rooms. Further, once the measurement and the simulated results are close enough it might be possible to investigate further the sound transmission through suspended ceiling with different room size, different plenum height and with different materials.

Simulations were done with the ODEON version 8.01 which is developed in Denmark Technical University Acoustical Department. It might be good to view some of the acoustical parameters that are dealt with ODEON before making the comparison with the measurements.

In ODEON version 8 two new methods *Reflection Based Scattering* method and *Oblique Lambert method* has been implemented to increase the accuracy of the calculation results and make easier to select more realistic values for scattering properties for the surfaces.

The Oblique Lambert method allows including frequency dependent scattering in late reflections of point response calculation and scattering method automatically takes into account scattering occurring due to geometrical properties such as surface size, path lengths and angle of incidence.

It should be known that, ODEON like other computer programs works by describing the room geometry and assigning the materials and properties like absorption and the scattering for the surfaces. The scattering coefficient based on diffraction is based on:

- Scattering coefficient provided for the surface - specifying the roughness of the surface

- Incident path length
- Reflected path length
- Dimensions of the surface
- Distance from reflection point to edge of the surface
- Angle of incidence

The rougher the surface, the more the scattering coefficients will be. Assigned values for smooth surfaces are between values of 0.02-0,1 where for the rough surfaces these values can take the value up to 0,7.

List of recommended scattering coefficients for ODEON are given in the table below.

Table 5.1: Recommended scattering coefficients.(Rindel *et al.,* 2006)

Material	Scattering coefficient at middle frequency
Audience area	0.6 - 0.7
Rough building structures, 0.3 – 0.5 deep	0.4 – 0.5
Bookshelf, with some books	0.3
Brickwork with open joints	0.1 – 0.2
Brickwok, filled joints but not plastered	0.05 – 0.1
Smooth surfaces, general	0.02 – 0.05
Smooth painted concrete	0.005 – 0.02

5.1. Simulation Method

The laboratory rooms with dimensions of 4680mm x 4160mm x 2250mm and 4160mm x 4160mm x 2250mm with a plenum height of 580 mm and a dividing wall between are modelled in ODEON. The wooden beams which could effect the sound transmission in the plenum are also modelled in the ODEON.

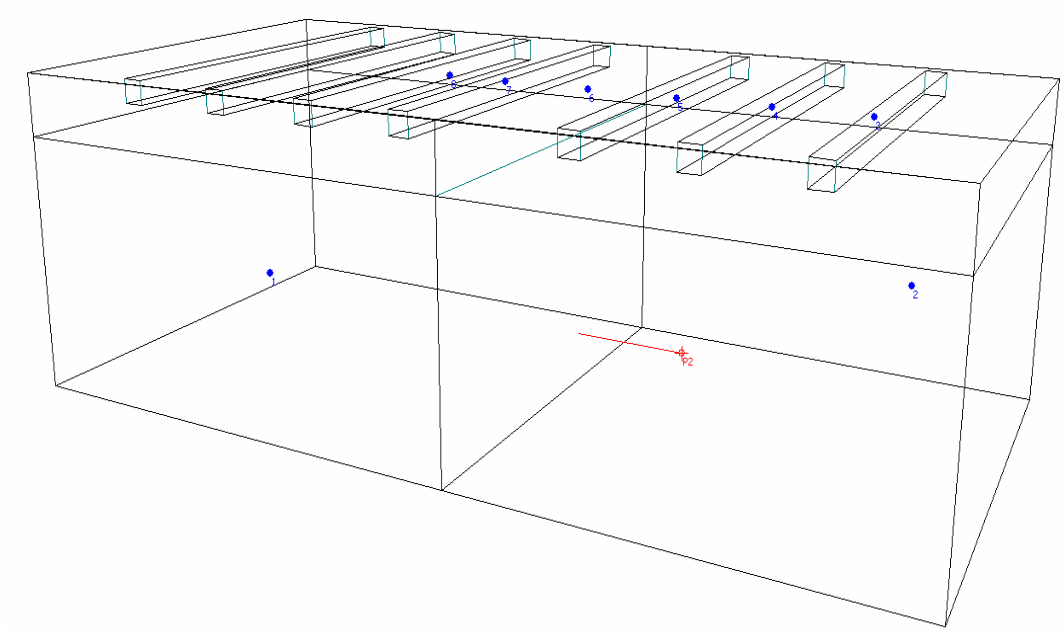

Figure 5.1: ODEON model illustration

With ODEON, it is possible to make the simulation of the transmission loss from one room to the other which is divided by a partition wall. The necessary data for this is the transmission loss in octave bands of the surface that separates the rooms.

The making of the model is explained step by step in the following order:

1. Room model with the dimensions has been prepared.
2. Source and receiver has been defined in the source room. Also, another receiver in the receiving room has been positioned.
3. For each room the surface (the ceiling in that case) through which the sound transmission has been simulated is given a transparency[1] τ=0,1
4. Engineering calculation method is used. The number of the rays has been set to one million to get sufficient number of rays to be transmitted to the plenum and receiver room.
5. The overall gain of the sound source in the source room has been set to 85 dB which is a good estimate for the measurement results.

---

[1] The reason why the transparency has been given is that the sound rays that are incident on the surface are transmitted from the source room to the plenum and to the receiver room.

6. The point response calculation has been done in the source room using the source and receiver in the source room.
7. The same source has been copied in the same position in the source room to define a second source. But, this time the overall gain of the source has been set to 20 dB higher because of the two way transmission (source room to plenum, plenum to receiver room).
8. One way sound reduction values of the ceiling tiles obtained from the sound intensity measurements are entered as negative values in each octave band[2] from 63 Hz to 8000 Hz.
9. The ceiling tiles whose absorption coefficients are known has been assigned to the ceiling surfaces.
10. The point response has been calculated using the second source and receiver in the receiving room.

It should be mentioned that the first models were done according to the steps above. But since the method described above requires that the absorption properties on both sides of the transmitting surface should be identical, the results obtained from the simulation were not very well accordance with the measured ones. It is known that, the ceiling tiles have different absorption properties since the two sides of the materials are different. For example, in one condition, the back side of the ceiling tile is aluminium which is reflective and totally different absorption values when compared to the front side. Because of this, it was decided to put the absorption values of the front side that faces the room, to the floor of the room and the absorption values of the back side that faces to the plenum, to the top ceiling. So, the absorption of the material was distributed to the floor and top ceiling. Of course, not all the materials' absorption coefficients were known. One of the reasons of the placing extra absorption material is the known values of the absorption of that material. Consequently, with the known values of the absorption material it was easy to distribute the absorption to the floor and to the top ceiling.

[2] Since the sound reduction values are measured between 100Hz and 4000 Hz, the sound reduction values for 63 Hz and 8000 Hz has been guessed. The value for 63 Hz has been set to equal or less than the value for 100 Hz that has been measured and the value for 8000 Hz has been set to equal or more than the measured value for 4000 Hz.

Furthermore, since the sound reduction is in two ways (room to plenum, plenum to room), the sound reduction values should have been multiplied by two before entering the values. But that was not the case. According to practice and some measurements from external acousticians, it was founded that the $R_w \leq 1.7\ D_{nc,\ w}$. The sound reduction values are multiplied by 1.5 in these simulations.

Since the measurements were conducted with the diffusers in the rooms, to simulate that condition the scattering values are given high values to obtain diffuse sound field.

Also, the measurements in the plenum have been simulated. As stated before because of the practical problems, there were not so many measurements that could set a reference point for the simulation But it was nice to have some measurement results to compare with the simulated results.

5.2. Simulation Results and Comparison with the Measurements

5.2.1. Comparison of Sound Pressure Level and Reverberation Time in Plenum

To understand the sound transmission through suspended ceiling, the behaviour of the plenum should be known. As stated before sound pressure level and reverberation time measurements in the plenum are conducted in the laboratory. Firstly, the plenum model was prepared and calculated as close as possible to the measured results. After the plenum calculations somehow get close to the measured values it is easy to construct the rooms on that basis of simulation of the plenum.

