SLOT-PERFORATED PANEL SYSTEM PROPOSAL FOR VARIABLE ACOUSTIC SOLUTIONS

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ABSTRACT

SLOT-PERFORATED PANEL SYSTEM PROPOSAL FOR VARIABLE ACOUSTIC SOLUTIONS

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Performance spaces are often employed for various functions. These functions require different acoustical qualities and conditions of the hosting space needs altering to meet these requirements. There exist solutions in practice for that concern. These methods focus to change the amount of sound absorptive material in the hall rather than changing sound absorption characteristics of the system. Hence, they have drawbacks in terms of adaptability and versatility. As a potential answer to the shortcomings of these solutions, this study focuses on the crossroads between tuning capacity of perforated panels and requirements of flexible variable acoustic solutions. Effects of perforated panel's design parameters on sound absorption capability of the system are studied. Furthermore, a prototype is developed to reveal the possibility of tuning a panel by controlling these parameters. Variations in sound absorption coefficients of the system are determined by impedance tube measurements. Maximum sound absorption coefficients are measured in 250 Hz and 2000 Hz for different panel positions. After the variable slot-perforated panel system is obtained, the system is tested on a case by computer simulations to demonstrate the capability of the proposal as a variable acoustic solution. The amphitheater of METU Faculty of Architecture Building as a small hall accommodating different functions is selected as a case and current acoustical condition of the hall are specified by field measurements. The hall is adapted to concert, musical and conference functions by the help of variable slot-perforated panel proposal.

Keywords: Perforated Panels, Variable Acoustics, Adaptive Volume Resonators, Acoustics of METU Architecture Amphitheatre

ÖZ

DEĞİŞKEN AKUSTİK ÇÖZÜMLER İÇİN ÇİZGİSEL PERFORE PANEL SİSTEMİ ÖNERİSİ

Eşmebaşı, Merve
Yüksek Lisans, Yapı Bilimleri
Tez Danışmanı: Doç. Dr. Ali Murat Tanyer
Ortak Tez Danışmanı: Prof. Dr. Mehmet Çalışkan

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Performans mekanları genellikle çeşitli işlevler için kullanılır. Bu işlevler farklı akustik niteliklere ihtiyaç duyacağı için mekanların buna uyumlandırılması gerekir. Bu amaca yönelik çözümler olsa da, alışılagelmiş uygulamaların (gözenekli ses yutucu malzemeler ve kumaşlar ile tasarlanan dönen paneller, toplanabilir perdeler) uyum ve çok yönlülük bakımından yetersizlikleri vardır. Mevcut değişken akustik çözümler, mekan içindeki ses yutucu malzeme alanını değiştirmeye odaklanırlar. Malzemenin ses yutuculuk performansı ve karakteri sabit kaldığı için farklı frekanslardaki ses yutuculuk performansını değiştirmede yetersiz kalırlar. Yaygın çözümlerin eksikliklerine olası bir cevap olarak, bu araştırma perfore panellerin ayarlanabilme kapasitesi ve salon içi işlev ve seyirci sayısındaki değişime karşılık verebilecek esnek, değişken akustik sistem ihtiyacının kesişimine odaklanmıştır. Bu amaçla perfore panellerin ses yutuculuk karakteristikleri incelenmiştir. Perfore panellerin tasarım parametrelerinin ses yutuculuk karakteri üzerine etkisi çalışılmıştır. Bu parametrelerin kontrolü ile değişken bir çizgisel perfore panel prototipi geliştirilmiştir. Bu prototip yardımıyla değişken perfore panel sistemin inşa edilebilme olasılığı ortaya konmuştur. Sistemin ses yutma katsayısındaki değişimler empedans tüpü ölçümleri ile belirlenmiştir. Farklı panel pozisyonları için maksimum ses yutma katsayıları 250 Hz ve 2000 Hz'de ölçülmüştür. Değişken çizgisel perfore panel sistemi elde edildikten sonra, perfore panel önerisi bir vaka üzerinde bilgisayar benzetimi çalışmaları ile test edilmiştir. Benzetim çalışmalarında vaka olarak farklı fonksiyonlara ev sahipliği yapan ODTÜ Mimarlık Fakültesi Amfi tiyatrosu seçilmiştir. Salonun mevcut akustik koşulları saha ölçümleri ile belirlenmiştir. Değişken çizgisel perfore panel yardımı ile amfinin akustik koşulları konser, müzikal ve konferans fonksiyonlarına uygun şekilde değiştirilmiştir.

Anahtar Kelimeler: Perfore Paneller, Değişken Akustik Çözümler, Adaptif Hacim Rezonatörleri, ODTÜ Mimarlık Amfisi Akustiği

To my family,

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LIST OF ABBREVIATIONS

C(80) Clarity

EDT Early Decay Time

G Strength

ITDG Initial-Time-Delay Gap

LF(80) Lateral Fraction

MDF Medium Density Fiberboard

NRC Noise Reduction Coefficient

PR Perforation Ratio

RT Reverberation Time

SPL(A) A-Weighted Sound (Pressure) Level

SPSS Statistical Package for the Social Science

STI Speech Transmission Index

T(30) Reverberation that twice of time for the first 30dB decay

LIST OF SYMBOLS

A Sabine absorption term

f_H Resonance frequency

S_H Open surface area, m^2

ms Millisecond

S Surface area, m^2

t_{eff} Effective thickness, m

V Volume, m^3

α Sound absorption coefficient

c Speed of sound

λ Wavelength

CHAPTER 1

INTRODUCTION

This research is related to variable acoustic solutions in the field of architectural acoustics. Potentials and capabilities of perforated panels are investigated with the motivation to obtain a variable acoustic system with wider sound absorption capability. The system was applied in a multi-purpose hall to discuss and test its potential as a variable acoustic solution. Sound absorption measurements and room acoustic studies, field measurements and simulations were used to support the discussion. Furthermore, a prototype of the variable perforated panel system was developed to reveal the realization possibility of the proposal. Problem statement with motivation and objectives of this research is shared in this chapter.

1.1. Motivation and Problem Statement

Acoustical conditions of multi-purpose halls must be arranged with variable acoustical solutions for different functions that the hall is charged with. Sound absorber materials used in architectural applications can be grouped as porous absorbers, panel absorbers and resonant absorbers (Long, 2005; Egan, 1988; Everest & Pohlmann, 2009). The problem about the adaptation of a hall for different functions is solved by variable acoustic solutions designed with porous materials. Acoustic open cell foams, curtains, cushions, mineral wools such as fiberglass are typical and common examples of porous materials (Cox and D'antonio, 2009). However, sound absorption performance of porous materials at low frequencies are not effective in comparison with high frequencies. To increase sound absorption performance of these materials for low frequencies, material thickness and distance from the solid wall surfaces need to be increased. In Figure 1.1, sound absorption coefficients of rock wool are presented for two different thicknesses. Decrease in sound absorption at low frequencies can be observed in comparison with the performance of the material at high frequencies.

On the other hand, overuse of porous absorbers causes over absorption of sound at high frequencies while the major room acoustic problems about low frequency standing waves are kept constant (Everest & Pohlmann, 2009). According to Cox et al. (2009), this makes these absorbers inefficient and not particularly useful at low frequencies. Hence, their impact is weak on reverberation times in low frequencies. Porous materials provide sound absorption by the friction forces caused by sound wave and air motion in pores or between fibers and particles. Therefore, sound absorption of these materials is highly dependent on materials' inherent characteristics such as thickness, density, length and distribution of fibers, which are hard to manipulate (Long, 2005).

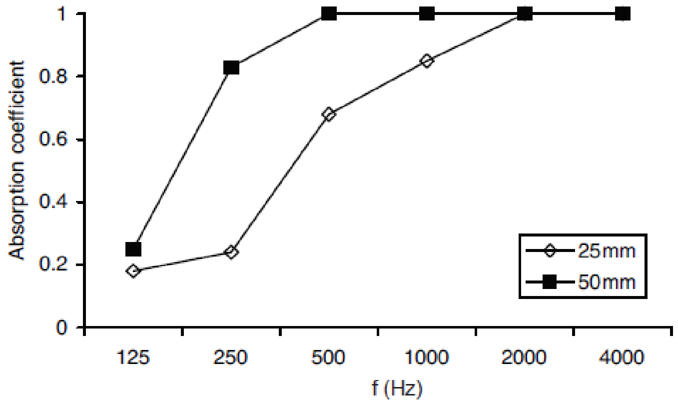


Figure 1.1. Sound absorption coefficients for 25mm and 50mm rock wool with rigid backing (Cox & D'antonio, 2009).

Therefore, variable acoustic solutions usually focused on altering the size of application area that is occupied by these materials rather than their sound absorption coefficients. Some mechanically supported systems like rotatable panels, retractable curtains and sliding facings (Figure 1.2) are designed and applied to provide these alterations (Egan, 1988). Perforated panels also take places in many multi-functional halls. Everest et al. (2009) define perforated panels as a "host of coupled resonators" and classified as a resonant type sound absorber. Hence, if porous absorbers are combined with perforated panels, the combination provides higher sound absorption for low frequencies. Moreover, sound absorption performance of perforated panels can be controlled by design parameters like perforation width, perforation ratio, panel thickness, air gap and backing material.

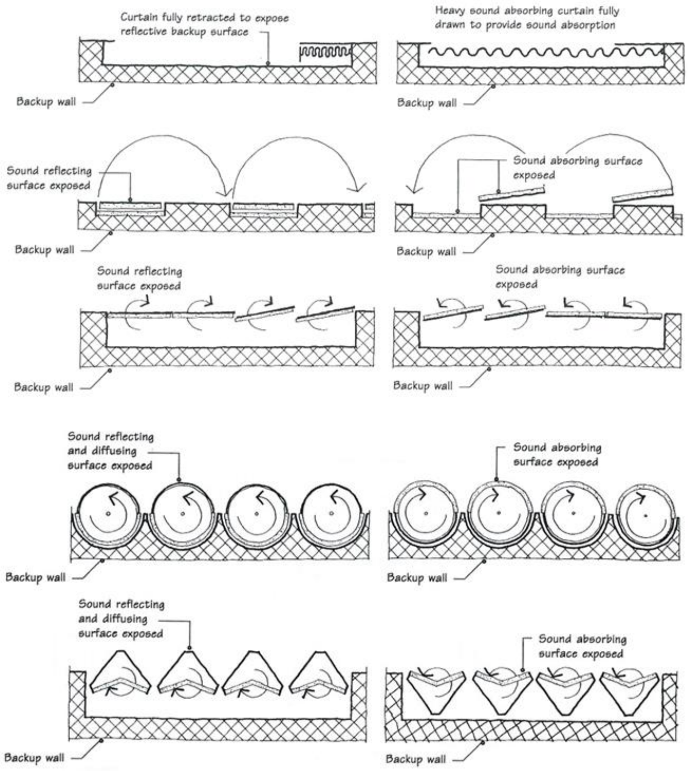


Figure 1.2. Rotatable panels and retractable curtains (Egan, 1988)

Measured sound absorption coefficients for perforated panels with different perforation ratios are presented in Figure 1.3. Perforated panels provide effective sound absorption at mid and low frequencies depending on neck diameter and perforation ratio.

To sum up, solutions including variable perforated panel systems may answer the needs and problems of the current practice considering their versatility. Most frequently encountered sound absorbers used in architectural applications are porous absorbers. Multi-functional halls are adapted to different functions by variable acoustic solutions designed with porous absorbers. However, sound absorption mechanism of these materials depends on inherent features of materials which are not easy to change. Sound absorption coefficients of porous sound absorber materials used in variable acoustic solutions as presented in Figure 1.2 cannot be changed. Primarily, sound absorption mechanism of the porous sound absorber materials used in these solutions causes this shortcoming. For instance, for rock wool as a fibrous material, this mechanism highly depends on inherent features like distribution, density, thickness and length of fibers. The variance provided by these variable acoustic systems depends on the application area rather than sound absorption characteristic of the material. However, it is easy to manipulate design parameters of perforated panels like perforation width, perforation ratio and air gap in comparison with the features of porous absorbers. Hence, by controlling these parameters, it is possible to change the sound absorption characteristics of the perforated panels. Variable sound absorption performance in mid and low frequencies can be obtained with perforated panels, because rather than controlling just application area, sound absorption characteristic of the system can be controlled. Combining expected qualities from variable acoustic systems with perforated panel’s potentials constitutes the main motivation.

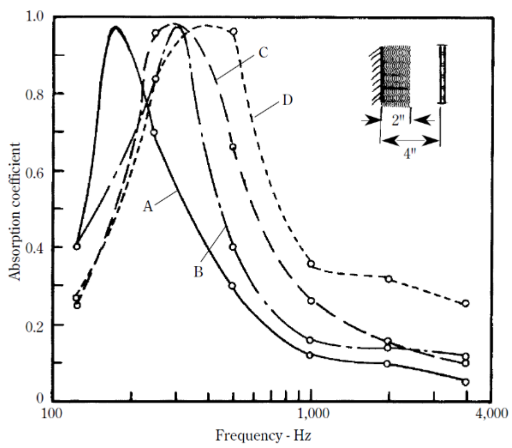


Figure 1.3. Measured sound absorption coefficient of perforated panels with constant air gap and mineral wool behind but different perforation ratios; A: %18. B: %0,79. C: %1,4. D: %8,7. (Everest et al. 2009)

This research proposes a variable perforated panel system for providing variable sound absorption coefficients. Primarily a prototype was designed to reveal construction possibility of an alternating perforated panel system. After that, sound absorption coefficients of perforated panel system for different phases were measured. Finally, after the variable perforated panel proposal is realized, investigation on possible uses of this system as a variable acoustic solution continues within room acoustics studies.

1.2. Aim and Objectives

This research focuses on the potential of perforated panels' sound absorption characteristics as a variable acoustics solution. The capability of perforated panels is investigated to provide a variable acoustic system and to fulfill different acoustical requirements of a multi-purpose hall. Variation in sound absorption performance of the perforated panel was obtained by controlling the design parameters of the perforated panels like the neck diameter, central distance between perforations and perforation ratio. The variable perforated panel proposal was tested on a case, to validate the effectiveness of the perforated panels to provide a variable acoustic solution.

The main aim of this research is to investigate the potential of perforated panels as a variable acoustic solution. In order to achieve this aim, following research objectives can be listed under two major concerns as in the following:

- Assessment of alterations in design parameters of perforated panels in terms of obtaining sufficient variation in sound absorption coefficients.
    - Understanding the effects of perforation size and perforation ratio on sound absorption coefficient of perforated panel system while air gap and porous absorber characteristics are constant.
    - Analyzing sound absorption characteristic of perforated panel proposal for different panel positions and revealing differences in sound absorption coefficients.

- Testing the perforated panel system proposal on a case to assess its competence about creating sufficient variations in room acoustic conditions.
  - Measuring the alterations in reverberation time provided by the help of variable perforated panel system.
  - Evaluating obtained alterations in room acoustic conditions in terms of perforated panel proposal's capability to tune the hall for different functions.

1.3. Methodology

The methodology of this research is summarized with the IDEF0 flowchart below. The research process can be interpreted with four functions. Each box represents a procedure; arrows from left are inputs while arrows to the right are outputs of these functions. Arrows joining to the boxes from below are mechanisms which are means used to perform the function. Then, control mechanisms which are factors that constrain and regulate the process are represented by the arrows above each box.

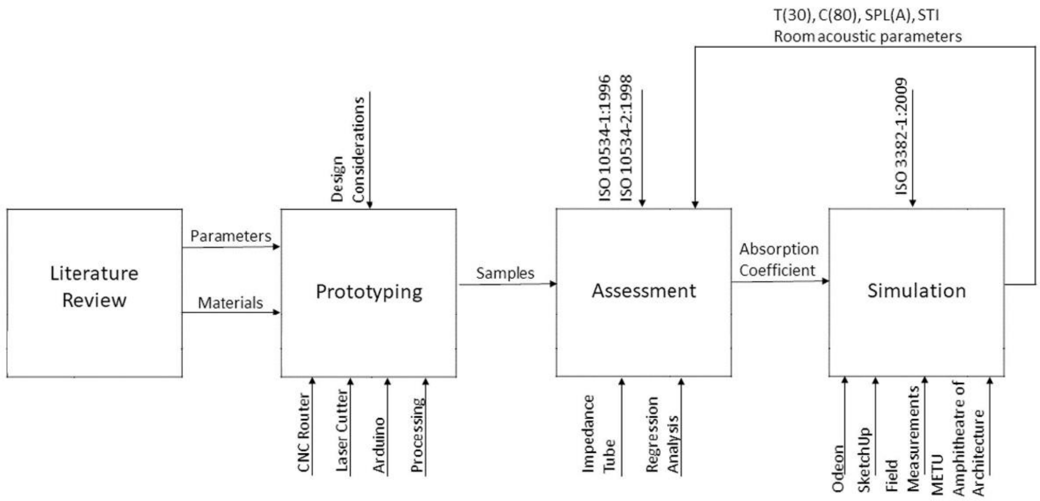


Figure 1.4. IDEF0 flowchart describing the methodology

1.4. Disposition

The study consists of five chapters; first, the motivation of the study and objectives are shared in the introduction chapter. Studies and information on perforated panels and variable acoustics are presented in the second chapter, literature review.