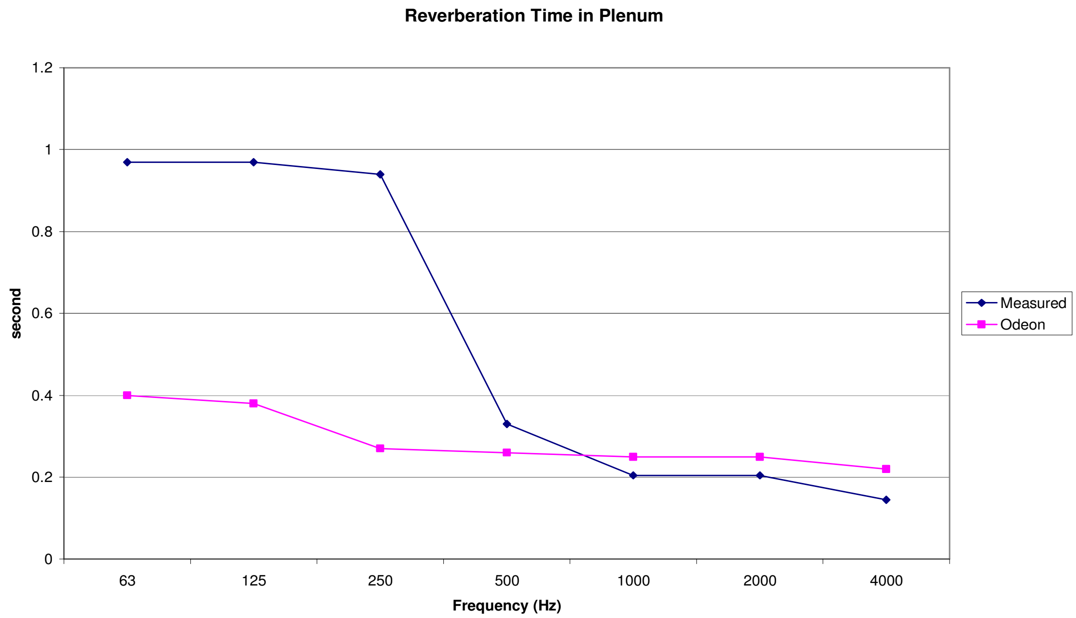

Figure 5.2: Reverberation time comparison in Plenum

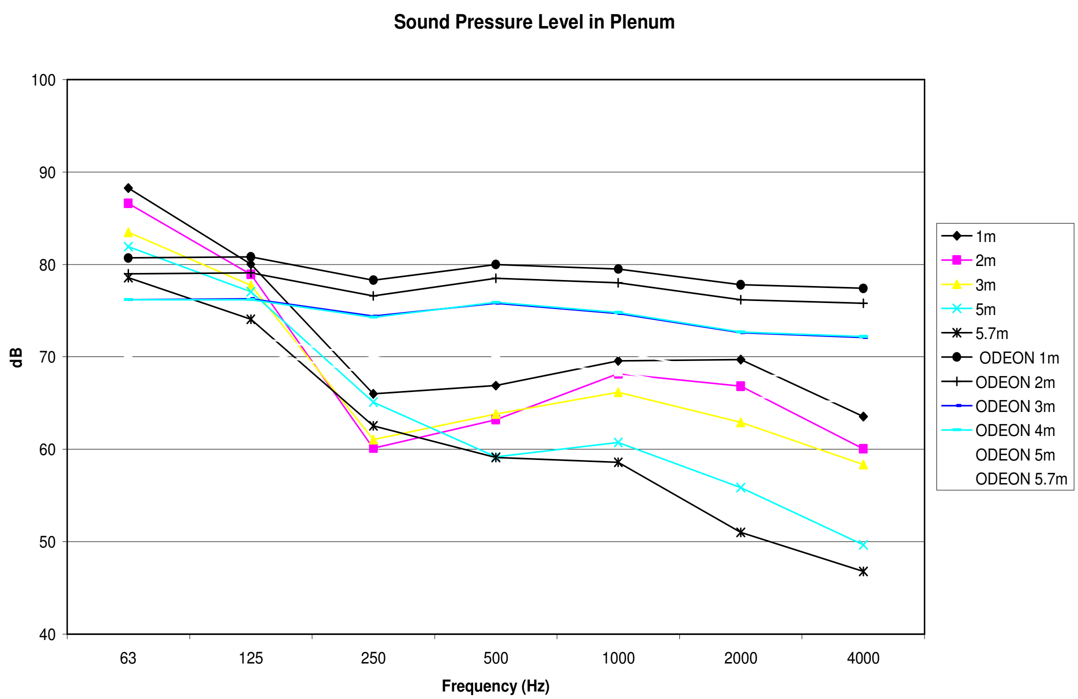

Figure 5.3: Sound Pressure level comparison in Plenum

The reverberation time simulation in the plenum was conducted though the back absorption of the product 1 was unknown. Since, it was aluminium foil was covered on that surface of the ceiling tiles, the absorption values were given low values. The results are in good agreement above 500 Hz. Below 500Hz. the reverberation time for measured values are around 1 second which is quite higher than the results obtained from the simulation.

The sound pressure levels in the plenum are simulated. The results do not show so much deviation as the distance from the source gets far like in the measurements. That might be because there were not so many measurement results to compare or the difficulty in simulating the plenum like putting the backside absorption of the ceiling tiles to the top ceiling. The ODEON was not very successful at simulating the sound pressure levels in the plenum at that matter.

5.2.2. Comparison of Sound Pressure Level, Reverberation Time and Suspended Ceiling Normalized Difference

Here, the measured and simulated (calculated) values of test 6 will be presented. The simulation was conducted for two ways of sound propagation (from room 5 to room 6 and from room 6 to room 5). The results presented here is the case for sound transmission from room 5 to room 6.

Because the measurement values for the D_{nc} values are between 100Hz and 3150 Hz, the 63 Hz and 4000 Hz in the ODEON calculation has been extrapolated .

Also, it should be mentioned that, the absorption values for the products used in the measurements are taken from the manufacturer's catalogue. Some of the absorption values for the ceiling tiles were measured for different plenum height other than 580 mm. So, one of the reasons why there were some deviations between the measured and the simulated results may be due to this. Additional measurements for the ceiling tile absorption could not be conducted due to the unavailable testing facility.

5.2.2.1. Simulation of Test 1 :

Table 5.2: Simulated and Measured values for Test 1

Frequency (Hz)	63	125	250	500	1000	2000	4000
L_1 (Measured Room 5)	71.4	86.7	82.6	77.4	78	75.2	79.3
L_2 (Measured Room 6)	55.9	62.7	51.7	50.37	27.26	21.35	11.77
T (Measured room 6)	0.71	0.71	0.44	0.47	0.37	0.65	0.44
L_1 (Simulated)	83.6	83.7	81.1	79.1	77.7	79.1	80
L_2 (Simulated)	68.4	65.9	50.6	50.5	34	29.1	29.1
T (Simulated room 6)	0.48	0.58	0.45	0.43	0.37	0.39	0.38
D_{nc} (Measured)	17.4	24.4	28.7	25.2	47.9	53.5	61.3
D_{nc} (Calculated)	13.4	28.4	28.3	26.7	40.7	49.5	48.0
Deviation	4	-4	0.4	-1.5	7.2	4	13.3