Moreover, collected studies are reviewed and the research gaps have been revealed for further studies.

Afterwards, the variable perforated panel proposal was presented. Furthermore, the realization possibility of the proposal was revealed by a prototype. To test the proposal as a variable acoustic solution the case of METU Architecture Amphitheatre is presented. Materials and examination methods were shared in the third chapter about research materials and methods. In the fourth chapter, results of impedance tube measurements, field measurements and computer simulations are presented and discussed. Objectives and motivation of the study in regard of acquired results are reassessed and outcomes are presented in the conclusion chapter.

CHAPTER 2

LITERATURE REVIEW

This chapter aims to provide necessary information about two topics, which constitute the main subject of this research: variable acoustics and perforated panels. In the first section, variable acoustic studies are presented, and the properties of perforated panels are given under the following section. In the third and final sections, the possible intersection of variable acoustic studies and perforated panels is revealed in the light of the cumulated knowledge from literature.

2.1. Variable Acoustics Solutions

Frequently, a single hall is charged with different functions because of the economic issues like; high real estate, construction, and maintenance costs. However, the proposed nominal acoustic conditions for a multi-purpose facility can be too reverberant for speech or not reverberant enough for music (Ellison & Schwenke, 2010). Reverberation time has an important role on the acoustical condition of the room. Depending on a volume and proposed function, proper reverberation time values differ as listed in Table 2.1 (Barron, 2009).

Table 2.1. *Reverberation time limitations according to functions (derived from: Barron, 2009).*

Function	Maximum seat capacity	Maximum audience distance from stage(m)	Optimum reverberation time (s)
Drama theatre	1300	20	0,7 – 1,0
Opera and ballet	2300	30	1,3 – 1,8
Chamber music	1200	30	1,4 – 1,8
Orchestral music	3000	40	1,8 – 2,2

Therefore, to obtain proper acoustical conditions, the hall needs to be arranged for different functions. Moreover, arrangements in the hall designed for generic functions may not be adequate to cover all requirements of defined function. For instance, musical performances cover different music sessions like chamber music, orchestral: romantic and classical music which have different acoustical requirements like shared in Figure 2.1. Reverberation time values strictly related with the volume of the space as presented in Table 2.2. Reverberation time is dependent on volume of the hall and larger hall volume result with longer reverberation time. Architectural configurations like; adding orchestra shell for concert use or using stage towers for scenery setting of theater, are adapted to alterations in the function of the hall. Acoustical conditions also need to be adapted these functional and architectural changings.

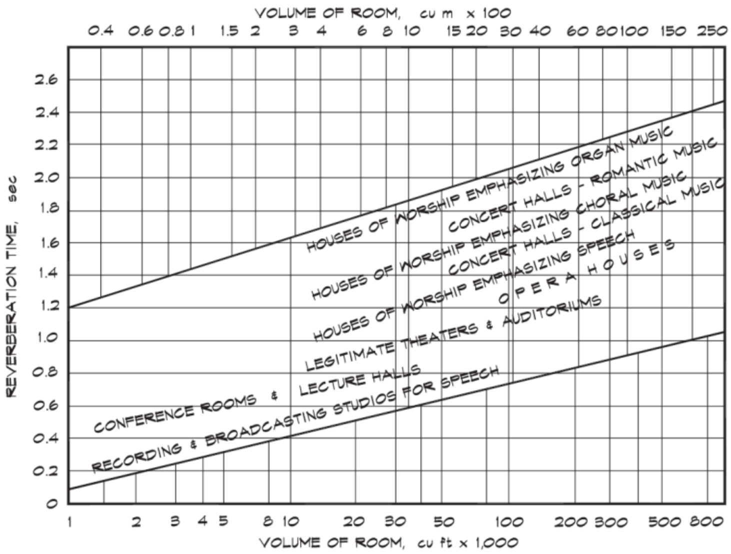


Figure 2.1. Proper reverberation times for different function and hall volumes (Long, 2005).

The acoustical condition of a hall, can be clarified with objective acoustical measures as; Reverberation time (T30), Strength (G), Early Decay Time (EDT), Initial Time Delay Gap (ITDG), Clarity (C(80)), Lateral Fraction (LF80), Speech Transmission Index (STI), A-weighted sound pressure level (SPL(A)). Moreover, there exist subjective parameters as an interpretation of objective parameters by human, like loudness, intimacy, warmth, envelopment, reverberance and brilliance. These parameters can be used to assess the differences between acoustical conditions of the hall, to investigate the effects of variable acoustic solutions in a multi -purpose hall.

Table 2.2. *Optimal reverberation times in mid-band frequencies for speech and amplified (popular/ country/western) music performances for different size of halls (derived from: Ellison & Schwenke, 2010).*

Function	Speech / Lecture / conference			
Volume (m^3)	1000	5000	10000	20000
RT	0.7	0.8	0.85	1.1
Function	Amplified (popular country/western) music			
Volume (m^3)	1000	2500	5000	6000
RT	0.65	0.8	1.05	1.2

Location and characteristics of sound absorbers with geometry and volume of the hall are decisive on these parameters. Occupancy conditions and seating decisions need to be considered to estimate total sound absorption in a hall. In comparison with an empty hall, presence of audience in a hall will decrease the reverberation times in mid-high frequency ranges. However, at the same time, effect of the presence of audience is not high as mid-high frequencies for low frequencies. Existence of audience while providing high sound absorption in high frequencies, in comparison with that, lower absorption in low frequencies is obtained as can be seen in Figure 2.2. The effective absorption area of an audience is not a simply two-dimensional surface. Therefore, in Figure 2.2, the upmost sound absorption coefficient is greater than 1. Furthermore, around audience members, a diffraction effect is also expected (Adelman-Larsen, Thompson & Gade 2010).

Therefore, estimations on reverberation times across frequencies for an empty hall, may end with a disproportionally long reverberation times at low frequencies when the hall is full. In order to obtain balanced acoustical conditions, for a fully occupied hall, the reverberation times for low frequencies can be lower than mid frequency bands when the hall is empty (Adelman-Larsen, Thompson & Gade 2010).

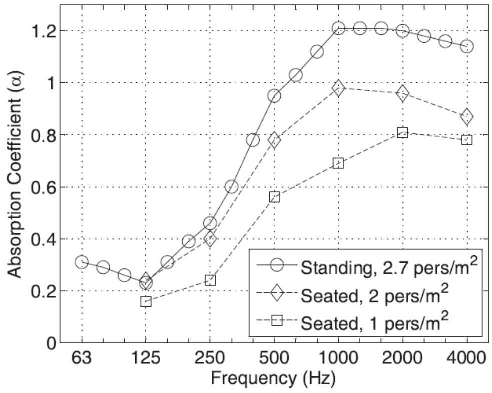
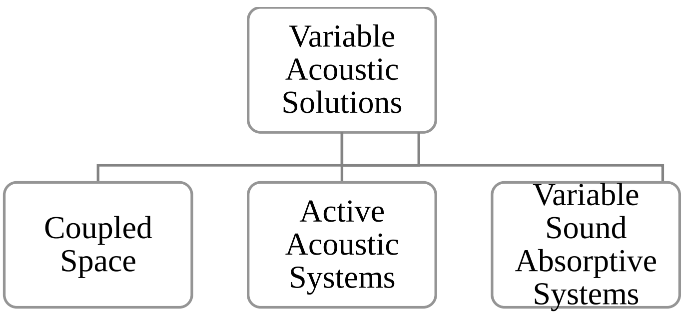


Figure 2.2. Sound absorption coefficients for audience, for seated audience on wood seating (Adelman-Larsen, Thompson & Gade 2010).

Varieties in proposed functions and audience size, required to be balanced with variable acoustic solutions to provide suitable acoustical conditions for each case. Variable acoustic solutions which are developed for multi-functional halls and contributed to literature are investigated. Such acoustic solutions analyzed under three sections as described in Table 2.3. First section is about coupled spaces and creating an additional volume in the hall. A chamber is built and separated by an aperture from the main hall. Longer reverberation times can be obtained by the additionally created space. The second section covers active acoustic systems as a variable acoustic solution. Multi-functional halls designed with electro-acoustic systems are presented under this section. The third section is about variable sound absorbers. Despite of that common variable sound absorbers, in scope of this research, the proposal is designed considering sound absorption mechanism of resonant absorbers.

Table 2.3. *Variable acoustic solutions grouped in three sections*



2.1.1. Coupled Space

The objective room acoustic parameters are directly related with room geometry, room volume and sound absorption characteristic of finishing materials. The strong relation between reverberation time and volume of the hall was underlined. Therefore, controlling room volume seems as a way of controlling reverberation time that is a primary objective room acoustic parameter. Herein, studies on controlling acoustical conditions of a multi-functional hall are investigated by altering room volume.

Coupled space can be created in a hall by combining a room with another more reverberant room separated by an aperture. Owing to coupled space, two often-competing room acoustic parameters clarity and reverberance can be reconciled. Double-sloped sound decay is obtained by the utilization of a reverberant secondary space to the main hall volume. Reverberant secondary space is connected to the main hall volume by opening of the aperture. This engagement produces a double-sloped energy decay. Longer reverberation times can be obtained for a hall with a fully opened aperture. Therefore, depending on the range of the opening size of the aperture from fully closed to open, reverberation time in the hall can be controlled (Ermann, 2005).

The first case of this chapter is Bruce Mason Theatre designed with an altering volume. Multi-purpose auditorium with 900 seats were designed for the primary uses of speech and music for a mid-size performing art venue. For the symphony; Reverberation Time: 1.7s; Early Decay Time (EDT): 1,6 s; Clarity (C(80)) >-1 dB; Loudness 2 dB and Lateral Fraction > 0,15 for mid frequencies are aimed to be obtained in the hall while proper values of objective room acoustic parameters for theater uses are; Reverberation Time:1.1s; EDT: 1,0 s; C(80):>+1 dB. To achieve these goals, a design concept with variable volume was developed. These variations in volume of the hall is provided by operable shuttered ceiling. In theater mode, closed ceiling panels create a lower ceiling plane and reduces the volume, hence, limits the reverberation time. For the symphony mode these panels open and enable the interaction of the upper ceiling void with the main hall volume (Figure 2.3). Therefore, while controlling reverberant volume, the reverberation time is obtained in desired ranges. Furthermore, detailed reverberation time calculations for different modes are conducted with a comprehensive ODEON simulation studies. During the detailed design phase, studies are carried out with a 1:25 scale acoustic model (Valentine & Day, 1998).

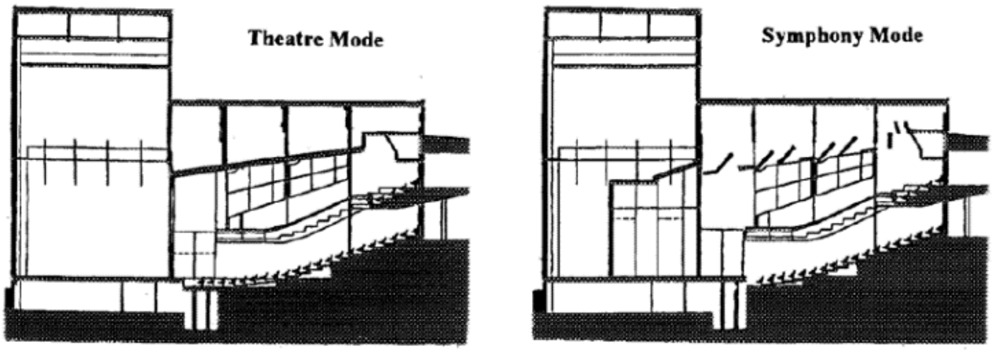


Figure 2.3. Position of ceiling panels for theater and symphony modes (Valentine & Day, 1998).

Coupled space design was proposed for auditorium in Heydar Aliyev Cultural Center, to provide requirements of the multipurpose hall (Figure 2.4). Target values for objective room acoustic parameters differentiates for the uses of conference, concert and opera that the hall is charged with. Graphical models were arranged according to alterations in the hall for different scenarios. The acoustical model was imported in ODEON room acoustics software and objective room acoustic parameters were assessed for each scenario of operation (Sü-Gül & Çalışkan, 2010).

Architectural configurations and condition of the coupled space for conference, concert and opera functions, are shared in Table 2.4. Owing to these arrangements; reverberation times are obtained in desired ranges: for conference use: average reverberation times of mid frequencies is 1.43s, for concert: this value increases to 2s owing to additional volume and for opera: 1/4 of the apertures are opened and reverberation time is obtained in between conference and concert functions as 1.65s.

Table 2.4. *Configurations for scenarios (derived from; Sü-Gül & Çalışkan, 2010).*

Design proposal	Stage shell	Pit	Coupled room apertures	Orchestra
Conference use	Lifted and stored in the stage tower	Closed	Closed	Absent
Concert use	In place	Closed	Open	On the stage
Opera use	Lifted and stored in the stage tower	Open	Partially open	In the pit

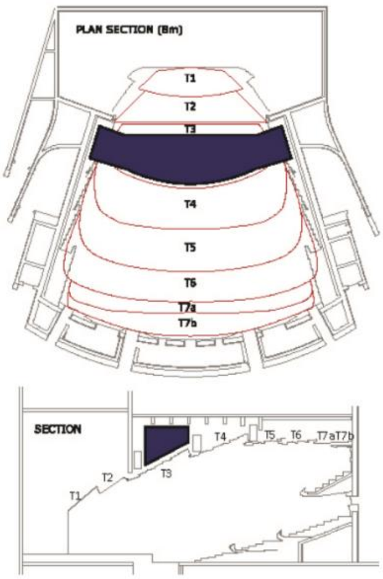


Figure 2.4. Location of the coupled volume in plan (above) and section views (below) (Sü-Gül & Çalışkan, 2010)

Opening size of the aperture is arranged to adapt the hall for different functions. Xiang, Escolano, Navarro & Jing (2013) investigated the effect of opening size of the aperture on energy decay by experiments with acoustical scale model (Figure 2.5). Natural mid frequency reverberation time for the main room is 0,46 s. The reverberation time for secondary space is 4,1s. Double-slope energy decay is expected to be observed as a result of coupled space. Decreasing aperture width decreases the starting level of the second slope decay too (Figure 2.6). Hence, it results in shorter reverberation time in comparison with wider aperture width.

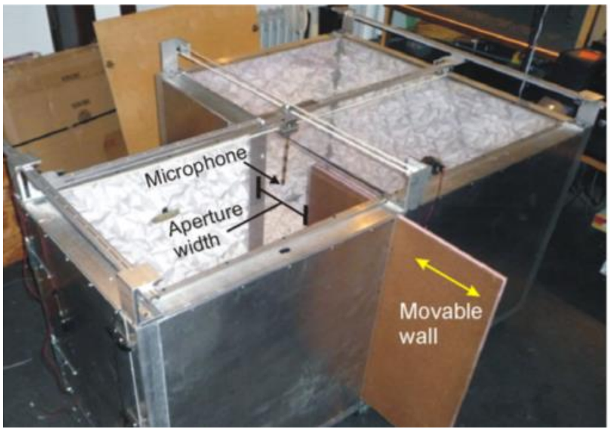


Figure 2.5. Acoustical scale model for coupled volume studies (Xiang, Escolano, Navarro & Jing, 2013).

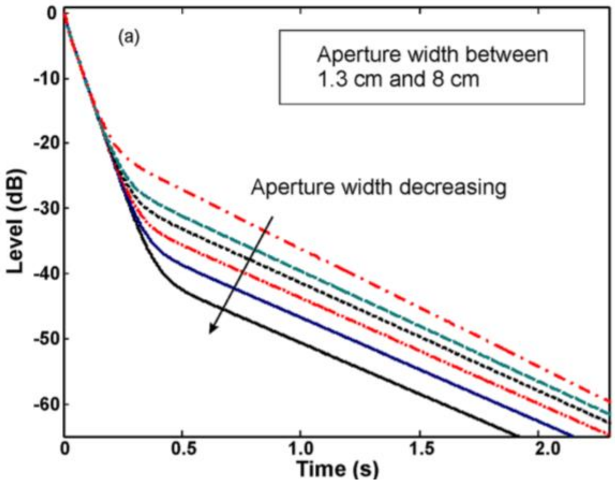


Figure 2.6. Decreasing aperture size and energy decay profiles depending on diffusion equation model (Xiang et al. 2013).