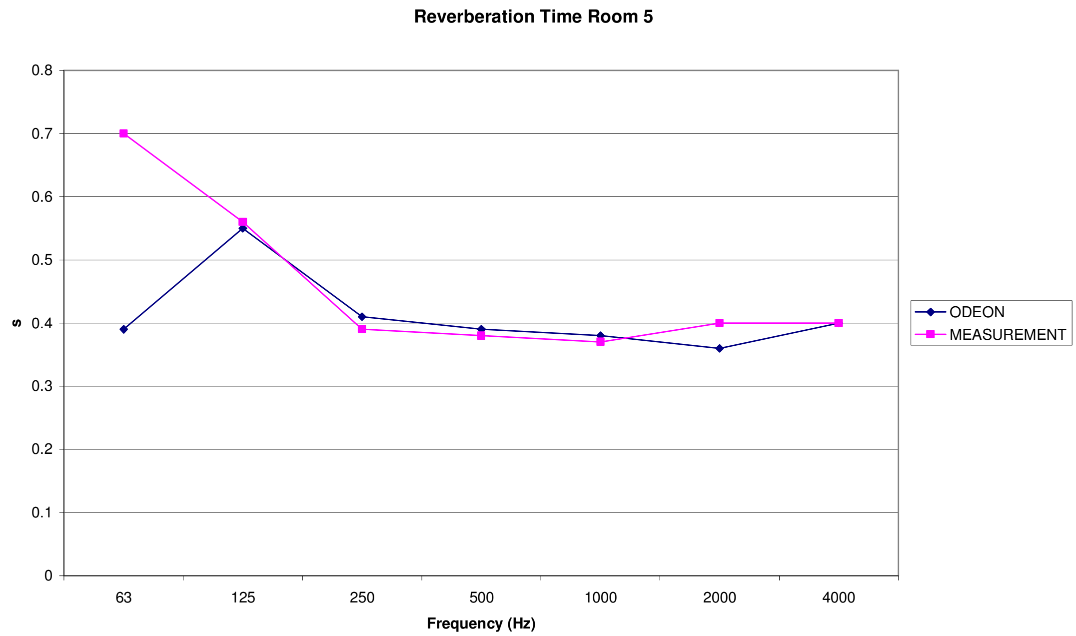

Figure 5.4: Reverberation times in room 5 for the ODEON simulation and measurements for test 1

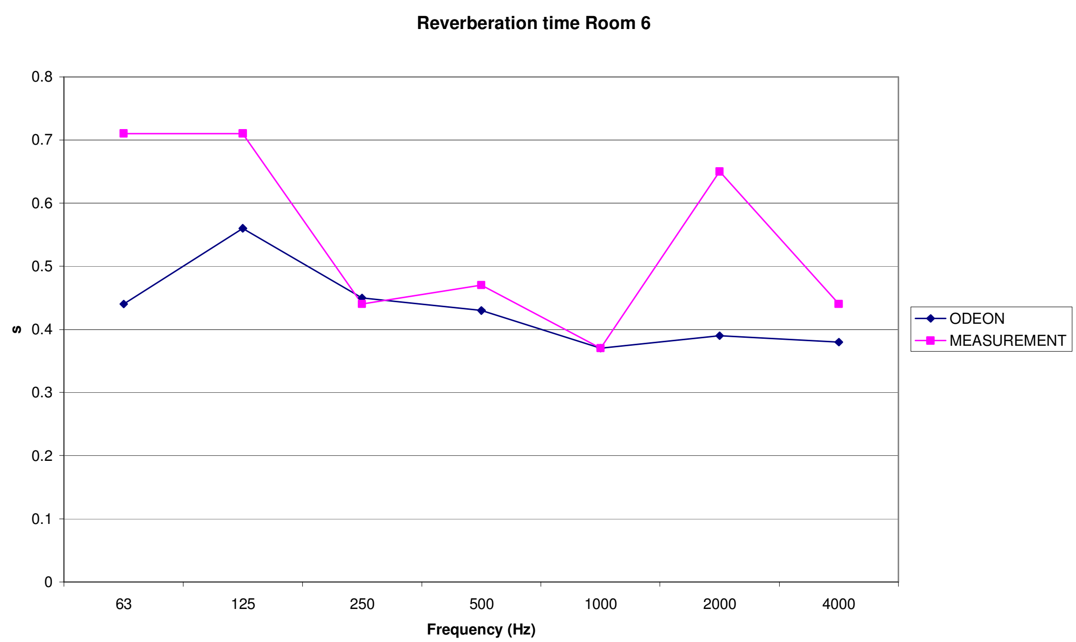

Figure 5.5: Reverberation times in room 6 for the ODEON simulation and measurements for test 1

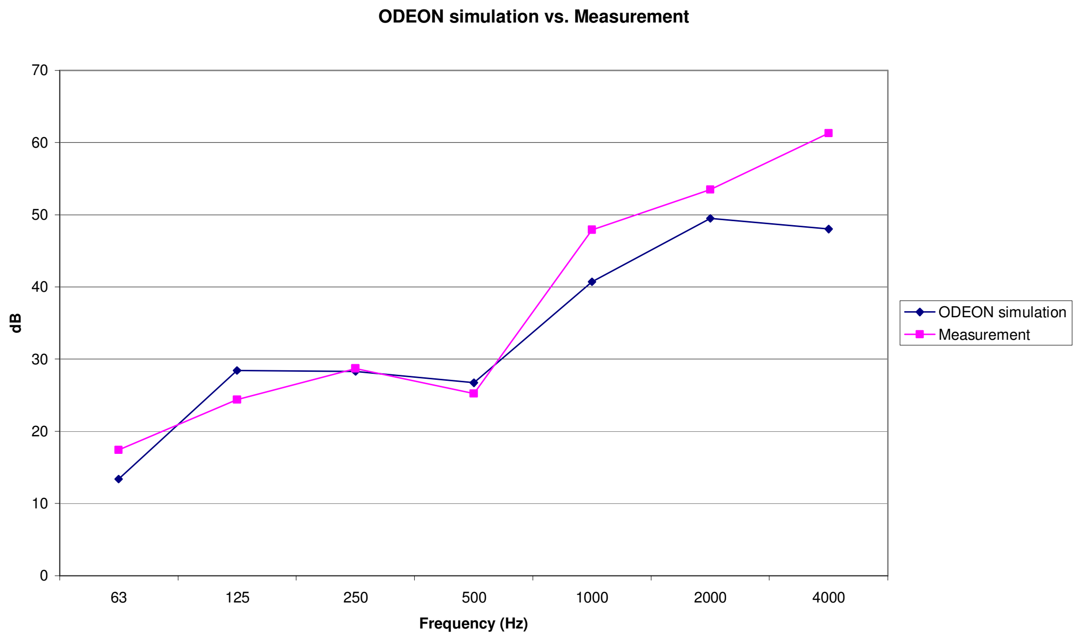

Figure 5.6: D_{nc} values for the ODEON simulation and measurements for test 1.

The reverberation times that ODEON estimates for test 1 is in quite good agreement with the measured values especially in room 5. In room 6 there is a peak at 2000 Hz. This peak might have occurred because of a measurement fault. So, it can be said that the ODEON simulatiıon is quite reliable in the reverberation time estimates.

The simulated D_{nc} values are in good agreement with the measurement except the high frequencies. Of course that should have many reasons that for example due to the lack information of the absorption values for the both sides of the ceiling tiles. In the test 1 the back absorption of the ceiling tiles were not known so, the values were assumed. That might have effected the results.

5.2.2.2. Simulation of Test 6

Table 5.3: Simulated and Measured values for Test 6

Frequency (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**
L_1 (Measured room 5)	65.2	73.2	78.8	82.2	80.2	77.1	78.4
L_2 (Measured room 6)	43	43.7	39.8	29.3	16.8	11.7	9.8
T (Measured room 5)	0.97	0.86	0.73	0.74	0.55	0.74	0.63
L_1 (Simulated)	77.3	80.2	80.2	79	77.7	78.8	78.4
L_2 (Simulated)	48.9	56.8	40.1	31	16.8	1.1	-16.8
T (Simulated room 5)	0.76	0.72	0.73	0.56	0.44	0.56	0.5
D_{nc} (Measured)	28.1	28.8	40.3	52.8	62.4	67.1	68.8
D_{nc} (Calculated)	23	23.7	40.6	47.4	59.2	77	94
Deviation	5.1	5.1	-0.3	5.4	3.2	-10.1	-26.8