Beside aperture size, the reverberation time of the secondary space is also important to define acoustical conditions of the main hall. The study of Prodi & Pompoli (2016) focuses on unintended effect of stage tower for an opera house. The stage tower by its large volume and reverberant environment causes an increase in reverberation time for the opera hall. To avoid this undesired coupled space effect, reverberation time of the stage tower was decreased by introducing additional sound absorptive materials. Acoustical conditions of the opera hall before and after these treatments are presented in Figure 2.7.

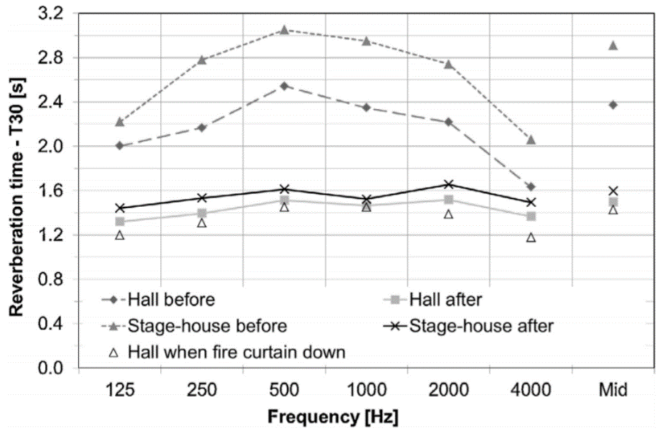


Figure 2.7. Reverberation time for the opera hall and stage tower before and after the restoration and acoustical treatment (Prodi & Pompoli, 2016).

In acoustical design of Studio Acusticum in Pitea, Sweden changeable volume and sound absorptive materials are combined. The hall is in a classic shoebox shape and has a seating capacity adequate to accommodate 600 persons. Finishing materials in the hall are primarily wooden and assumed to provide good reflection. The variable volume is achieved owing to operable ceiling. The ceiling is divided to five parts and height of these parts can be changed vertically in 5 meters, hence 30% changing in volume of the hall is obtained. Moreover, additional retractable curtains are located on side walls to reduce lateral reflections for electronically amplified speech and concerts (Öqvist, Ågren & Tunemalm, 2008).

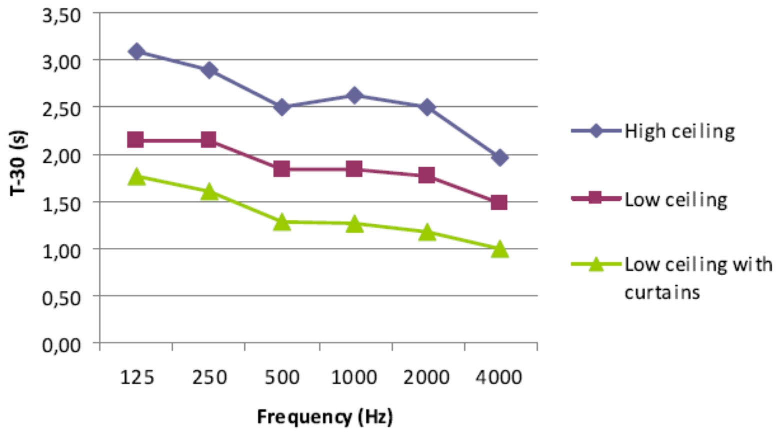


Figure 2.8. Reverberation times in 1/1 octave bands for different acoustical configurations (Öqvist, Ågren & Tunemalm, 2008).

Depending on adjustments in the height of ceiling and curtain positions, reverberation times for the hall are presented in Figure 2.8. Decreasing in ceiling height and volume of the hall, decrease the reverberation times in 1/1 octave band frequencies. However, provided variable absorption by retractable curtains effects the higher frequencies more. In addition to reverberation time other objective room acoustic parameters in the hall like Clarity and Strength also evaluated in this study. Clarity decreases depending on increase in reverberation time in an expected way. Loudness is negatively affected by the addition of sound absorptive curtains (Öqvist, Ågren & Tunemalm, 2008).

Therefore, beside alterations in volume of the hall, effects of sound absorptive materials on reverberation time and other objective room acoustic parameters like clarity and strength need to be considered.

2.1.2. Active Acoustic Systems

Halls can be adapted to different functions with active acoustic systems rather than creating additional volume or adding variable sound absorbers in a hall. In principle, active acoustic systems detect the sound in auditorium and process electronically before broadcasting by speaker. Beside advantages like providing novel acoustic conditions for contemporary performance halls, active acoustic systems may bring some risks. Unnatural artifacts, coloration or noticeable pitch-shifting effect can be observed in relation with their operation method (Poletti, 2011). Multi-purpose halls designed with active acoustic systems will be investigated to see the capabilities of active acoustic system.

From the early examples, The Renold Theatre in University of Manchester Institute of Science and Technology designed with artificial reverberation system is the following case. The theater is primarily designed for lectures, but the theater is also available for full stage facilities at the same time. The reverberation time at mid-frequency is 0.8s which suitable for primer function: lecture. High standard of intelligibility is provided. However, proper acoustical design for speech is not expected to satisfy requirements of the music at the same time. An active acoustic system was proposed to improve acoustical conditions of the theatre for music. The active acoustic system is described via schema in Figure 2.9. Owing to reverberation time reinforcement, 1.3s reverberation time at mid-frequencies is obtained (Jones & Fowweather, 1972). The difference between reverberation times with and without artificial reverberation system is revealed at Figure 2.10.

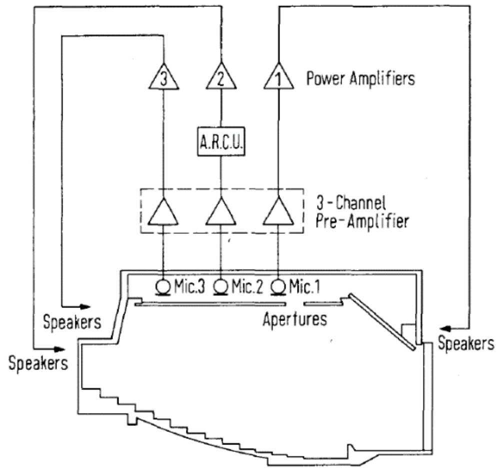


Figure 2.9. Schematic diagram of active acoustic system for reverberation reinforcement (Jones & Fowweather, 1972).

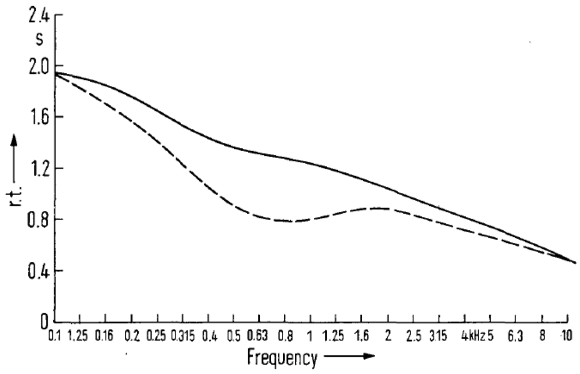


Figure 2.10. Reverberation time against frequency for the Renold Theatre. With (−) and without (- - -) reverberation reinforcement (Jones & Fowweather, 1972).

An active acoustic system was proposed for the Beattie Theatre with seating capacity of 400 and volume of 2000 m^3 to adapt the hall conference and concert use. Reverberation time in the hall for 1 kHz is increased from ~1.25sn to 2sn by an active acoustic system (Figure 2.11) (Guelke & Broadhurst, 1971).

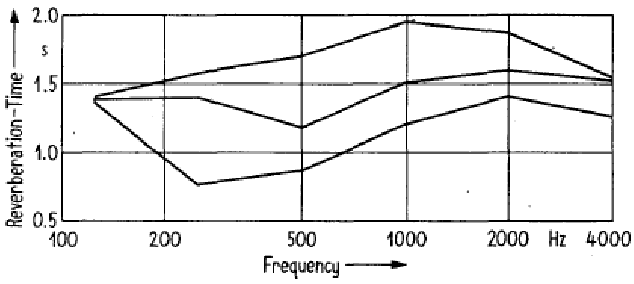


Figure 2.11. Reverberation times for the Beattie Theatre. Without active acoustic system (below), with active acoustic systemhas single feedback system (middle), with the phase modulated active acoustic system (above) (Guelke & Broadhurst, 1971).

Electronic enhancement system was designed for the multi-purpose hall in the Akranes School of Music to obtain proper reverberation times for various functions. The hall has 177 seats in an area of 240 m^2 and ceiling height changes from 5 m to 5,8 m. The requirements for a successful electro acoustic system with clear and uncolored direct sound, are listed as; very low background noise level, proper delayed lateral reflections and later reverberation provided by electronics and attenuation of strong early reflection with adequate absorption and diffusion. Obtained reverberation times owing to electronic enhancement are shared in Figure 2.12. The reverberation time of the hall is increased from 0.75 sn to 3.2 sn artificially (Guðjohnsen & Jónsson, 2008).

In addition to previous examples, when the hall volume is subjected to alterations, beside changings in proposed function; the acoustical conditions of the hall need to be arranged. Furthermore, seating capacity is also affected by alterations in volume and affects the total sound absorption in the hall. In Table 2.5, arrangements in reverberation times by an active acoustic system, for different functions and for alterations in room volume and seating capacities, are presented for Logomo Hall in Turku, Finland (Schwenke & Ellison, 2013).

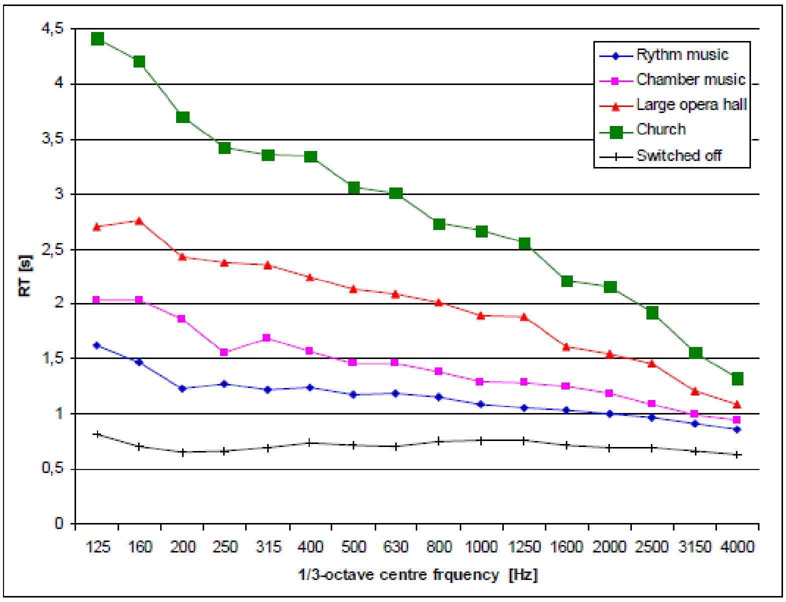


Figure 2.12. Reverberation times for the multi-purpose hall in the Akranes School of Music with electronic enhancement (Guðjohnsen & Jónsson, 2008).

Figure 2.13. Zellerbach Hall at University California, Berkeley (Ellison & Schwenke, 2010).

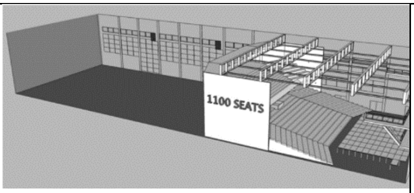
Zellerbach Hall at University California, Berkeley has 2000 seats (Figure 2.13). Orchestra pit exist in the hall. Microphones are installed in pit. While musicians are performing in the pit, microphones provide early reflections to the hall. Generated early reflections improve the acoustical conditions of the hall (Ellison & Schwenke, 2010).

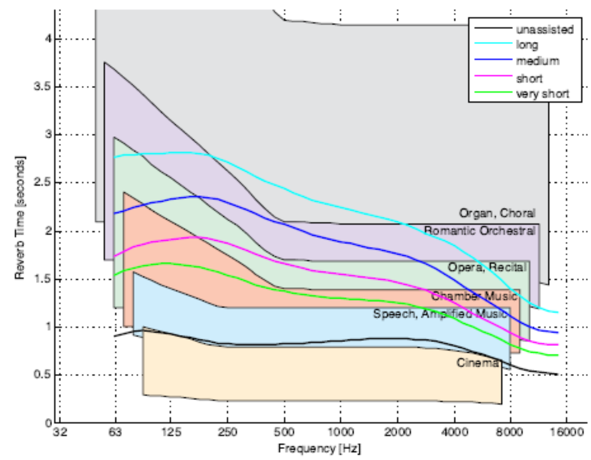
Active acoustic systems can provide longer reverberation times even for outdoor spaces as in case Jay Pritzker Pavilion in Chicago. Speakers were placed on a grid for the pavilion which is directly engaged with free field (Figure 2.14). The system works by adding reverberant energy. It cannot remove the energy from echoes or from background noise, (Asselineau & Serra, 2010) operating only to extend reverberation times to the functional limits.

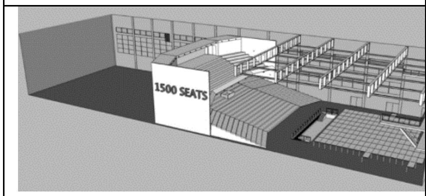
Figure 2.14. Jay Pritzker Pavilion as an outdoor venue (Asselineau & Serra, 2010).

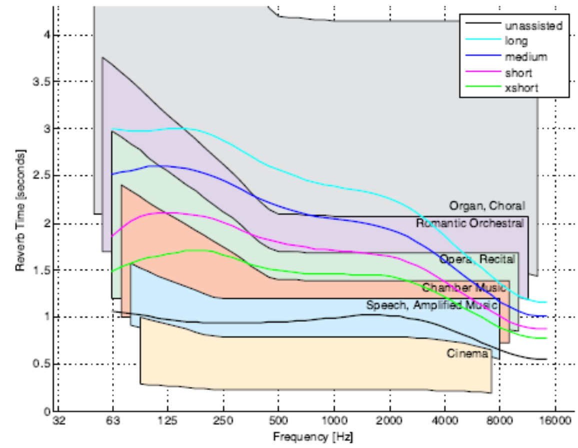
Beside mentioned successful applications of active acoustic systems in terms of providing proper acoustical conditions for performance spaces even in outdoor environment, Dodd (2004) underlines the electro-acoustic systems' incapability of preserving the originality of content. Due to that concern of originality, musicians and listeners tend to reject changes in live performances by electro-acoustic systems. Thus, Dodd introduced a need for more intelligent passive systems. With that respect, he sought for a "actively passive" system which can offer what is required from it as a variable acoustical solution, while also providing originality, both audially and visually.

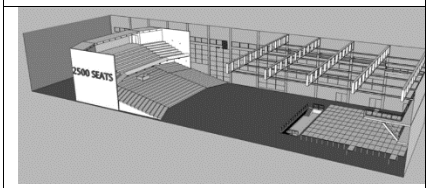
Table 2.5. *According to hall settings, reverberation times for different functions provided by active acoustic systems (derived from: Schwenke & Ellison, 2013).*

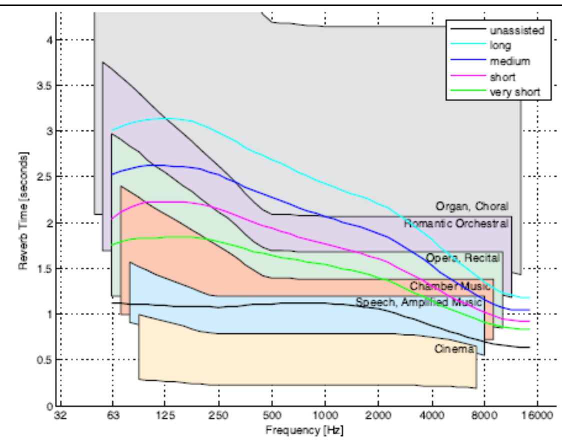












2.1.3. Variable Sound Absorptive Systems

Multi-purpose halls can be adapted to different functions by alterations in the volume of the hall or by active acoustic systems. Moreover; sound absorption characteristic of finishing materials is effective on acoustical conditions of the hall. Therefore, variable acoustic solution designed with sound absorptive materials were investigated as a passive way of adaptation to different functions. In addition to previously shared cases, many small concert halls which are built for universities or music departments in schools, should satisfy requirements of a wide variety of musical performances from orchestras to solo performances. Such diverse programs require different reverberation time and loudness; therefore, variable sound absorbers like moveable drapes or panels are provided for these halls to meet different acoustical requirements (Aretz, & Orlowski, 2009). Widely used variable sound absorbers: curtains, despite of contributions of draping and air cavity behind, are not still good sound absorbers at low frequencies beside their higher sound absorption performances at high frequencies. Effects of the distance between the curtain and the wall behind and draping are presented in Figure 2.15 and Figure 2.16.