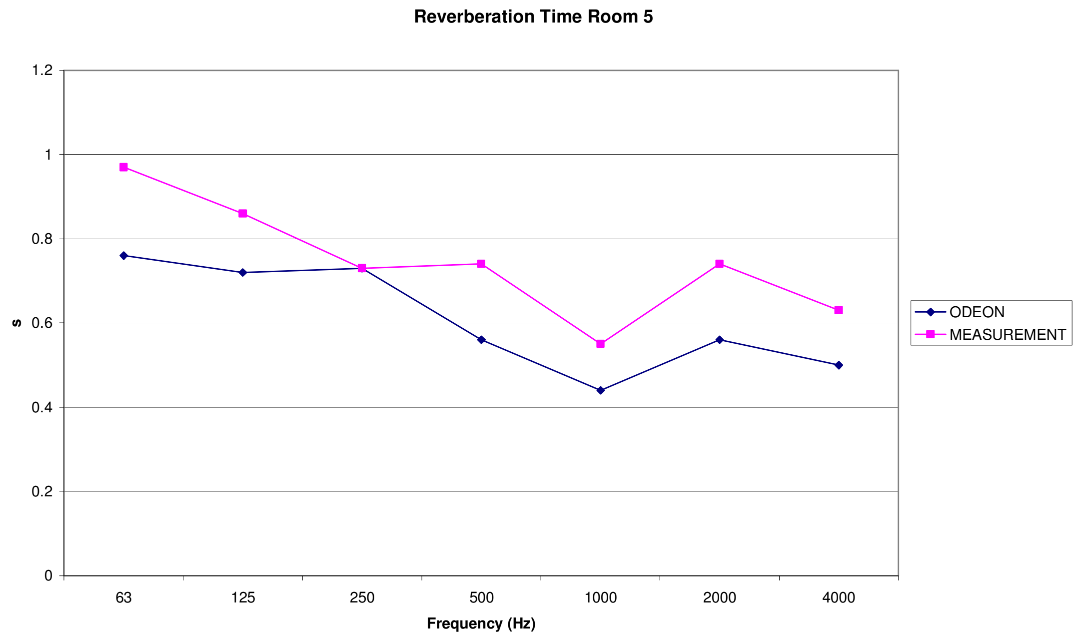

Figure 5.7: Reverberation times in room 5 for the ODEON simulation and measurements for test 6

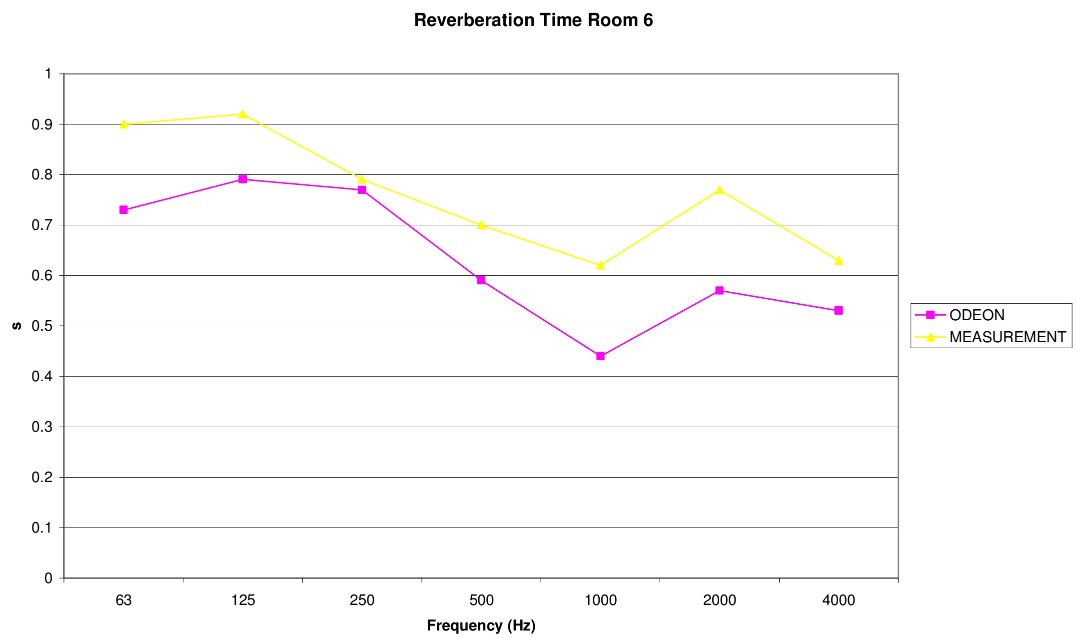

Figure 5.8: Reverberation times in room 6 for the ODEON simulation and measurements for test 6

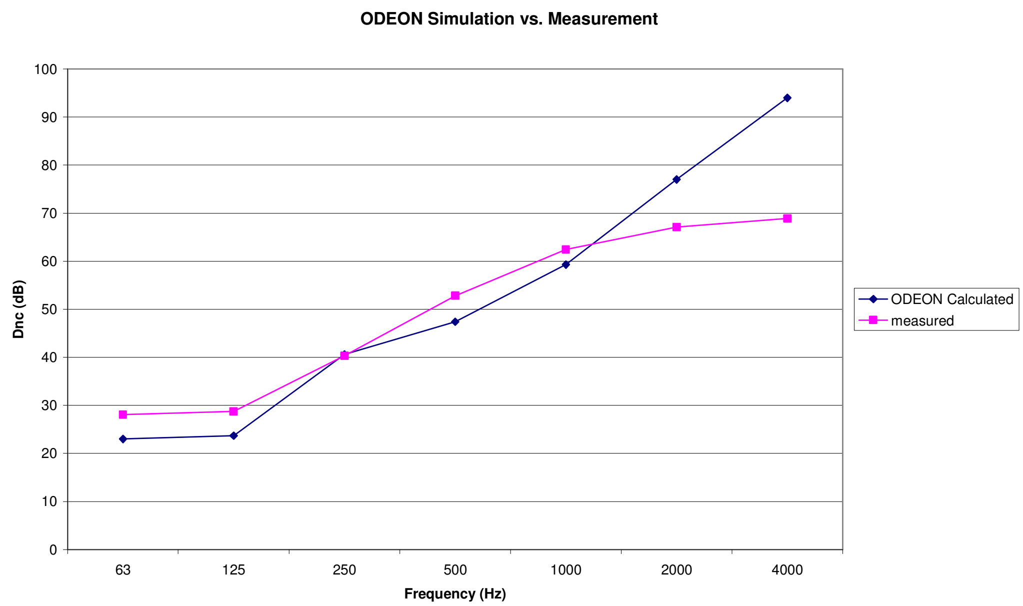

Figure 5.9: D_{nc} values for the ODEON simulation and measurements for test 6

Although, there are some small differences, the reverberation times are in quite well accordance in both rooms with the ODEON simulation as can be seen in the Figure 5.7 and Figure 5.8.

It is seen that till 2000 Hz the D_{nc} values are in almost good accordance with the measurements. Although, the back absorption properties are known because of the additional absorption material that has been put over the ceiling tiles, above 2000 Hz, the results deviate too much, especially at 4000 Hz the deviation is up to 27 dB which is way off the measured value. It is probably that, it is up to one point that the sound insulation is made by the ceiling tiles, after that there are other transmission paths that should be taken into account like flanking transmission or transmission through the wall or leakage through the grid system. So, ODEON does not take into account these transmissions at high frequencies. This could be why the values deviate much at high frequencies.

5.2.3. Simulation with Different Size Rooms and Variable Plenum Heights

In this study, also, two different sized rooms with 250 mm. and 1000 mm. plenum height have been simulated in ODEON. The same materials have been used in this simulation as the test 6. The illustration of the rooms can be seen in the Figures 5.10 and 5.11. The big room simulated has dimensions of 15m. x 6m. x 2.5 m. and the size of the small room is 5m. x 3m. x 2.5m. The simulation of sound transmission has been conducted from small room to big room. Usually, in real conditions these values of the room sizes are used in offices that share a common plenum.

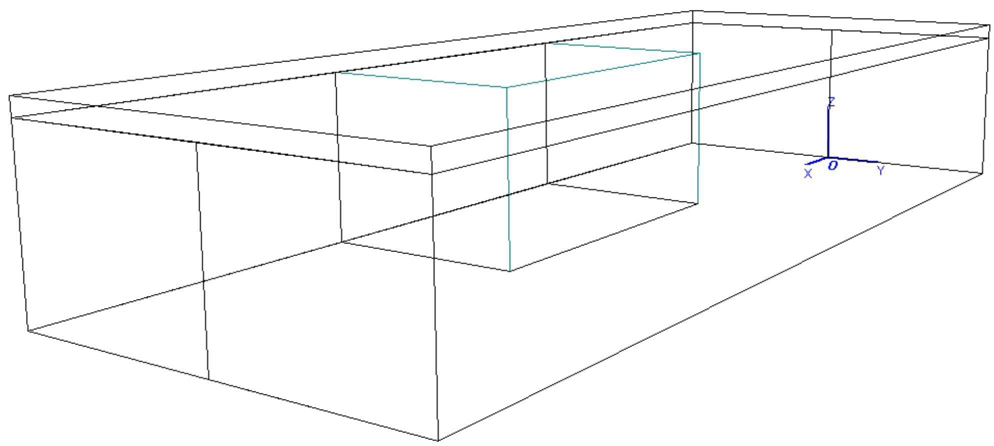

Figure 5.10: Illustration of simulation with plenum height of 250 mm.

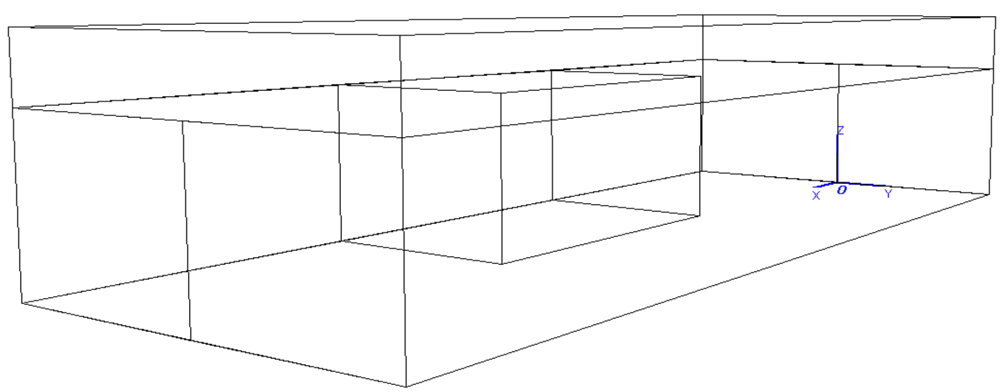

Figure 5.11: Illustration of simulation with plenum height of 1000mm.

The simulation has been made exactly the same as explained before. The absorption of the ceiling tiles has been shared between the floor and the top ceiling. The walls are hard surfaces.The three sides of the plenum has been simulated with absorption material.

The reverberation times of the rooms are different as can be seen in the table 5.4.

Table 5.4: Reverberation times for the rooms

Condition/Frequency	63	125	250	500	1000	2000	4000
Small room **5m. x 3m. x 2.5m.**	0.35	0.43	0.75	0.75	0.72	0.76	0.7
Big room **15m. x 6m. x 2.5 m**	0.96	1.2	1.24	1	1.02	1	0.95

Table 5.5: $D_{nc,\,w}$ values for 250mm and 1000mm plenum heights

Condition	$D_{nc,w}$ (C, C_{tr})
250 mm Plenum Height	43 (-3.7, -9.9)
1000 mm Plenum Height	38 (-2.3, -8,2)

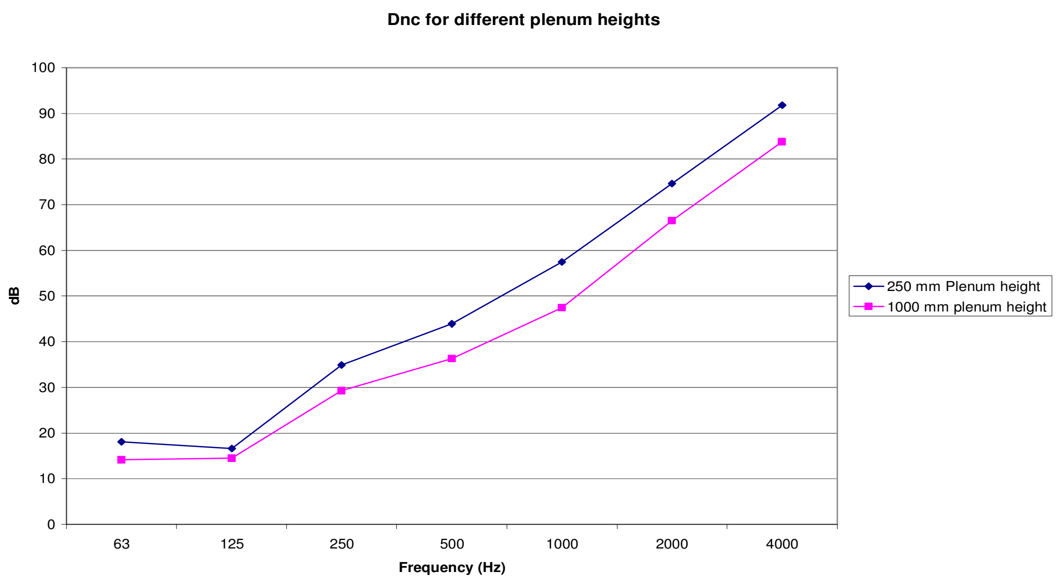

Figure 5.12: D_{nc} values for 250mm and 1000mm plenum heights

So, although, there are some known flaws at high frequencies from the laboratory measurement simulations, the ODEON simulation here is used for investigating the ‘real world’ conditions with different plenum heights. As the plenum height is reduced the $D_{nc,w}$ value obtained increased by 5 dB. Of course, the values at 4000 Hz. and 2000 Hz. seem quite unrealistic when compared with the laboratory measurement, but still the curves are in well agreement with the laboratory measurements except the high frequencies because of the fact that ODEON is not taking into account the other transmission paths in the simulation at that frequencies (like from the wall or from the floor).

6. CONCLUSIONS

In this study, several series of laboratory tests of room to room sound transmission via suspended ceiling are conducted in order to investigate the performance of different suspended ceiling systems. The results obtained from the measurements are compared with the results obtained from ODEON acoustics computer programme. Also, the effect of the depth of the plenum and different room sizes are investigated by simulating the rooms and plenum in ODEON.

On basis of the results it can be said that:

From theory and from the computer simulation it is seen that, as the depth of the plenum reduces more increase in the sound transmission loss is obtained. The usage of the absorption in the plenum also increases the transmission loss up to a point. In this study up to 8 dB increase in the sound transmission loss has been investigated. There is a limit in the insulation of the sound transmission through the ceiling. After this limit, the acoustical performance of the ceiling tiles make no difference at all. So, other transmission paths (flanking, through the wall, through the floor, through the grid system) should be improved.

The ODEON model shows good agreement with the measurements except the high frequencies due to the fact that ODEON does not take into account the other transmission paths like flanking, etc. Also, not so much information were known about the absorption of the ceiling tiles. Once, more information about the absorption properties the ceiling system is known, even closer results with the measurements can be obtained.

Because the plenum has different dimensions than a regular room, the acoustical properties of the plenum are investigated. Some measurement results in the plenum are not in good agreement with the ODEON results maybe because of the number of the measurements or the measurement technique. More measurements should be taken in the plenum with absorption and without absorption to make the comparison both in the measurements and ODEON model.

In the end it can be said that, although, the ODEON model does not give precise results in room to room sound transmission through suspended ceilings, the results obtained can be used as a powerful tool to give a general idea about the sound transmission via suspended ceilings.

APPENDIX : GRAPHS AND TABLES OBTAINED FROM THE TESTS

The reverberation time and sound pressure level measurements are represented in the appendix.