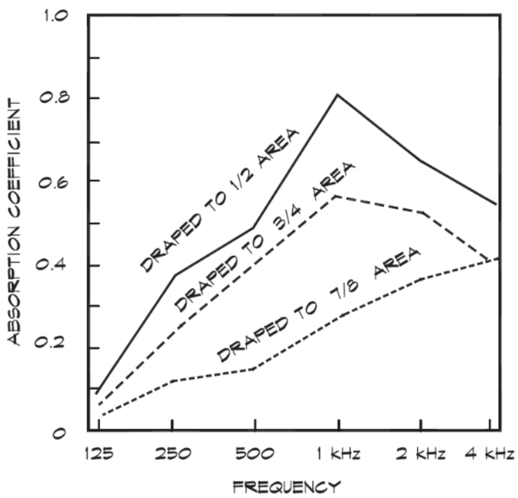


Figure 2.15. Effects of draping on the sound absorption of curtains (Long, 2006)

Effects of increase in weight of curtains on sound absorption at mid and low frequencies are limited according to Figure 2.17. Molton/Wool Serge type, nonbacked fabrics are compared in terms of weight. Relation between weight of curtains and sound absorption is not linear as relation between distance of the curtain from wall and absorption (Möller, 2006).

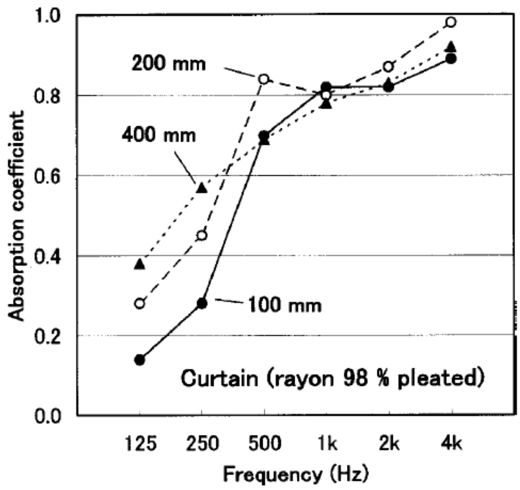


Figure 2.16. Effects of air layer depth (mm) between pleated thick curtain (mass density 350 g.m-2) and the rigid wall on the sound absorption of curtains (Hidaka & Nishihara, 2004).

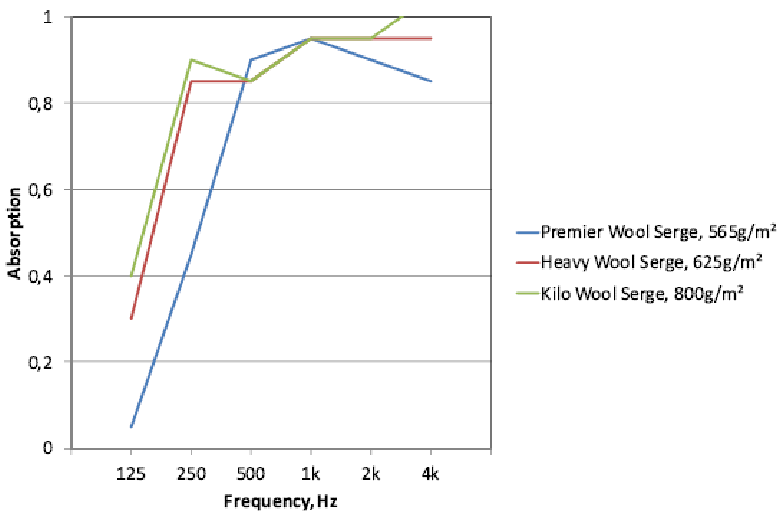


Figure 2.17. Effects of curtain’s weight on the sound absorption of curtains (Möller, 2006).

Drapes and curtains are not quite effective on low frequencies. For instance, case specifically, while the addition of porous absorber in a room is decreasing strength in mid and high frequencies, at the same time, they can hardly affect strength in low frequencies (Aretz & Orlowski, 2009).

Awaza Convention Center in Turkmenbashi accommodates hall with 2015 seating capacity, charged with conference, opera and concert use (Sü Gül, Meriç Nursal, Bora, Çalışkan, 2016). The multi-purpose hall was designed with variable sound absorbers. Sound absorptive material applications and architectural configurations of stage tower and orchestra pit for different functions are presented in Table 2.6 shared below. The number of curtains vary according to function but the other sound absorber material in the hall; perforated panel is constant for each scenario as can be seen in the table with red indicators. The 3D OpenGL view exported from ODEON room acoustics software is shared in Figure 2.18.

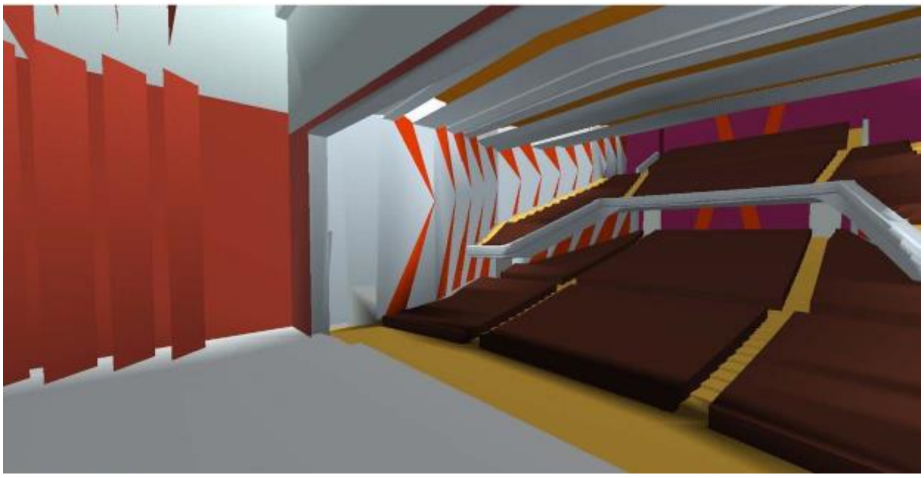


Figure 2.18. 3D OpenGL view of multi-functional auditorium, exported from ODEON room acoustics simulation software (Sü Gül, Meriç Nursal, Bora, Çalışkan, 2016).

Variations in acoustical conditions between the scenarios were provided with additional curtains in accordance with architectural conditions and their effects on the total volume of the auditorium. Beside these curtains, the other sound absorptive material in the hall is a perforated panel system applied on back wall and ceiling surfaces. These perforated panels are constant for each scenario.

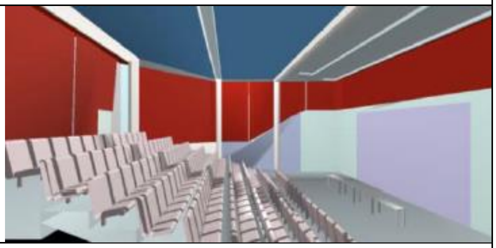
Concert use requires longer reverberation times; therefore, the number or area of curtains in the hall is lower than the other scenarios. On the other hand, for conference use to decrease the reverberation time, the maximum number of curtains is employed.

Table 2.6. *Sound absorptive materials and architectural configurations for different functions proposed for the multi-functional auditorium (derived from; Sü Gül, Meriç Nursal, Bora, Çalışkan, 2016).*

Location	Material type	Conference	Concert	Opera
Main hall and orchestra pit				
Main hall – under roof slab	25 mm 48-52 kg/m^3 mineral wool with acoustical fleece	✓	✓	✓
Back wall, back ceiling surfaces	16 mm thick perforated wood, 12 % perforation ratio with 48-52 kg/m^3 mineral wool inside 20cm gap	✓	✓	✓
Decorative slotted wood wall panels	25mm 110 kg/m^3 mineral wool with acoustical fleece	✓	✓	✓
Orchestra pit back wall	Orchestra pit back wall	(pit closed)	(pit closed)	✓
Orchestra pit front wall (h: 80cm)	16mm thick perforated wood, 7.4% perforation ratio with 48-52 kg/m^3 mineral wool backing	(pit closed)	(pit closed)	✓
Stage				
Stage tower ceiling	50 mm 48-52 kg/m^3 with acoustical fleece, 10 cm air gap behind	✓	✓	✓
Back stage ceiling	25 mm 48-52 kg/m^3 mineral wool with acoustical fleece	(backstage closed)	✓	(backstage closed)
Side stages		(side stages closed)	✓	✓
Stage back curtain	Molton (300g/m^2) cotton curtain	✓	-	✓
Legs masking the wings		✓ (total #8)	-	✓ (total #12)
Side stage curtains		✓	-	-
Border/frieze curtains		✓ (total #4)	✓ (total #2)	✓ (total #2)
Mid separator		✓	-	-
Stage/orchestra shell		-	✓	-

The other case designed with variable curtains is the Multi-Functional Hall of the New Deichman Library. The volume of the hall is 1800 m^3. Its dimensions are 7,5 m height, 16,5 m width and 15m length. It has 200 seats (Olshausen & Rindel, 2015). The scenarios with different number of curtains are presented in Table 2.7. ODEON room acoustics software was used to assess acoustical conditions of the hall.

Table 2.7. *3D OpenGL view of the hall with different number of curtains, exported from ODEON room acoustics software (derived from; Olshausen & Rindel, 2015).*

2/3’rds of the glass walls are covered with curtains	All curtains are drawn
	
1/4 of the glass walls are covered with curtains	Back wall covered with curtains
	

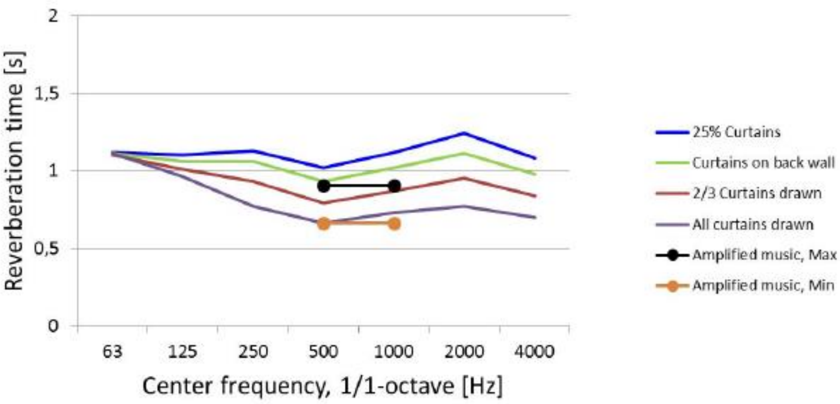


Figure 2.19. Reverberation times for four different scenarios and comparison with recommended ranges for amplified music (Olshausen & Rindel, 2015).

The reverberation time calculations for these four scenarios, according to analysis in ODEON simulation software, are presented in Figure 2.19. Sound absorption at low frequencies is insufficient, especially at 125 Hz. This issue needs to be dealt with (Olshausen & Rindel, 2015). The alterations in low frequencies caused from variation in curtain amount is negligible. When sound absorption characteristic of the curtains is considered, this result can be expected.

For the multi-purpose hall in Sibbo, Finland; Möller (2017) indicates that variable sound absorbers were designed, which provides scattering/diffusion when they are closed and provide sound absorption by the interaction of the filled porous absorber with the hall volume when they are opened (Figure 2.20). Similar with curtains, porous absorbers without air gap are not good absorbers at low frequencies. Their performances at low frequencies can be improved by increasing thickness, but it is limited (Figure 2.21) (Möller, 2017).

Figure 2.20. Variable acoustic solution in the Topelius hall in Sibbo, Finland (Möller, 2017).

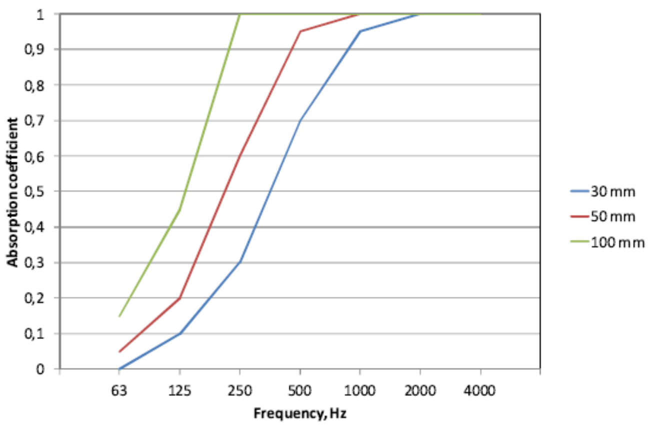


Figure 2.21. Effects of material thickness on the sound absorption of mineral wool (Möller, 2006).

The Fitzwilliam College Auditorium was equipped with various functions like concert, drama, musical dance performances and conferences. The small multi-purpose hall is in a rectangular shoebox shape with a seating capacity of 250 seats. Inner surfaces of the hall are generally covered with hard and reflective finishes. The hall was designed with variable sound absorbers to satisfy the requirements of a multipurpose hall. Sound absorber panels, as can be seen in Figure 2.22, can be opened on the upper part of the side walls.

Figure 2.22. Variable rotating sound absorber panels on the upper side of wall at Fitzwilliam College Auditorium (Aretz & Orlowski, 2009).

Variable panels are designed with two faces: one of these is covered with sound absorptive porous material, the other is wooden reflective panel. Reverberation time in the hall is tried to be controlled by the help of these panels. Total sound absorption in the hall is increased by opening of these variable rotating panels and as a result of this, reverberation time is expected to decrease. The hall is tuned for more convenient conditions for speech, lecture and conference functions by the help of increase in area of sound absorptive materials in the hall. Difference in reverberation time about 0.2 s at mid and high frequencies can be obtained by the help of variable acoustic panels as can be seen in Figure 2.23. However, the effect of panels on reverberation time for low frequencies is negligible. Aretz and Orlowski (2009) explain the incapability of panels at low frequencies, by limited thickness of sound absorber material.

Nevertheless, for mid-frequencies reverberation time in the room can be arranged in between 1.3s and 1.5s. Moreover, measurements about another objective room acoustic parameter; strength show similar results by the influence of variable sound absorber panels. However, like reverberation time, strength at low frequencies, is not affected considerably from these alterations in sound absorbers (Aretz & Orlowski, 2009).

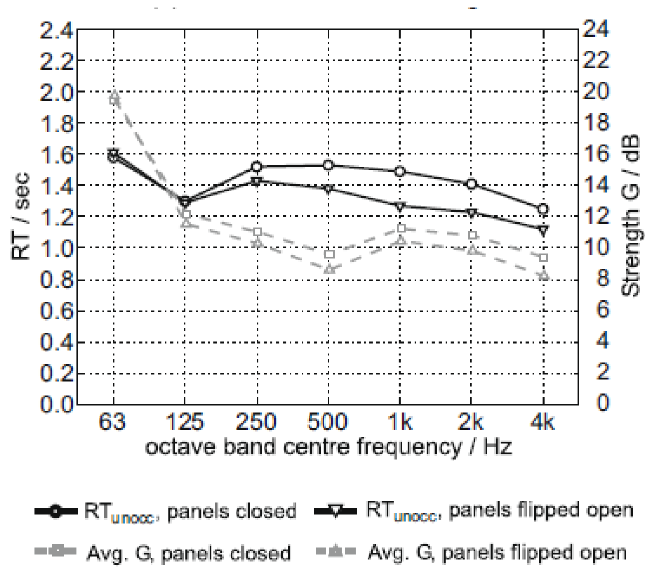


Figure 2.23. For Fitzwilliam College Auditorium, average unoccupied 1/1 octave band reverberation time and strength comparison for open and closed rotating variable panels (Aretz & Orlowski, 2009).

In studies of Kousi, Gyftopoulos, Karagiannis & Sotiropoulou (2016) a multipurpose auditorium was designed with the help of variable acoustic modules. The hall with varying ceiling height, volume and seating capacity was adapted acoustically to different functions owing to variable acoustic modules. The module is schematically described in Figure 2.24. Each side of the cubes was designed with different acoustical characteristics like absorptive, reflective and diffusive (mid-tone or high-tone) (Figure 2.25). Three cube types used in the hall. Acoustical conditions and reverberation time of the hall were tuned according to proposed functions by the help of variable acoustic cubes as presented in the Table 2.8 (Kousi, Gyftopoulos, Karagiannis & Sotiropoulou, 2016).