Table A.1: Reverberation time measurements for test 1

Room 6			Room 5	
Hz	Avg (Hz)		Hz	Avg (second)
100	0.71		100	0.7
125	0.71		125	0.56
160	0.58		160	0.48
200	0.4		200	0.45
250	0.44		250	0.39
315	0.39		315	0.46
400	0.4		400	0.4
500	0.47		500	0.38
630	0.41		630	0.37
800	0.39		800	0.36
1000	0.37		1000	0.37
1250	0.44		1250	0.36
1600	0.42		1600	0.4
2000	0.65		2000	0.4
2500	0.62		2500	0.42
3150	0.44		3150	0.4

Table A.2: Reverberation time measurements for test 2 and test 3

Room 6			Room 5	
Hz	Avg (second)		Hz	Avg (second)
100	0.84		100	0.79
125	0.99		125	0.83
160	0.82		160	0.79
200	0.57		200	0.73
250	0.52		250	0.53
315	0.45		315	0.55
400	0.42		400	0.43
500	0.38		500	0.43
630	0.42		630	0.44
800	0.37		800	0.38
1000	0.41		1000	0.34
1250	0.39		1250	0.34
1600	0.44		1600	0.38
2000	0.55		2000	0.4
2500	0.61		2500	0.45
3150	0.42		3150	0.39

Table A.3: Reverberation time measurements for test 4, test 5 and test 6

Room 6			**Room 5**	
Hz	Avg (second)		Hz	Avg (second)
100	0.9		100	0.97
125	0.92		125	0.86
160	0.99		160	1.01
200	0.85		200	0.8
250	0.79		250	0.73
315	0.85		315	0.75
400	0.73		400	0.7
500	0.7		500	0.74
630	0.65		630	0.64
800	0.64		800	0.63
1000	0.62		1000	0.55
1250	0.68		1250	0.58
1600	0.72		1600	0.66
2000	0.77		2000	0.74
2500	0.73		2500	0.7
3150	0.63		3150	0.63

Table A.4: SPL measurements for product 1 Room 5 to Room 6

Room 5 (Source Room)				
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	68.36	67.28	72.39	75.49
80	80.79	79.07	78.69	73.06
100	77.93	80.59	78.99	71.94
125	84.73	86.35	88.97	87.33
160	85.21	82.6	82.69	85.32
200	79.96	78.22	84.42	78.07
250	81.75	83.14	83.1	81.69
315	77.75	80.7	78.3	75.66
400	78.47	77.9	78.72	76.37
500	78.01	77.11	78.9	75.77
630	75.78	76.61	78.15	74.99
800	74.7	75.65	79.32	75.53
1000	77.89	77.61	80.95	77.16
1250	78.08	79.82	80.25	75.95
1600	75.94	78.21	75.78	74.16
2000	74.91	75.51	79.4	73.6
2500	77.89	78.38	80.25	76.03
3150	81.62	80.67	81.14	79.34
4000	80	79.38	80.95	78.74

Room 6 (Receiver Room)				
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	55.14	59.32	54.05	55.52
80	65.75	66.47	64.64	68.33
100	56.99	62.43	55.75	67.1
125	62.69	66.08	59.36	62.32
160	62.51	61.17	64.79	63.52
200	58.22	57.26	57.06	58.31
250	52.74	51.32	53.72	52.58
315	48.41	45.98	47.54	46.32
400	47.51	45.43	46.32	46.35
500	48.59	50.8	50.49	49.76
630	41.94	42.14	44.88	41.79
800	33.3	34.93	34.2	33.86
1000	28.15	26.69	26.51	27.05
1250	23.78	24	24.4	23.66
1600	23.84	25.46	23.6	23.98
2000	21.67	22.13	21.17	21.69
2500	18.35	19.06	17.04	17.42
3150	17.54	17.19	16.4	16.44
4000	12.48	11.19	11.74	11.32

Table A.5: SPL measurements for product 1 Room 6 to Room 5

Room 6 (Source Room)				
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	65.87	69.97	77.12	76.93
80	77.79	76.44	73.63	80.48
100	78.48	74.22	75.57	71.26
125	77.24	82.83	86.92	82.35
160	79.45	85.37	85.02	88.17
200	83.74	84.35	84.31	84.82
250	84.34	77.32	79.3	79.46
315	79.04	82.39	79.91	79.49
400	75.69	76.68	74.87	77.32
500	77.67	76.46	76.21	77.21
630	74.14	76.67	73.31	75.83
800	74.68	75.27	74.53	71.04
1000	76.76	75.14	77.71	77.15
1250	77.06	75.55	77.15	75.47
1600	75.88	75.27	75.29	74.72
2000	73.94	74.84	74.83	73.05
2500	76.37	78.19	79.55	78.14
3150	76.84	78.47	81.88	79.07
4000	76.73	79.91	78.82	75.32

Room 5 (Receiver Room)				
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	51.35	56.68	53.02	57
80	58.13	58.45	64.55	54.89
100	62.71	59.78	58.43	54.64
125	62.83	69.15	62.83	64.03
160	67.39	63.61	64.17	61.55
200	58.76	57.43	57.27	57.76
250	51.99	52.02	54.43	50.71
315	50.41	48.83	47.46	46.5
400	46.61	46.54	45.17	44.75
500	50.03	49.14	49.96	49.79
630	44.14	42.11	42.86	42.35
800	34.3	36.1	33.22	33.58
1000	29.49	28.35	27.88	27.23
1250	24.85	23.2	25.09	24.72
1600	24.81	23.69	23.2	23.31
2000	21.71	21.75	20.94	22.25
2500	19.2	19.81	19.65	20.33
3150	18.95	17.91	19.41	20.24
4000	13.78	14.24	14.47	15.41

Table A.6: SPL measurements for product 2 Room 5 to room 6

Room 5 (Source Room)						
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	52.89	49.78	57.27	55.19	50.62	51.26
80	67.7	61.12	61.79	71.64	67.86	67.84
100	72.2	69.04	64.09	71.71	70.54	75.63
125	79.38	77.84	78.48	64.89	75.75	72.93
160	68.5	72.06	68.49	66.77	70.05	66.9
200	73.34	73.76	70.83	68.38	69.34	70.82
250	75.42	71.51	75.64	73.43	72.06	73.55
315	72.83	72.88	73.91	71.3	70.67	71.3
400	73.22	72.16	67.86	69.73	70.27	71.59
500	73.15	72.69	72.1	70.3	73.86	74.87
630	71.01	69.64	67.89	67.03	70.22	70.81
800	75.39	70.79	69.94	70.22	73.13	71.72
1000	77.7	75.21	74.88	70.74	72.37	75.17
1250	77.01	74.69	71.23	70.18	71.62	75.17
1600	71.71	71.75	69.97	71.75	71.83	73.01
2000	74.66	71.24	69.71	70.42	70.52	72.25
2500	75.45	75.47	71.33	73.65	71.96	75.35
3150	76.69	80.83	71.15	73.82	74.92	79.75
4000	76.65	76	69.25	74.82	74.62	75.98

Room 6 (Receiver Room)						
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	36.02	31.24	36.29	34.7	33.48	39.66
80	54.26	50.62	50.36	48.27	44.05	49.29
100	54.26	48.06	54.77	50.71	52.12	54.78
125	52.9	49.14	57.51	49.56	51.98	55.37
160	49.55	49.45	51.71	50.78	48.66	47.71
200	48.52	48.36	45.86	51.31	51.03	47.9
250	46.82	45.63	44.25	45.79	47.33	46.97
315	43.16	43.61	40.85	40.93	38.95	39.88
400	34.31	33.21	35.44	34.59	35.29	35.91
500	33.21	33.07	34.02	33.25	32.67	33.49
630	27.2	26.25	26.07	27.73	25.77	26.09
800	22.93	25.99	27.23	26.61	25.72	26.41
1000	24.84	25.91	25.82	25.24	26.25	25.3
1250	21.82	23.39	22.69	23.11	23.55	22.71
1600	24.84	23.15	25.2	25.39	23.19	23.1
2000	29.52	28.73	30.42	30.18	28.6	28.79
2500	29.89	29.54	27.63	29.03	28.22	28.96
3150	20.34	20.92	20.66	20.32	20.06	19.69
4000	13.23	13.19	13.99	13.24	13.6	13.2

Table A.7: SPL measurements for product 2 Room 6 to room 5

Room 6 (Source Room)					
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	51.49	54.43	51.99	47.67	42.94
80	61.72	58.02	66.6	59.18	58.7
100	65.78	76.02	76.33	72.3	76.37
125	68.61	77.97	75.23	72.74	73.53
160	68.16	69.65	70.69	65.85	69.12
200	73.4	72.68	69.94	74.27	68.89
250	72.66	76.56	74.43	74.12	73.38
315	70.84	72.09	74.34	69.73	74.43
400	70.98	70.34	69.61	68.85	68.7
500	71.99	73.7	69.6	70.25	75.59
630	70.22	69.91	69.23	66.8	68.04
800	72.15	71.48	70.7	69.56	67.82
1000	73.03	75.15	72.8	73.69	75.32
1250	72.98	76.56	71.82	72.47	70.47
1600	72.24	73.68	69.9	69.23	70.6
2000	69.56	72.74	69.31	69.01	69.72
2500	71.38	75.33	73.5	72.95	73.4
3150	72.57	79.36	74.73	73.44	73.16
4000	74.3	74.72	70.54	74.75	71.32

Room 5 (Receiver Room)					
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	44.54	39.04	27.65	34.53	44.81
80	38.64	51.28	46.71	43.99	44.67
100	47.82	53.59	49.96	52.9	47.28
125	55.54	55.36	57.37	56.63	56.16
160	48.27	50.73	49.74	49.63	49.9
200	44.06	45.87	45.37	46.95	47.04
250	45.08	46.61	48.97	44.95	48.04
315	39.87	40.57	39.27	41.24	41.5
400	35.48	34.5	35.41	33.95	35.82
500	34.64	33.54	34.08	30.3	31.63
630	27.61	27.39	26.45	27.19	27.3
800	26.59	28.85	26.39	26.98	25.86
1000	25.98	23.99	23.31	25.14	23.76
1250	22.46	22.63	22.05	23.06	21.96
1600	23.62	23.6	21.07	22.77	23.76
2000	27.97	27.07	27.92	27.42	28.23
2500	29.03	28.07	27.68	28.36	28.08
3150	21.86	20.68	21.84	21.05	20.58
4000	15.69	15.12	15.16	16.83	16.06

Table A.8: SPL measurements for product 3 Room 5 to room 6

Room 5 (Source Room)						
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	63.11	60.6	69.34	60.11	66.81	63.42
80	79.86	66.9	80.65	79.65	71.28	81.67
100	80.87	79.75	84.7	78.54	75.33	78.9
125	71.1	79.82	73.23	72.88	72.94	73
160	73.04	72.69	75.2	70.03	70.23	72.02
200	77.75	70.02	78.77	74.23	78.49	77.65
250	80.75	75.79	81.73	80.48	79.99	77.52
315	82.68	78.96	83.12	78.42	81.6	83.08
400	74.64	81.37	77.52	75.03	75.86	75.99
500	82.16	76.31	82.3	79.45	83.26	84.46
630	78.4	81.24	77.42	74.41	77.22	78.6
800	78.39	77.35	77.63	79.66	78.84	80.67
1000	82.37	79.45	80.81	77.12	81.91	81.52
1250	78.04	82.05	79.18	77.48	78.45	78.74
1600	77.02	77.62	78.42	79.29	77.84	77.67
2000	77.54	78.81	78.74	77.92	77.4	77.3
2500	79.53	77.99	80.98	78.65	79.24	79.93
3150	80.52	81.39	81.67	79.76	77.55	79.84
4000	78.75	80.68	79.87	80.19	77.89	78.48

Room 6 (Receiver Room)						
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	49.14	42.25	41.71	37.67	47.21	39.24
80	47.17	47.4	58.81	50.21	49.28	55.35
100	53.18	53.2	53.53	54.95	52.02	51.88
125	51.09	48.77	42.38	48.74	52.01	49.73
160	40.7	40.12	43.53	43.15	43.91	41.37
200	44.96	47.84	47.42	48.23	45.77	45.09
250	40.89	44.59	44.9	47.12	46.39	44.6
315	41.62	42.56	41.81	42.87	43.31	45.95
400	34.53	35.72	34	34.86	35.35	35.1
500	32.92	33.59	32.63	36.85	36.89	33.04
630	24.87	25.35	26.16	24.83	25.79	24.96
800	21.23	19.58	21.85	20.75	22.78	20.65
1000	18.05	17.27	19.52	19.33	18.74	19.54
1250	15.61	15.14	14.91	14.86	15.94	15.38
1600	11.54	12.1	12.47	11.53	12.59	11.4
2000	10.3	12.06	12.41	10.25	11.32	10.1
2500	13.04	13.74	13.4	12.25	13.6	12.44
3150	11.81	12.03	11.44	10.98	12.53	11.71
4000	9.76	9.25	10.12	9.56	12.62	9.61

Table A.9: SPL measurements for product 3 Room 6 to room 5

Room 6 (Source Room)						
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	69.02	57.77	63.69	68.48	67.41	64.87
80	75.73	76.68	77.03	79.44	81.6	79.2
100	78.47	77.96	77.91	81.3	85.54	83.42
125	77.77	77.97	82.39	75.21	81.07	74.44
160	69.35	63.26	66.4	64.99	65.82	65.99
200	77.92	70.7	74.54	71.94	74.41	76.38
250	81.65	79.97	77.05	79.09	79.61	81.76
315	81.23	80.5	81.55	81.54	79.51	78.18
400	76.87	78.03	74.75	77.43	73.86	78.29
500	76.6	77.73	78.53	79.17	77.54	77.48
630	78.15	79.56	76.3	77.64	77.3	75.66
800	77.94	79.37	78.06	78.02	77.6	75.3
1000	79.83	82.51	78.52	80.39	80.39	80.25
1250	78.87	80.64	79.91	78.82	78.4	78.07
1600	80.52	78.56	78.78	79.38	79.38	78.05
2000	80.17	78.18	78.18	78.28	77.21	77.41
2500	80.28	82.26	79.97	80.36	78.52	79.28
3150	83.01	80.68	79.85	82.5	80.38	80.26
4000	78.26	76.8	77.67	77.93	78.62	77.08

Room 5 (Receiver Room)						
Frequency [Hz]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]	LLSmin [dB]
63	46.96	47.27	48.11	43.62	42.2	36.5
80	50.12	51.08	51.76	55.89	55.9	57.12
100	53.43	56.14	55.37	51.74	57.7	59.1
125	56.5	50.59	55.47	49.74	53.24	56.5
160	39.11	40.23	39.81	44.85	42.34	42.14
200	42.22	42.41	41.63	39.93	42.96	42.22
250	43.35	45.64	43.21	44.46	47.06	43.37
315	41.61	41.93	44.72	41.85	43.29	45.14
400	36.33	37.94	36.17	35.11	37.11	35.81
500	29.72	29.8	31.24	34.78	31.14	29.58
630	24.41	25.82	26.2	25.37	26.51	23.43
800	20.64	20.79	22.41	23.62	23.41	20.47
1000	20.97	20.36	19.57	18.93	21.01	19.69
1250	16.69	15.4	13.41	16.39	14.57	15.01
1600	12	12.53	10.17	13.64	11.61	12.32
2000	11	10.84	9.86	11.48	10.25	10.84
2500	11.81	13.11	11.97	13.05	11.56	12.31
3150	12.09	12.83	11.18	12.23	11.41	12.34
4000	10.66	11.82	10.39	11.22	10.41	10.97

The following is the text editor for the ODEON model simulation for the measurements

```
###
Const d 1
Const l 2
Const m 3
Const n 4.6
Const o 5.6
Const p 6.6
Const q 7.6

Pt 1 0 2.170 0
Pt 2 0 -2.170 0
Pt 3 4.230 -2.170 0
Pt 4 4.230 2.170 0
Pt 5 8.910 2.170 0
Pt 6 8.910 -2.170 0
:ceiling points
Pt 11 0 2.170 2.250
Pt 12 0 -2.170 2.250
Pt 13 4.230 -2.170 2.250
Pt 14 4.230 2.170 2.250
Pt 15 8.910 2.170 2.250
Pt 16 8.910 -2.170 2.250
:ceiling above suspended ceiling
Pt 21 0 2.170 2.80
Pt 22 0 -2.170 2.80
Pt 23 4.230 -2.170 2.80
Pt 24 4.230 2.170 2.80
Pt 25 8.910 2.170 2.80
Pt 26 8.910 -2.170 2.80
:wood in the ceiling 20 cm x 20 cm x 4m
Pt 27 d -2 2.8
Pt 28 d+0.2 -2 2.8
Pt 29 d+0.2 2 2.8
Pt 30 d 2 2.8
Pt 31 d 2 2.6
Pt 32 d+0.2 2 2.6
Pt 33 d+0.2 -2 2.6
Pt 34 d -2 2.6

Pt 35 l -2 2.8
Pt 36 l+0.2 -2 2.8
Pt 37 l+0.2 2 2.8
Pt 38 l 2 2.8
Pt 39 l 2 2.6
Pt 40 l+0.2 2 2.6
Pt 41 l+0.2 -2 2.6
Pt 42 l -2 2.6

Pt 43 m -2 2.8
Pt 44 m+0.2 -2 2.8
Pt 45 m+0.2 2 2.8
Pt 46 m 2 2.8
Pt 47 m 2 2.6
Pt 48 m+0.2 2 2.6
Pt 49 m+0.2 -2 2.6
Pt 50 m -2 2.6
Pt 51 n -2 2.8
Pt 52 n+0.2 -2 2.8
Pt 53 n+0.2 2 2.8
Pt 54 n 2 2.8
Pt 55 n 2 2.6
Pt 56 n+0.2 2 2.6
Pt 57 n+0.2 -2 2.6
```