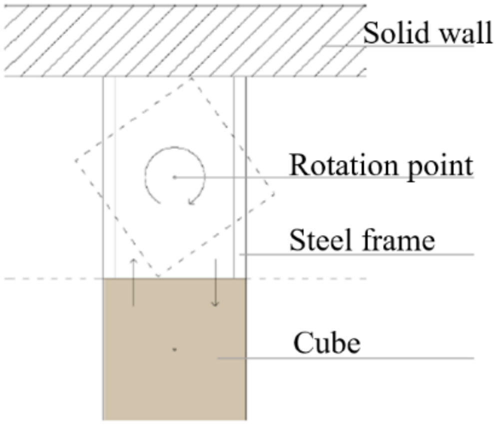


Figure 2.24. Schematic description of variable acoustic cube (derived from; Kousi, Gyftopoulos, Karagiannis & Sotiropoulou, 2016).

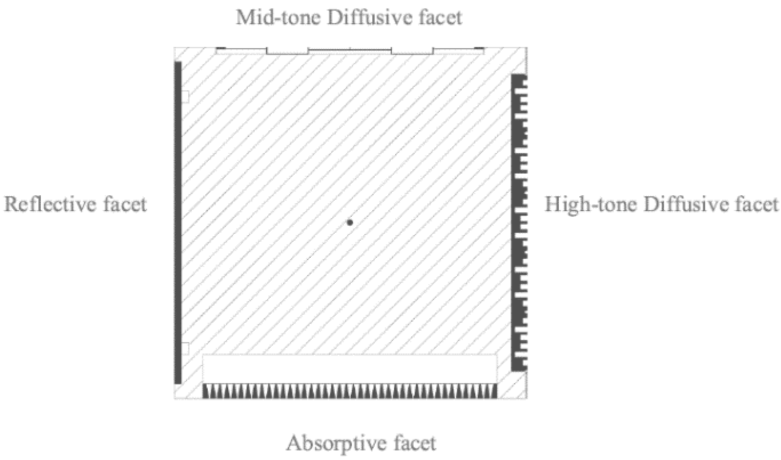
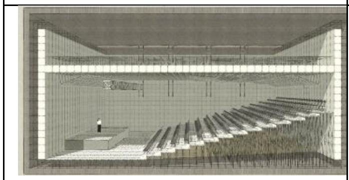
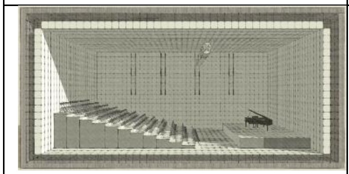


Figure 2.25. Acoustical characteristics of variable cube surfaces (Kousi, Gyftopoulos, Karagiannis & Sotiropoulou, 2016).

The multi-purpose hall in Music Academy in Zagreb is designed to host chamber music, full symphony orchestra performances, operas and speech-based events. The hall can accommodate 300 visitors with a volume of 2.500 m^3. Stage organization and seating capacity of the hall is designed to vary in three scenarios for speech events, opera performances and big music ensembles. Number of seats in the hall for these three scenarios; speech, opera and music are respectively; 294, 246 and 198. Moreover, the volume of the hall varies as 2380 m^3, 2540 m^3 and 2330 m^3 for speech, opera and music setups, respectively.

Table 2.8. *Configuration and reverberation time of the multi-purpose hall for different functions (C: Capacity / V: Volume, m^3 /CH: Ceiling height, m / RT: Reverberation time, sec.) (derived from; Kousi, Gyftopoulos, Karagiannis & Sotiropoulou, 2016).*

Hall configuration	Use	C	V	V/C	CH	RT
	Speech	322	2229	6.9	7.2	0.69
	Chamber music	180	3851	21.3	10.8	1.52

The primary criterion for the acoustic quality is assessed as a reverberation time by Jambrošić, Domitrović & Horvat, (2016). In mid frequencies (500 Hz and 1 kHz), aimed reverberation times are 1.1 s for speech events, 1.4 s for opera performances and 1.6 s for chamber music. Optimum reverberation times for these three scenarios were specified regarding to leadings found in the literature. Variable acoustic elements were designed and placed on the ceiling of the hall to achieve these reverberation times in a single hall (Figure 2.26). The rotary cylinders have reflective surfaces at half of it while the other half of the cylinder is covered by sound absorptive material. Each cylinder can be operated individually. Reverberation time, early decay time and clarity are assessed for each scenario as an objective room acoustic parameter. Reverberation times in the hall for opera and music settlements are compared in Figure 2.27. In this case, the alteration in the reverberation time is restricted because the other sound absorptive materials already exist in the hall, (Jambrošić, Domitrović & Horvat, 2016).

Figure 2.26. Cylindrical variable acoustic elements (Jambrošić, Domitrović & Horvat, 2016)

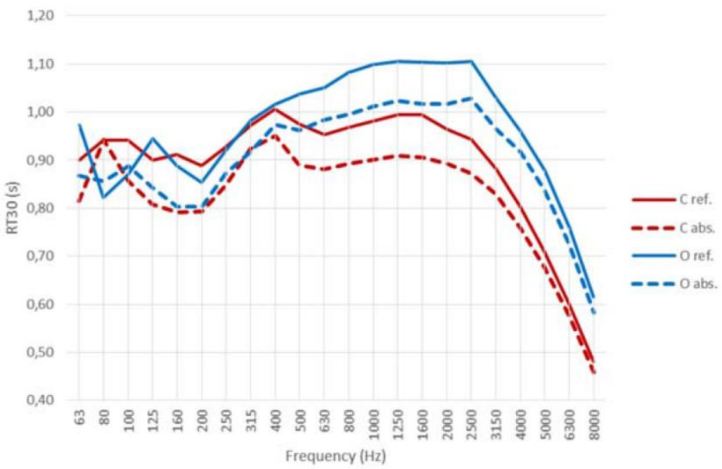


Figure 2.27. Reverberation times for the concert (C) and opera (O) setups for both cylinder positions (Jambrošić, Domitrović & Horvat, 2016)

2.2. Perforated Panels

Acoustical behavior of perforated panels has been a subject of several researches for decades (Arenas & Crocker, 2010; Jaouen & Bécot, 2011). Sound absorber systems composed with perforated panels are widely used for noise control and architectural acoustic requirements. Perforated panels with perforation more than 1 mm radius can be named as macro-perforated panel (Ingard & Bolt, 1951). Perforated panels' acoustical effect depends on the perforation size and flow resistivity, thickness of panel and their mounting conditions. Porous materials which are generally combined with perforated panels, are effective at high frequencies while their absorption performances at low frequencies are limited (Atalla, Panneton, Sgard & Olny, 2001).

Perforation ratio of panels usually changes between 0.02 and 0.20 (Fuchs, 2013). Perforated facings can be acoustically transparent depending on perforation size and ratio. Bolt (1947) stated that a facing with 10% or 15% perforation ratio can be regarded as “impervious” and it reduces the sound absorption performance of the porous material slightly for considerable range of frequencies. In addition to that, acoustic behavior of perforated facings is reduced to the following variables as design parameters to control sound absorption of the system; perforation ratio, diameter of holes, thickness of facing, weight/surface density of perforated facing and frequency.

Perforated screens can enhance the sound absorption performance of the materials with low-flow resistivity at low frequencies; on the other hand, the sound absorption performance of porous materials at high frequencies can be decreased by the perforated facings depending on the properties of the facing and mounting conditions (Atalla & Sgard, 2007). Sound absorption characteristic of materials can be controlled via perforated facings with an arrangement of size and number of holes.

As a volume absorber, perforated panels can be regarded as a series of Helmholtz resonators (Berardi, 2013). If Helmholtz principles are transferred to perforated panels, holes of perforated panels represent the neck of Helmholtz resonator. The air gap between the perforated panel and rigid wall act as a cavity of Helmholtz resonator (Figure 2.28) (Negro, Cremonini, Properzi & Zanuttini 2010).

The resonance frequency of perforated panel is represented with f_H: depending on a formula composed of; S_H open surface of perforation cm^2, V: volume (cavity) cm^3, t_{eff}: (effective) plate thickness mm as (Fuchs, 2013):

$$f_H = 17.10^3 \sqrt{(S_H / V.t_{eff})} \qquad (1)$$

In following chapters, researches about the effects of hole diameters, distance between holes, perforation ratio, air gap behind and porous materials placed in cavity on perforated panels' sound absorption capacities, are presented.

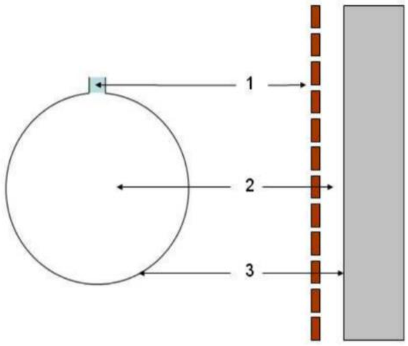


Figure 2.28. Comparison of Helmholtz resonator and perforated panel sections. 1 represents the hole of perforated panel and neck of Helmholtz resonator. 2 is the air gap behind the perforated panel and cavity of the resonator. 3 is the rigid wall behind the panel and cavity surface (Negro et al. 2010).

2.2.1. Perforation Diameter / Width and Distance

Perforation diameter / width of a perforated panel has a similar role with the neck width of a Helmholtz resonator on defining the resonance frequency and sound absorption characteristic of the system. Studies investigating the effects of hole diameter / width on sound absorption performance of perforated panels are gathered under this section.

Studies on Helmholtz resonators point that neck width and resonance frequency are directly related. A resonator which has variable opening was designed by Estève & Johnson (2004). The resonator is a cardboard tube which has 24-inch (~ 61cm) length and has a variable aperture size controlled by step motors (Figure 2.29). The motorized diaphragm mechanism controls the size of the opening. Adaptive Helmholtz resonators were designed and tested to tune the acoustic mode (Estève & Johnson (2004). As a result of this study, the relation between the neck width and resonance frequency is represented graphically as shared in Figure 2.30.

Smaller opening size decreases the resonance frequency, while increasing opening diameter makes resonance frequency move towards to high frequencies. These results are also coherent with the studies of Norris & Wickham (1993). The range of the opening size from 16mm to 49mm shifts the resonance frequency from 120 Hz to 224 Hz (Norris & Wickham, 1993).

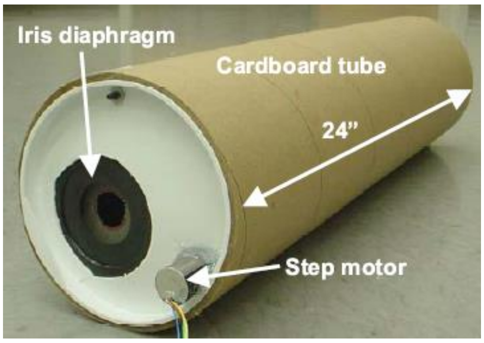


Figure 2.29. Helmholtz resonator with variable opening (Estève & Johnson (2004).

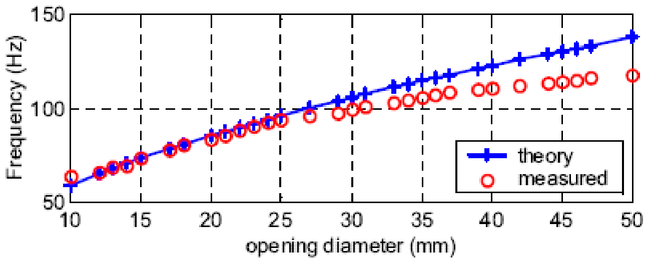


Figure 2.30. Resonance frequency of Helmholtz resonator as a function of the opening size (Estève & Johnson, 2004).

The effects of perforation diameter were also tested with perforated panels which have different opening sizes. More broadband sound absorption capacity can be obtained by perforated panels rather than a single Helmholtz resonator, owing to multiple opening on the panel. Furthermore, multiple openings highlight another parameter as the distance between perforations. Studies which contribute the analysis of perforation diameter and distance between perforations were investigated and presented.

In Takahashi's studies (1997) three perforated panels with various perforation diameters were used. Common panel properties of these three samples are; the plate thickness (5 mm), and 40mm airgap with porous material in the cavity (constant porous material properties; thickness: 50mm, density:10 kg/m^3, flow resistivity: 0.5 x

10^4 MKS.rayl/m). While these design parameters are constant, hole diameters are varied for these three samples. In Figure 2.31, test results obtained from reverberation room experiments are shown for these three samples.

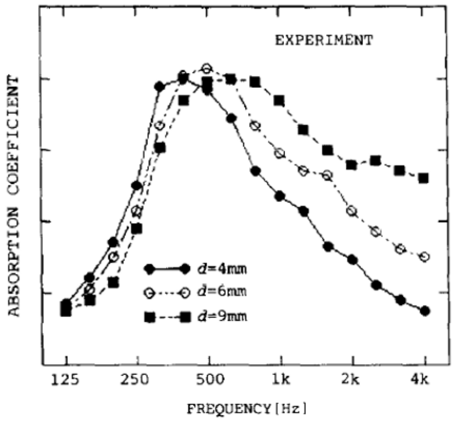


Figure 2.31. Sound absorption coefficients of perforated panels with varying hole diameters (Takahashi, 1997).

When hole diameters are increased, sound absorption characteristics of porous material in the cavity become dominant on the sound absorption performance of the system. Therefore, higher sound absorption coefficients are observed at high frequencies depending on the increase in hole diameter.

Fuchs (2013) shared slot width and central distance information of test specimens as described in Figure 2.32. Varying hole widths were analyzed with the help of prepared test samples and results were shared for the same panel with the same perforation ratio (0.02). A porous absorber material was placed in the cavity (50mm soft open-cell melamine resin foam) (Figure 2.33) (Fuchs, 2013).

	1	2	3	4	5	6
a	-	13	41	80	118	230 mm
b	-	2	6	10	13	20 mm

Figure 2.32. Samples of perforated panels varying slot widths and distance between slots (Fuchs, 2013).

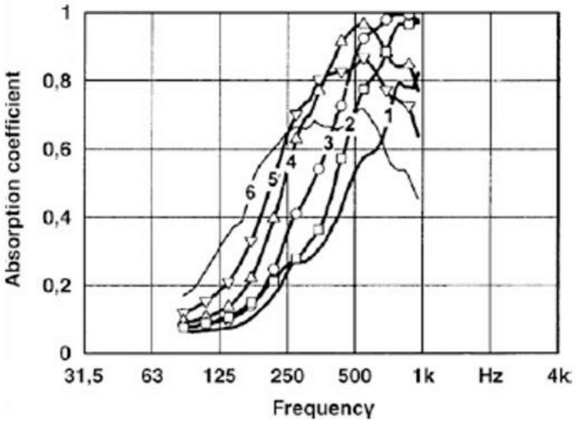


Figure 2.33. Test results of perforated panels (6: a= 230, b=20; 5: a= 118, b=13; 4: a= 80, b=1; 3: a= 41, b=6; 2: a= 13, b=2; 1 plane plate) (Fuchs, 2013).

As Helmholtz resonators, slotted panel absorbers can shift the frequency where maximum sound absorption is observed by two or four third-octave bands in comparison with homogeneous fibrous/porous materials. Unlike a conventional Helmholtz resonator that has only one hole, slot panels can be arranged considerably more broadband. Slotted panel absorbers can provide high and broadband sound absorption in the medium frequency range. Their striped covers are easy to design and apply (Fuchs, 2013).

Effects of the hole interaction and heterogeneous distribution on acoustic impedance and sound absorption of perforated plates were investigated by Tayong (2013). Four samples that have different hole placement and distance between holes were used in the study as seen in Figure 2.34.

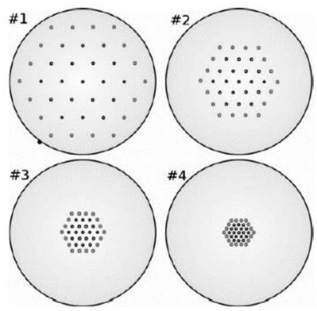


Figure 2.34. Schematic pictures of samples of perforated panels. #1: b = 14,18mm, #2: b= 8mm, #3: b=3,5mm, #4: b= 2,5mm. b is the center to center distance between holes (Tayong, 2013).