Pt 58 n -2 2.6

Pt 59 o -2 2.8
Pt 60 o+0.2 -2 2.8
Pt 61 o+0.2 2 2.8
Pt 62 o 2 2.8
Pt 63 o 2 2.6
Pt 64 o+0.2 2 2.6
Pt 65 o+0.2 -2 2.6
Pt 66 o -2 2.6

Pt 67 p -2 2.8
Pt 68 p+0.2 -2 2.8
Pt 69 p+0.2 2 2.8
Pt 70 p 2 2.8
Pt 71 p 2 2.6
Pt 72 p+0.2 2 2.6
Pt 73 p+0.2 -2 2.6
Pt 74 p -2 2.6

Pt 75 q -2 2.8
Pt 76 q+0.2 -2 2.8
Pt 77 q+0.2 2 2.8
Pt 78 q 2 2.8
Pt 79 q 2 2.6
Pt 80 q+0.2 2 2.6
Pt 81 q+0.2 -2 2.6
Pt 82 q -2 2.6

Surf 1 floor
1 2 3 4
Surf 2 floor
3 4 5 6
Surf 3 endwall
1 2 12 11
Surf 4 partition
3 4 14 13
Surf 5 endwall
5 6 16 15
Surf 6 sidewall
1 4 14 11
Surf 7 sidewall
2 3 13 12
Surf 8 sidewall
4 5 15 14
Surf 9 sidewall
3 6 16 13
Surf 10 endwall plenum room 5
11 12 22 21
Surf 11 endwall plenum room 6
15 16 26 25
Surf 12 sidewall plenum room 6
14 15 25 24
Surf 13 sidewall plenum room 6
16 13 23 26
Surf 14 sidewall plenum room 5
11 14 24 21
Surf 15 sidewall plenum room 5
12 13 23 22
Surf 16 celing rooom 6
13 14 15 16
Surf 17 ceiling room 5
11 12 13 14
Surf 18 top ceiling
21 22 26 25
Surf 19 wood 1 upsurface
27 28 29 30

Surf 20 wood 1 sidesurface right
31 30 27 34
Surf 21 wood 1 sidesurface left
32 29 28 33
Surf 22 wood 1 bottom
31 32 33 34
Surf 23 wood 2 upsurface
35 36 37 38
Surf 24 wood 2 sidesurface right
39 38 35 42
Surf 25 wood 2 sidesurface left
40 37 36 41
Surf 26 wood 2 bottom
39 40 41 42
Surf 27 wood 3 upsurface
43 44 45 46
Surf 28 wood 3 sidesurface right
47 46 43 50
Surf 29 wood 3 sidesurface left
48 45 44 49
Surf 30 wood 3 bottom
47 48 49 50
Surf 31 wood 4 upsurface
51 52 53 54
Surf 32 wood 4 sidesurface right
55 54 51 58
Surf 33 wood 4 sidesurface left
56 53 52 57
Surf 34 wood 4 bottom
55 56 57 58
Surf 35 wood 5 upsurface
59 60 61 62
Surf 36 wood 5 sidesurface right
63 62 59 66
Surf 37 wood 5 sidesurface left
64 61 60 65
Surf 38 wood 5 bottom
63 64 65 66
Surf 39 wood 6 upsurface
67 68 69 70
Surf 40 wood 6 sidesurface right
71 70 67 74
Surf 41 wood 6 sidesurface left
72 69 68 73
Surf 42 wood 6 bottom
71 72 73 74
Surf 43 wood 7 upsurface
75 76 77 78
Surf 44 wood 7 sidesurface right
79 78 75 82
Surf 45 wood 7 sidesurface left
80 77 76 81
Surf 46 wood 7 bottom
79 80 81 82

###

REFERENCES

DS/ EN 12354-6, 2004, Estimation of acoustic Performance of Buildings from the performance of elements- Part 6: Soud Absorption in Enclosed Spaces.

DS/ ISO 140-9, 1986, Measurement of sound insulation in buildings and of building elements-Part 9: Laboratory measurement of room to room airborne sound insulation of a suspended ceiling with a plenum above it.

DS/ EN ISO 717-1, 1997, Acoustics- Rating of sound insulation in buildings and building elements- Part 1: Airborne sound insulation.

DS/ ISO 354, 1986, Acoustics- Measurement of Sound absorption in a reverbaration room.

DS/ ISO 15186-1, 2000, Acoustics- Measurement of sound insulation in buildings And ofbuilding elements using sound intensity-Part 1:Laboratory measurement

Delany, M. E.& Bazley, E. N., 1970, Acoustical properties of fibrous absorbent materials, Applied Acoustics 3, pp. 105-116.

Fasold, W.& Sonntag, E., 1976, Bauphyikalische Entwurfslehre, 4: Bauakustik, VEB Verlag fürBauwessen, Berlin, DDR.

Hamme, R. N., 1961, "Laboratory Measurements of Sound Transmission through Suspended Ceiling Systems", *The Journal of the Acoustical Society of America,* Vol. 33, No.11., November, pp. 1523-1530.

Halliwell, R. E. and Quirt, J. D., 1991, "Controlling Interoffice Sound Transmission through a Suspended Ceiling", *The Journal of Acoustical Society of America,* Vol. 90, No. 3, September, pp. 1446-1453

Hodgson, M. R., 1994, On measures to increase sound-field diffuseness and the applicability of diffuse-field theory, *The Journal of the Acoustical Society of America*, pp. 3651–3653.

ISO 15712-1, 2005, Building Acoustics- Estimation of acoustic Performance of Buildings from the performance of elements- Part 1: Airborne Sound Insulation between Rooms.

Kutruff, H., 1991, Room Acoustics, Applied Science, New York.

Mariner, T., 1950, Theory of sound transmission through suspended ceilings over partitions, Noise Control 4, pp.13-18.

Mechel, F. P., 2002, *Formulas of Acoustics,* Springer, pp. 504-511

Mechel, F. P., 1995, "Theory of Suspended Ceilings", *Acoustica,* Vol. 81, Issue 6, pp. 491-511.

Rindel, J.H., Christensen, C.L. and Zeng, X., 2006, Practical methods to define scattering coefficients in a room acoustics computer model. *Applied Acoustics 67,* pp. 771-786

Nickel, J., 2006, Room to room sound transmission in an office with suspended ceiling paper.

Rindel, J. H., 2005, Odeon Auralization Paper.

Rindel, J. H., 1982, Sound Absorbers, Architectural Acoustics Course Notes.

Eurima, 2005, Suspended Ceilings, Technical Paper.

ODEON Acoustic Programme Manual.

CV

Born in 23rd of September 1981. After completing primary and high school education in İstanbul, he began studying undergraduate degree in İstanbul Technical University Engineering Faculty Civil Engineering Department in 1999. In 2003 he has graduated from Civil Engineering and at the same year he has been accepted to Boğaziçi University Civil Engineering Msc. Programme and İstanbul Technical University Architecture Department's Environmental Control and Building Technology Msc. Programme. He earned his Civil Engineering Master's degree from Boğaziçi University in 2005. In 2005-2006 he has participated in ERASMUS Exchange programme and studied in Denmark Technical University Acoustics Department for a year. He has finished his master's project in Denmark.