Sound absorption measurement results are discussed with the following graph (Figure 2.35). Shift of the resonance frequency towards the low frequency range is observed by decreasing central distance between perforations while plate thickness and hole diameters are kept constant. Decrease in the central distance, from 14,18 mm to 2,5mm, has almost practically equivalent effect with 20mm increasing in air cavity depth for the sample with sparsely distributed perforations.

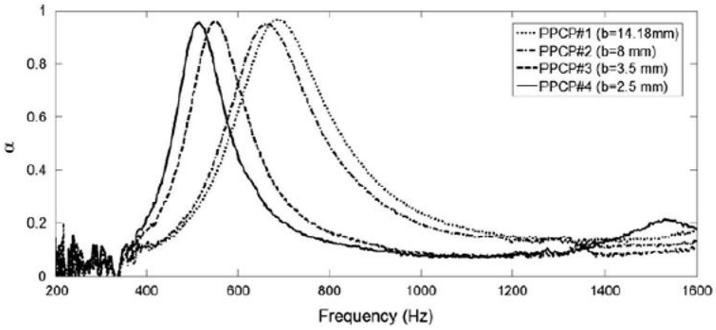


Figure 2.35. Impedance tube measurements of samples with 20mm air cavity (Tayong, 2013).

Alterations in perforation width and distance between perforated panels of multi-layer perforated panel system were examined in the studies of Randeberg (2002) as mentioned in Fuchs's (2000) research; sound absorption spectra of a single micro perforated panel are tried to be obtained with two macro perforated panels. Multiple layer perforated panel was designed with two panels and distance between panels were studied in the range of 0.10mm and 0.58mm (Randeberg, 2002). Shift in resonance frequency and aimed alteration in sound absorption coefficients are achieved by the system designed with two slot panels with constant air gap and without porous absorber, depending on the alteration in perforation width (0 to 3mm) and distance between panels (0.1mm to 0.58mm). Randeberg focuses the effect of distance between panels. According to Randeberg (2000), obtaining equivalent absorption characteristic with a single microperforated panel by the multi layered system designed with two macro-perforated panel is possible.

Lee & Chen (2001) studied with more than one perforated panel and examined the effects of the perforation ratio on sound absorption by increasing the hole diameter.

Perforated panels which have different perforation ratios and hole diameters were tested in those studies as represented in Figure 2.36. Sound absorption performance of three different perforated panels having same thickness (1mm), air space(19mm), hole pitch (6mm) but different hole radius (0.5mm; 0.75mm; 1mm), therefore, different perforation ratios (2.2%; 4.9%; 8.7%) are compared in Figure 2.36. Similar to previously discussed studies; decrease in perforation ratio and hole diameter increase the sound absorption of the system at low frequencies. Shift of resonance frequency towards to low frequencies decrease the performance of the system at high frequencies at the same time. By combining perforated panels having different resonance frequencies, a composed system was designed, and a multi-layer acoustic absorber was obtained. Furthermore, more broadband sound absorption was observed owing to combination of perforated panels. Respectively, lower and higher resonance frequencies are observed regarding to resonance frequencies of individual components (Lee & Chen, 2001).

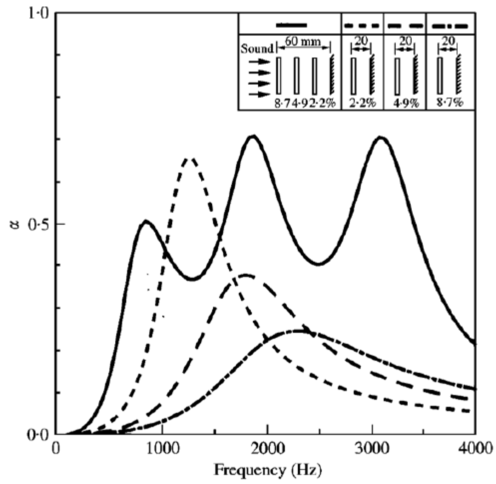


Figure 2.36. Resonance frequencies of the multi-layer sound absorber and its compartments (Lee & Chen, 2001).

To sum up, as a result of the experiments, perforated plates are sensitive to the distribution effects and interaction between the perforations. With presence of these effects, sound absorption performance of the system at low frequencies can be improved.

2.2.2. Perforation Ratio

Besides the diameter of holes, the other parameter which is mainly effective on sound absorption performance of perforated panels is the perforation ratio (Pfretzschner, Simón & Colina, 2004). Effects of the perforation ratio on sound absorption of perforated panels are investigated in following researches.

Hou, Yu, Wang & Guo (2010) examined the effects of perforation ratio on sound absorption by medium density fiberboard (MDF) perforated panels. Test samples were produced from 3mm MDF panels. Perforation width is 2mm for test samples. They are mounted with 50mm air gap distance. Experiments show that decreasing perforation ratio causes resonance frequency to decrease in Figure 2.37.

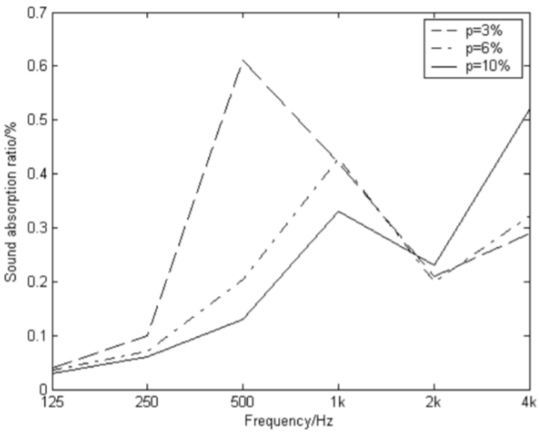


Figure 2.37. Effects of perforation ratio on sound absorption coefficients of perforated panels (Hou et al. 2010).

Peng (2018) compared three perforated panels with different perforation ratios. Panels were designed with the same perforation diameter (2mm) and neck width (0,9mm). Perforation ratios for PP1, PP2 and PP3 are respectively; 5%, 9% and 23%. Peng compared the sound absorption of these three perforated panels by impedance tube measurements and theoretical calculations (Figure 2.38). Sound absorption at high frequencies increases with increasing perforation ratio.

Increasing the perforation ratio raises the resonance frequency. As a result, sound absorption performance of the system at low frequency range decreases. With the high perforation ratio, sound absorption performance of porous material at high frequencies become dominant on sound absorption characteristic of the system.

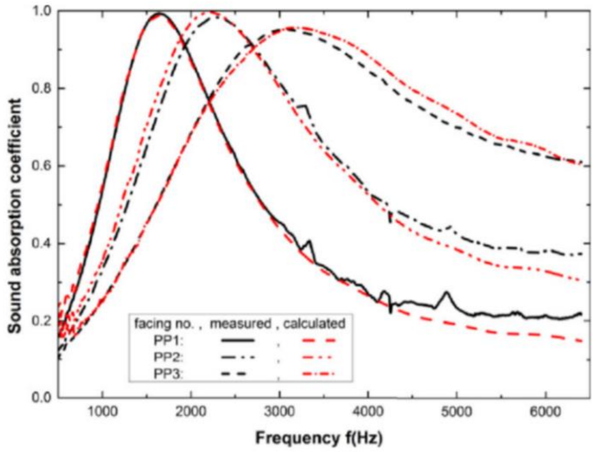


Figure 2.38. Comparison of perforated panels with different perforation ratios by impedance tube measurements and theoretical calculations (PP1: 5%, PP2: 9%, PP3: 23%) (Peng, 2018).

In studies of Borelli, Schenone & Pittaluga (2013), sound absorption coefficients of perforated panels with same perforation diameter (2mm) but different perforation ratios are compared as presented in Figure 2.39. Results support the previously mentioned studies, with decrease of perforation ratio, resonance frequency moves towards to low frequencies.

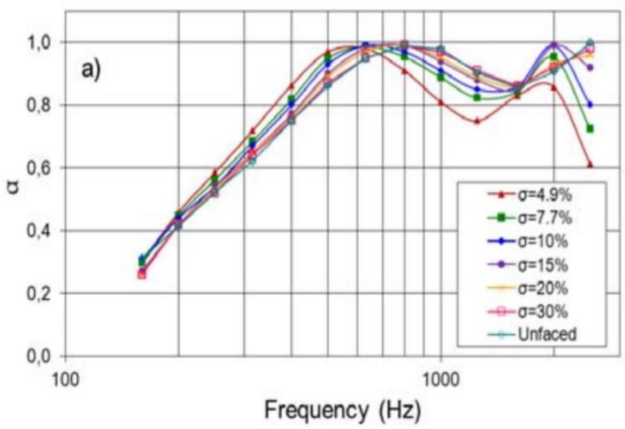


Figure 2.39. Sound absorption coefficients of perforated panels with different perforation ratios (Borelli, Schenone & Pittaluga, 2013).

Selamat, Mat Tahir, Zulkifli, Mohd Nor, Sabri, Elwaleed, & Siti-Munirah (2014) designed three different manually operated system with different perforation ratios (5%, 7.5%, 10%, 15%) and air gaps (20mm, 25mm, 30mm). As a porous absorber 35mm coir fiber, produced from agricultural waste, was used in the air gap. Perforated panels were examined in frequencies between 100 Hz and 4250 Hz by impedance tube measurements. Maximum sound absorption was observed at high frequencies for 15% perforated panel. Obtained maximum sound absorption (α 0,851 in 5000 HZ) increases with addition of 30mm air gap (α 0,963 in 3129 Hz). For the same tunable perforated panel 0,1-point alteration is obtained in sound absorption coefficients for 10%, 12% and 15% perforation ratios (Figure 2.40).

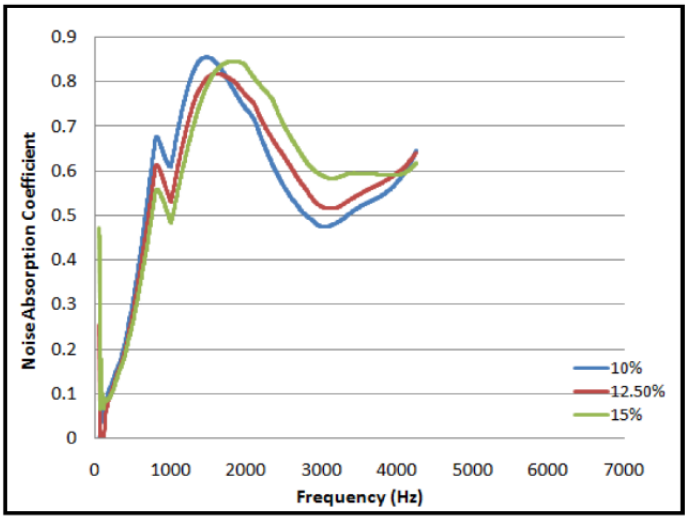


Figure 2.40. Impedance tube measurements for tunable perforated panel with 10%, 12% and 15% perforation ratios (Selamat, Mat Tahir, Zulkifli, Mohd Nor, Sabri, Elwaleed, & Siti-Munirah, 2014)

Increase in perforation ratio can be provided by increasing the hole number on the panel while keeping the width of the perforation constant. In Cox & D'antonio (2009)' study, five perforated samples were produced with 2.5mm hole radius and 6,3mm panel thickness. Samples were installed with 25mm porous absorber with 20.000 rayls m^{-1}; flow resistivity and 25mm air cavity behind. Sound absorption coefficients of samples with different perforation ratios vary from 6% to 100% are shared in Figure 2.41.

Similar with the results shared before, higher perforation ratio increases sound absorption of the system at high frequencies and shifts resonance frequency towards higher frequencies at the same time. Therefore, small perforation ratio provides higher sound absorption at low frequencies as mentioned before.

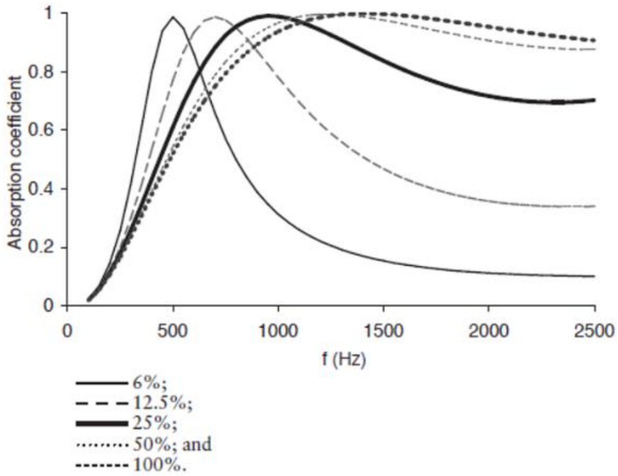


Figure 2.41. Absorption coefficients of the resonators with varying perforation ratio (Cox & D'antonio, 2009).

Relation of perforation ratio and sound absorption performance was tested by Lee and Kwon (2004). Multi-layered acoustical systems were analyzed in terms of the number of perforated panels' effects on sound absorption performance of the system. Furthermore, the system was composed with perforated panels with different perforation ratios and effects of the arrangement was investigated. Three-layer perforated panel system with 70mm air space was configured in different arrangements as shared in Figure 2.42. According to the obtained results; increasing number of perforated panels in the system leads to a more broadband sound absorption. Arrangement of panels from higher perforation ratio to lower results with higher sound absorption performance and this phenomenon was associated with the impedance-matching effect. Therefore, as can be interpreted from Figure 2.42, arrangement of perforated panels in different perforation ratios has a significant role on sound absorption performance of the multi-layered acoustical system (Lee & Kwon, 2004).

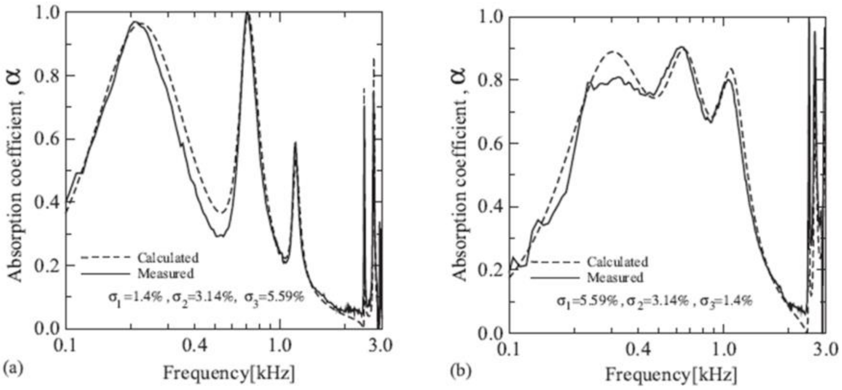


Figure 2.42. Effect of the array of perforated panel compartments on the sound absorption coefficient of the multi-layer sound absorber (Lee & Kwon, 2004).

2.2.3. Panel Characteristics

Perforated panel's material characteristics are also effective on sound absorption characteristic of the system. Perforated panel may also act as a panel absorber and two different resonance frequencies can be observed in sound absorption behavior. As a volume absorber, thickness of the perforated panels is definitive on neck conditions, hence, for resonance frequency.

Effects of neck conditions like length and geometry on resonance frequency are discussed via Helmholtz resonators. These analyses on neck conditions of a Helmholtz resonator can provide a background to understand effects of panel thickness and way of drilling of perforations on sound absorption characteristics of perforated panels.

In studies of Tang (2005), Helmholtz resonators designed with cylindrical necks have neck lengths as 5.5mm and 9mm. Sound absorption coefficient of these Helmholtz resonators are compared in Figure 2.43. For same air cavity length 160mm, increasing in neck length cause the shift of resonance frequency towards to low frequencies and cause the increase in the sound absorption performance of the Helmholtz resonator at low frequencies. At the same time for same Helmholtz, absorption coefficients for higher frequencies than resonance frequency, decrease. For same neck length, neck geometry was altered by tapering from the degree of 0% to 85%. According to results, resonance frequency and sound absorption performance of the system increases with the tapering degree of neck geometry. Therefore, with thicker plates providing longer neck length sound absorption performance of perforated panels can be increased at low frequencies. Moreover, drilling method of perforations (cylindrical or conical neck geometry) is also effective on sound absorption coefficients of the system. Increase in tapering degree increase the resonance frequency.

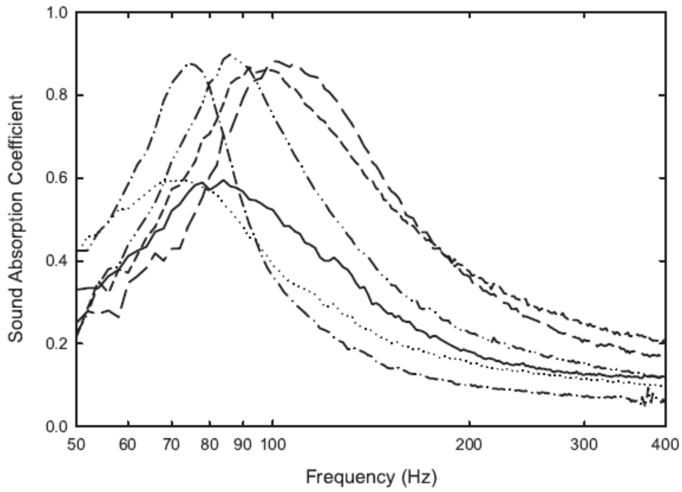


Figure 2.43. Comparison of frequency variations of sound absorption coefficients of Helmholtz resonators with different neck length (nl) and tapering degree: (-) nl=5.5mm, 0% tapered; (---) nl=5.5mm, 69% tapered; (- -) nl=5.5mm, 85% tapered. (···) nl=9mm, 0% tapered; (-·-) nl=9mm, 49% tapered; (-··-) nl=9mm, 69% tapered (Tang, 2005).

Sound absorption coefficients of perforated panel system are tested regarding the plate thickness in studies of Takahashi and Tanaka (2002). Samples were prepared with acrylic plates of 6mm and 0,5mm thickness. One group of perforated panels have 0.2% perforation ratio; with 0.5mm hole diameter and 10 mm hole spacing. Air cavity behind the panel is 100mm. The other sample group has 4.9% perforation ratio with 5mm hole diameter and 20mm hole spacing and installed with 100mm air gap.

Increase in panel thickness increases the length of the neck and affects the vibrating air in the orifices (Mechel, 1994). Depending on impedance of the vibrating air and mass reactance, end correction of the neck is also effective on resonance frequency of Helmholtz resonators. Hence, as can be observed in Figure 2.44, shift of resonance frequency towards to low frequencies by the increase in the panel thickness is expected. Higher sound absorption coefficients can be obtained in low frequencies owing to increases in the thickness of perforated plate.

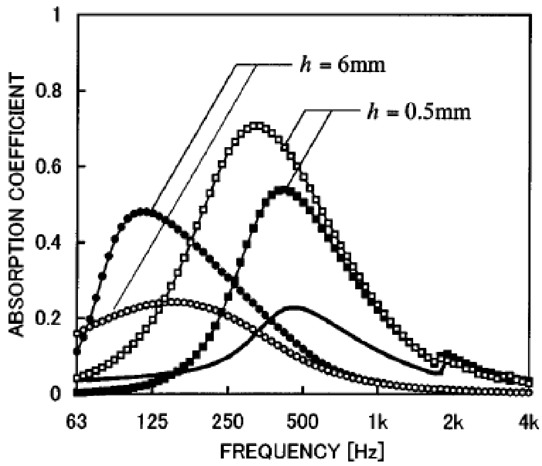


Figure 2.44. Effects of vibration and panel thickness on sound absorption coefficients. (-): 6mm thick perforated panel with 4.9% perforation ratio. Results for with (-●-) and without (-○-) the vibration effect for 6mm thick perforated plate with 0.2% perforation ratio. With (-■-) and without (-□-) the vibration effect for 0.5mm thick perforated plate with 0.2% perforation ratio (Takahashi & Tanaka, 2002).

Lee & Selamet (2003) compared four Helmholtz resonators with different neck lengths. The radius of the Helmholtz resonator is 7,62cm and the length of the resonator is 20,32cm. The neck of the resonator has 2cm radius and 8,5cm length. The total neck length of the resonator was increased with extended necks as described in Figure 2.45. Effects of neck length on the resonance frequency and loss of the energy between input and output are depicted in Figure 2.46. Depending on the increase in the neck length, resonance frequency moves towards to low frequencies.

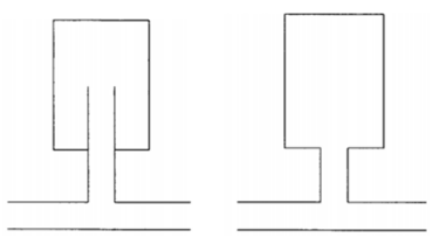


Figure 2.45. Helmholtz resonators with (left) and without (right) extended neck (*derived from;* Lee & Selamet, 2003).

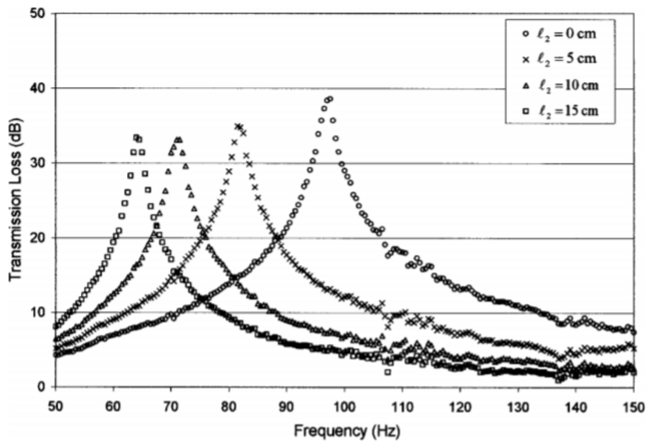


Figure 2.46. Measured transmission loss values for Helmholtz resonator with different extended neck (L2: 0-15 cm) lengths (L1: 8,5 cm) (Lee & Selamet, 2003).

2.2.4. Air Cavity

The defined volume behind necks of perforated panels becomes important to define resonance frequency of the perforated panel system as a volume absorber. Air cavity left behind of perforated panel, increases the sound absorption performance of the system at low frequencies. Moreover, porous sound absorber material can be placed in that cavity. According to wavelength of the frequency that aimed to be absorbed, distance of air cavity can be arranged (λ / 4 distance from backup wall for maximum compression for impinging sound waves) (Egan, 1988).

Effect of air gap is studied for Helmholtz resonators. Resonance frequency decreases towards to low frequencies with the increasing in volume of the resonator. Variable Helmholtz resonators were studied by De Bedout, Franchek, Bernhard & Mongeau, 1997 to control noise as an adaptive – passive sound absorber system. The volume of resonators is arranged with the help of a movable panel and neck diameters were changed to tune the resonator.

Volume of the resonator is arranged, and resonance frequency is controlled with the help of a DC motor and separating plate. Example of an adaptive-passive Helmholtz resonator is described with the Figure 2.47. The position of the separating panel is measured by ten turns of the potentiometer and nine turns of the potentiometer covers a full sweep of the resonance frequency range. Resonance frequency shifts towards to low frequencies with increasing of air cavity. Hence, sound absorption performance of the system increases at low frequencies.

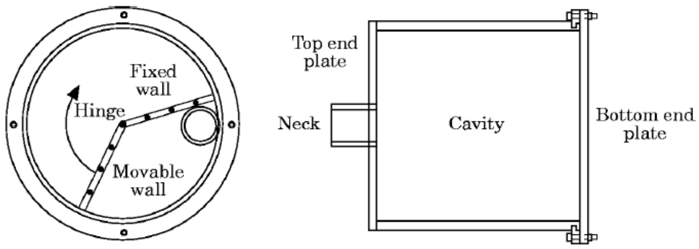


Figure 2.47. Variable cavity of Helmholtz resonator (De Bedout, Franchek, Bernhard & Mongeau, 1997).

Callaway and Ramer (1952) investigated effects of air cavity depth between the perforated panel and porous material for perforated panels. Three samples in studies were installed with glass wool and varying air cavity depths as 1inch (2.54cm), 1/4 inch (6.35mm) and 1/6 inch (1.59mm) (1952). Plywood perforated panels have the same hole diameter 1/2 inch (1.27cm) and perforation ratio 1.28%. In comparison of these three samples, as can be seen in Figure 2.48, increase in air cavity depth also increases the sound absorption coefficients at low frequencies.

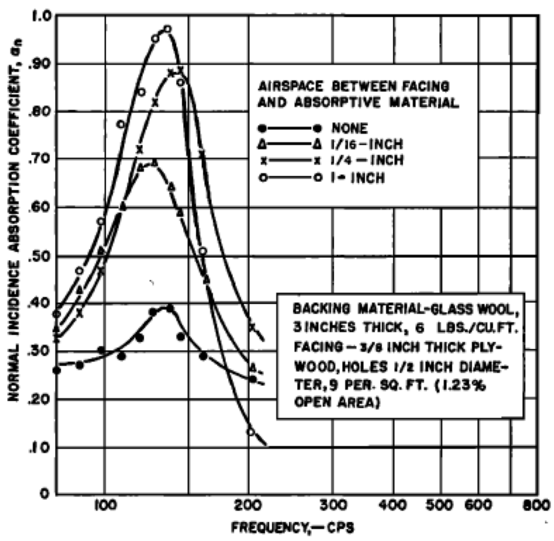


Figure 2.48. Effects of air cavity between perforated facing and porous absorber on sound absorption coefficients (Callaway & Rader, 1952).

In studies of Lee and Kwon (2004) perforated facing with 3.14% perforation ratio and 2mm hole radius is placed with varying air cavities while the other parameters are constant. Samples are analyzed with four air gap alternatives. While keeping other parameters constant, by changing air cavity, its effects on sound absorption coefficients are tested by impedance tube measurements. Peak absorption coefficient for four samples are observed almost equal but, resonance frequency shifts through to low frequencies depending on the increasing in the air gap. Resonance frequency is affected by the depth of air cavity according to the analysis as can be seen in Figure 2.49. Because of the shift towards to low frequencies, although the peak sound absorption is kept constant, sound absorption performance at low frequencies is improved by increasing in air gap according to studies by Lee & Kwon (2004).

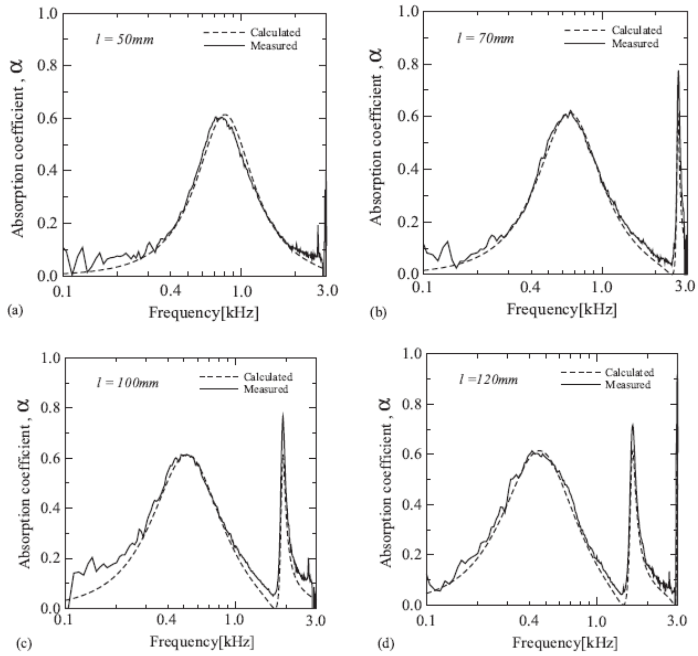


Figure 2.49. Perforated facings with various air cavities (Lee & Kwon, 2004).

Elwaleed, Nikabdullah, Nor, Tahir & Zulkifli (2013) studied macro-perforated aluminum panel. The effect of the air gap was tested, and results are presented in Figure 2.50. Resonance frequency of perforated panel shifts from 2kHz to 1kHz depending on increase in air-gap distance.

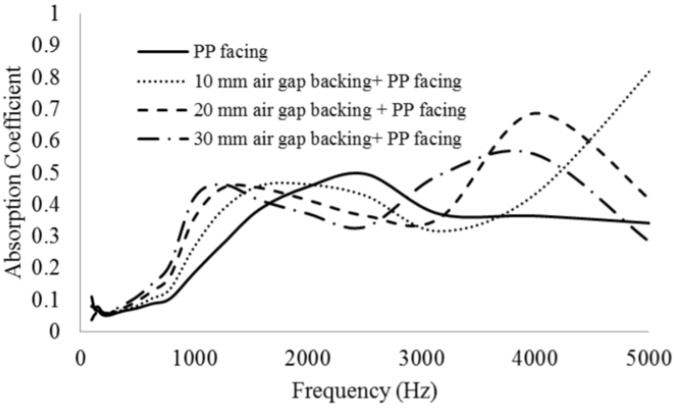


Figure 2.50. Effect of air gap on sound absorption coefficient of perforated panel (PP) with and without porous material produced by palm date (Elwaleed, Nikabdullah, Nor, Tahir & Zulkifli, 2013)

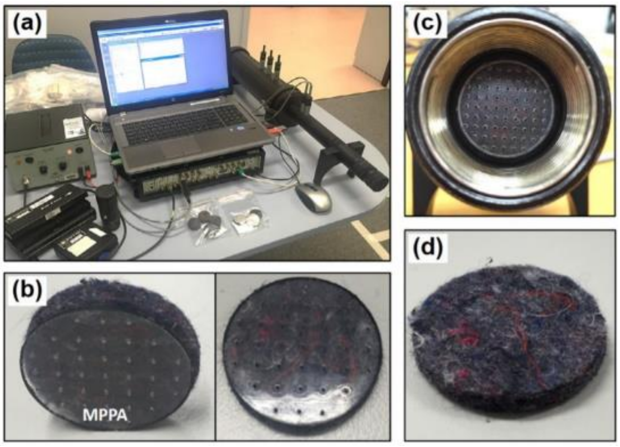


Figure 2.51. a) impedance tube measurement setup b) perforated panel backed with porous material c) test sample in impedance tube d) porous backing material sample (Liu, Zhan, Fard & Davy, 2017).

In studies of Liu, Zhan, Fard & Davy (2017) four micro-perforated panel groups were prepared. Perforation ratios for these groups (MPPA 1-2-3-4) are respectively; 0,9%, 1,59%, 2,63% and 5,9%. Perforation diameter of the panels is 0,6 mm. Sound absorption coefficients of each group are measured by impedance tubes (Figure 2.51). Air gap behind the panels were increased from 2mm to 8 mm. Shift of resonance frequency towards to low frequencies with the increasing of air gap is represented in Figure 2.52. Increasing in sound absorption performance at low frequencies by the increase of air gap can be predicted in consideration with the Helmholtz resonator principles.

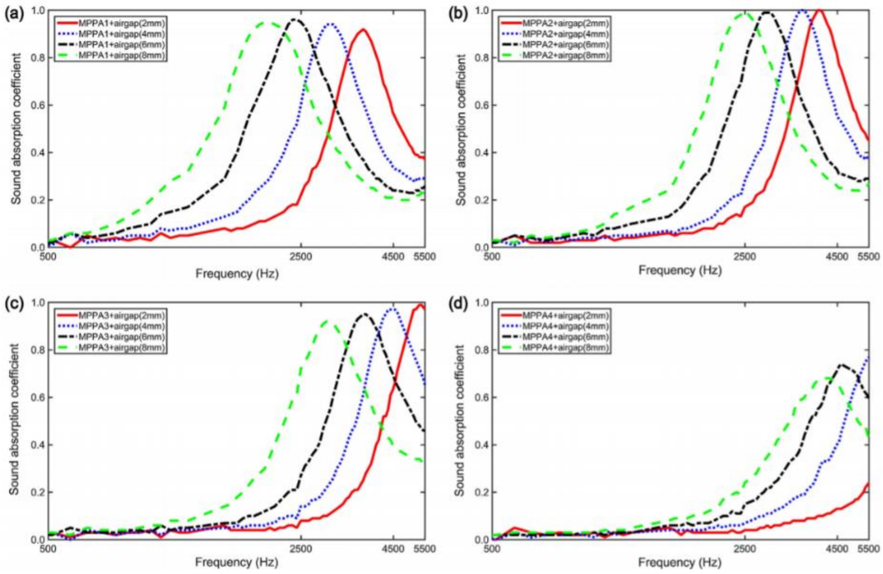


Figure 2.52. Sound absorption coefficients of micro-perforated panels (a, b, c, d) (perforation ratios respectively; 0,9%, 1,59%, 2,63%, 5,9%) with different air gap distances (airgap: 2mm-red, 4mm-blue, 6mm-black, 8mm-green) (Liu, Zhan, Fard & Davy, 2017).

2.2.5. Porous Sound Absorber as Backing Material

The fibrous and granular porous materials transfer acoustic energy to thermal losses with the help of fibers and micro tubes which form the material (Simón & Pfretzschner, 2004). Macro-perforated panels are widely configured with air cavity and porous absorbers to solve architectural acoustics and noise control problems (Takahashi, 1997). Porous absorbers are good absorbers for high frequencies. However, in comparison with their performances at high frequencies, sound absorption performances of porous materials without air gap or perforated facing, are not good at low frequencies. When porous materials are combined with perforated panels, the performance of the system increases at low frequencies. Depending on backing material, alterations in sound absorption characteristics of perforated panels' as a volume absorber, are examined with the help of researches in the literature as presented below.

Volume resonators' sound absorption behavior at resonance frequency may decrease depending on flow resistance of backing material, but higher sound absorption can be obtained in wide band of frequencies (Figure 2.53). Sound absorption performance of perforated panels as a volume absorber needs to be considered with porous material placed in cavity and its flow resistivity (Sakagami, Kobatake, Kano, Morimoto & Yairi, 2011).

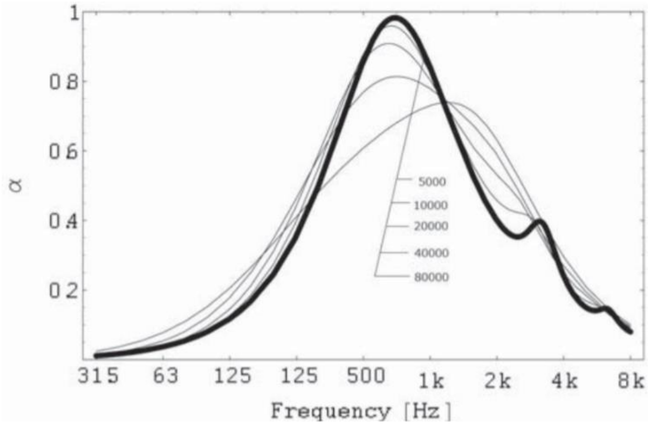


Figure 2.53. Comparison of sound absorption coefficients of a perforated panel with 0.3mm hole diameter, 0.3mm thickness, 0.8% perforation ratio and 50mm cavity depth but different porous material. Flow resistance of porous backing material differs between 5 to 8 kPa.s.m-1 (Sakagami et al. 2011).

Increasing in the thickness of sound absorber material decreases the resonance frequency and the peak sound absorption value of the Helmholtz resonator. For low frequencies below the resonance frequency, slightly higher sound absorption values can be obtained with thicker absorbent. These results can be expected in consideration with the research of Sakagami et al. (2011).

For perforated panel system, placement of porous absorber needs to be considered. Figure 2.54, reveals the effects of difference in placement of porous absorber. For the same air gap, a porous absorber (Glasswool of 25-mm thickness and 32- kg/m^3 density) was placed directly after the panel and as an alternative, the same absorber placed on the rigid wall. Sound absorption coefficients are affected by the position of porous absorber and higher sound absorption performances are predicted when the sound absorber material is placed directly after the perforated panel. The effect of alteration in position of the sound absorber material was quantitatively estimated and represented in reference to the experimental data in studies of Takahashi (1997).

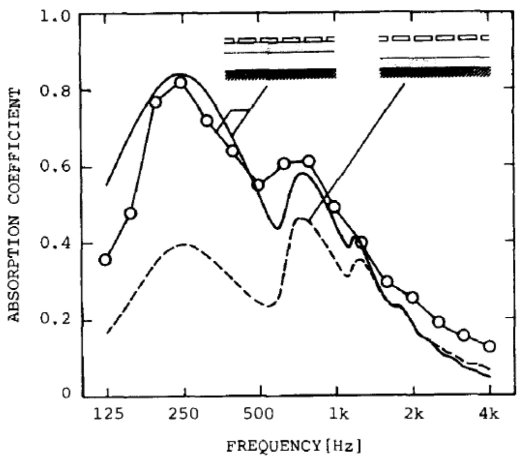


Figure 2.54. Estimation of the effect of difference in porous material's position on sound absorption coefficients (Takahashi, 1997).

Density of porous materials is also effective on sound absorption. A perforated panel and four backing materials with different densities were tested. Perforated plates were produced from 6,5mm hardboard and perforated with 4.7% perforation ratio. Panels were installed with porous materials and 25-mm air cavity (Davern, 1977). Three samples of glass fibers placed as a porous absorber have the same thickness but varying densities. Limits of material-density on sound absorption in comparison with the material thickness are revealed (Figure 2.55).

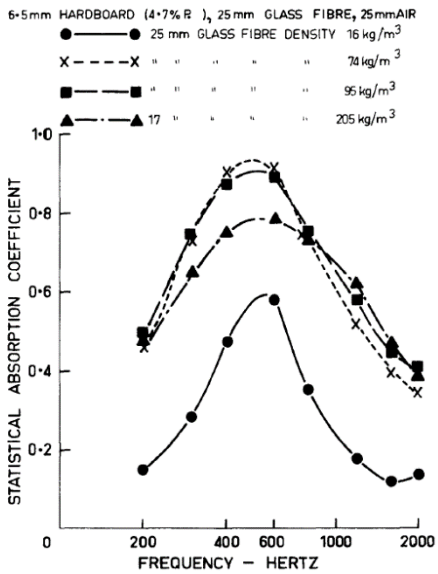


Figure 2.55. Absorption coefficients of samples with varying backing material (Davern, 1977).

Higher sound absorption at low frequencies can be obtained with perforated panels in comparison with porous materials. Placement of sound absorptive material is effective on sound absorption coefficients of the perforated panel system. Presented researches show that, increase in thickness of porous sound absorber material in cavity increases the sound absorption of the system at low frequencies. In Figure 2.55, sound absorption increases up to 74 kg/m^3 density for glass fiber material. Effects of increasing in density of glass fiber on sound absorption is negligible between 74 kg/m^3 and 95 kg/m^3. Sound absorption performance of the system decreases for the sample with 205 kg/m^3 density.

Studies of Patraquim, Godinho, Tadeu & Amado-Mendes (2011) reveal the effects of existence and absence of porous backing material. 12-mm thick wooden panels were used in experiments. Perforated panels have the same perforation diameter: 8mm and perforation ratio: 4,5%. Existence of porous backing material improves the sound absorption performance of the perforated panel system. Difference in density of porous absorber between 40 and 70 kg/m3 does not affect the sound absorption performance of the system significantly (Figure 2.56). The results support the Davern's previously examined studies.

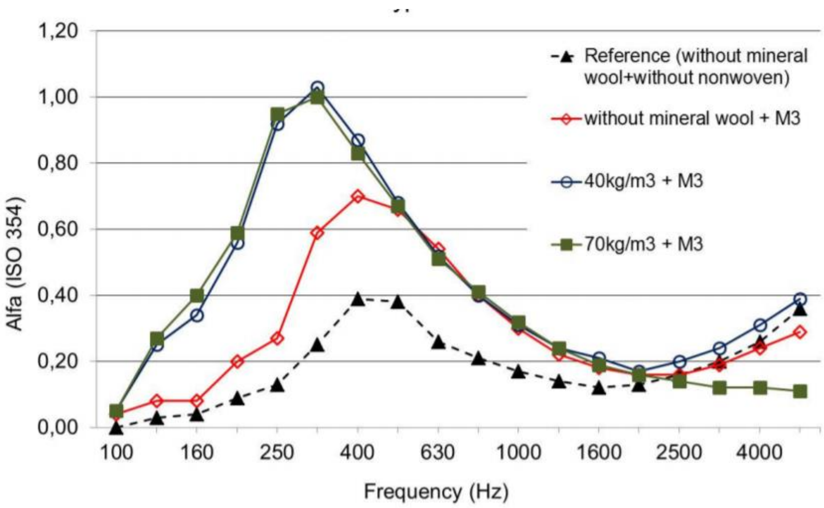


Figure 2.56. Effects of mineral wool and nonwoven textile (M3) on sound absorption coefficient of perforated panels (Patraquim et al. 2011).

Thickness of the backing material supports the sound absorption performance of the system. Moreover, increase in density contributes to the sound absorption of the system up to a certain level, but after that, this contribution decreases.

2.3. Discussion on Literature Review

Variable sound absorptive systems designed with porous absorbers are used to achieve the adaptation of multi-purpose halls to different functions. Porous materials as the most encountered sound absorbers function in variable acoustic solutions. However, changing the sound absorption coefficients of porous materials in the hall is not possible because sound absorption mechanism of these materials depends on inherent features of the material like porosity, fiber length, density and thickness (Long, 2005). Therefore, variable sound absorptive systems focus on changing the application area of sound absorptive materials rather than changing their sound absorption coefficients. On the other hand, studies in literature reveal that perforated panels can operate as tunable sound absorbers (Tayong, 2013). Variable sound absorption coefficients can be obtained by perforated panels.

Perforation width, central distance between perforations and perforation ratio affect the resonance frequency and sound absorption characteristics of the perforated panels. These parameters are also in interaction and can affect each other (Fuchs, 2013; Hou et al. 2010; Peng, 2018). Panel properties, such as; thickness, density and stiffness are also effective on sound absorption characteristics of the system. Perforated panels may work as panel absorber depends on panel thickness and perforation ratio. Hence, increase in panel thickness make perforated panels work as volume absorber (Zwikker & Kosten, 1949). Moreover, thickness of the plate is effective on neck conditions; therefore, it is effective on defining resonance frequency (Takahashi & Tanaka, 2002). Perforated panels are mostly combined with air gaps and porous backing materials. Air cavity increases the sound absorption performance of the system especially at low frequencies (Lee & Kwon, 2004). The thickness of the porous material in cavity also contributes the sound absorption at low frequencies. Increasing the density of porous material up to a certain level can improve the performance of the system but then, continuing to increase the density of porous material further than this level may cause that the material to lose its effect and lead to a decrease in the sound absorption performance of the system (Davern, 1977; Sakagami et al. 2011).

Sound absorption characteristics and capacities of perforated panels have become the subjects of many investigations (Ingard, 1953). Their properties were theoretically identified and the limits of each of these properties are tested with impedance tube measurements or the reverberation room method. Impedance tube measurements can be leading references to design sound absorptive systems (Davern, 1967). Theoretical calculations about sound absorption performances of perforated panels are tested by impedance tube measurements. Comparisons of theoretical results with impedance tube measurements are used to define the accuracy of the numerical methods (Kristiansen & Vigran, 1994).

Helmholtz resonators can be controlled by their design parameters such as volume of air cavity and neck diameter. Cherrier, Pommier-Budinger & Simon (2012) worked on resonators with variable resonance frequencies. Studies reveal that, in the method of decreasing neck opening by shifting overlapped panels, resonance frequency can be arranged. Perforated panels have tunable parameters like Helmholtz resonators. Sound absorption characteristic of perforated panels also depends on design parameters like hole diameter, central distance between perforations, perforation ratio, panel thickness, air cavity, and porous material. In the light of studies on tunable Helmholtz resonators, possibility of designing a tunable perforated panel were examined to obtain a variable acoustic solution in this thesis.

The perforated panel proposal for the research of Randeberg (2000) was also prepared with two macro perforated panels. Randeberg (2000) stated that, distance between panels is more effective in determining the resonance frequency rather than the width of slits.

In studies by Randeberg (2000) parameters of perforated panels used in the experiment vary in the range of 0.11mm to 0.52 mm for the distance between panels; and 1mm to 3mm for the slit width of first panel facing the room volume; 1,5mm to 3mm for the slit width of second panel. In comparison with Randeberg's studies, a broader changing range was proposed for slot widths in this research and variety in sound absorption coefficients of the perforated panel system was aimed to be obtained depending on the changings in the slot width. In addition to that, the proposal aims to be used in halls for room acoustic studies, as a variable acoustic solution.

In the studies of Selamat, Mat Tahir, Zulkifli, Mohd Nor, Sabri, Elwaleed, & Siti-Munirah (2014) according to the impedance tube measurements; the maximum alteration observed in sound absorption coefficients is approximately 0,1 points for the same tunable perforated panel model which was operated in 10%, 12% and 15% perforation ratios. In this research the proposed perforated panel proposal needs to provide more variation than 0,1 points, because the system is proposed to be used as variable acoustic solution as a part of studies in architectural acoustic. The proposed variable sound absorber needs to create more variation in sound absorption to manipulate the acoustical conditions of the hall.

Until this time, several researches investigate the improvement of perforated panels' sound absorption performance and prediction of their acoustical behaviors. Perforated panel systems are proved to be "easily tunable" with high sound absorption coefficient at low and medium frequencies (Tayong, 2013). This cumulated knowledge in literature is regarded as a leading guideline to use these structures as a problem solver, for instance when solving a variable acoustic problem.

Variable acoustic solutions have been developed to tune halls for different proposed functions as conference, opera and concert uses. Objective room acoustic parameters can be controlled by the help of these solutions. Variable acoustic requirements are not only caused from major functional differences: from rock music to folk music many different acoustical requirements need to be considered separately (Barron, 2009). Therefore, the variable acoustic system needs to have a high capacity of adaptability.

Size of occupancy is another parameter need to be considered. In comparison with an unoccupied hall while assessing the acoustical conditions of a hall, presence of audience may cause lower reverberation time than the estimated conditions for an unoccupied hall. In terms of alterations in a hall, variable acoustic solutions have been developed and improved to change acoustical conditions. During the rehearsals of orchestra, variable absorptions can be used to adjust the reverberation time to obtain performing conditions with audiences matching with rehearsal conditions. Investigated cases reveal that variable sound absorptive systems are mostly developed with curtains or with other porous/fibrous absorbers (Aretz et al. 2009; Möller, 2017). Sound absorption characteristic of these porous materials does not let an easy tuning. Hence, developed mechanical systems as; retractable sound absorbing curtains, hinged panels, rotatable elements, sliding facings, change the application area of proposed materials in the hall rather than sound absorption performance of these materials (Egan, 1988).

Most of the multi-purpose halls which are tuned with variable sound absorptive systems, also contain perforated panels applied on side walls, back wall or ceiling panels for acoustical reasons. These perforated panels are kept unchanged in the hall and porous absorber amount in the hall is altered by previously mentioned mechanical systems to configure the hall for different functions. On the other hand, studies on Helmholtz resonators as a volume absorber indicate that tuning these absorbers by altering design parameters like neck dimension and volume of air cavity is possible. Similar to Helmholtz resonators, sound absorption characteristics of perforated panels is also dependent on that kind of design parameters; neck dimension, central distance between holes, perforation ratio, air cavity, panel thickness and properties of porous absorber that the system is combined with. Capacity of each parameter were investigated, and their possibilities were shown in previous studies. At the end, it can be interpreted as: perforated panels can be tuned like Helmholtz resonators. Perforated panels can act as an acoustically transparent screen and characteristics of the porous material as a backing material may become dominant depending on perforation ratio. On the other hand, high sound absorption performance can be obtained in mid and low frequencies depending on neck diameter. Studies on tuning perforated panels and tuning a hall will be combined and potentials of perforated panels as a variable acoustic solution will be investigated in this research.

CHAPTER 3

MATERIAL AND METHOD

The research materials and the methodology of the research are presented and described within this chapter. Structure of variable perforated panel, construction of the prototype and architectural features of the case, METU Architecture Faculty Amphitheatre, are explained as materials. Then, the process for the assessment of perforated panel proposal is elucidated mainly in two steps as the method of the research. First, perforated panel samples are produced, and variable sound absorption performance of the proposal is tested by impedance tube measurements and regression analysis. Secondly, the proposal is examined on a case as a variable acoustic solution by field measurements and room acoustic simulations by ODEON room acoustic software.

3.1. Research Materials

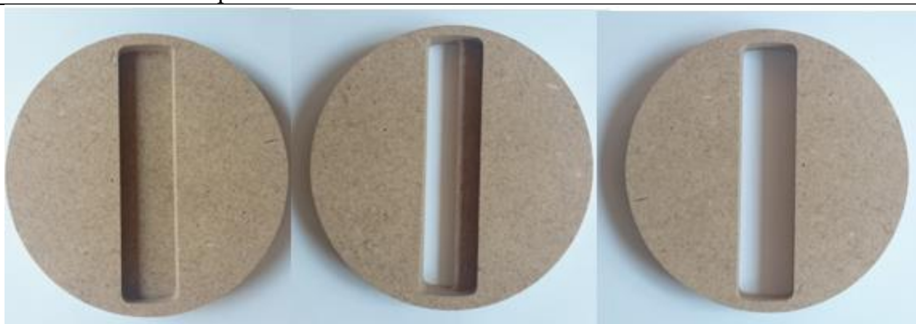
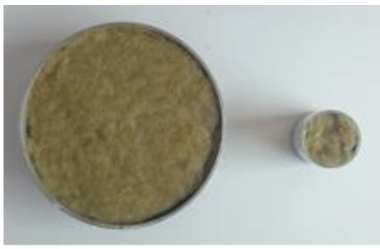
The variable perforated panel system and its sound absorption performance are aimed to be controlled by variation in perforation ratio while other design parameters like air gap and porous material were kept constant. The variable perforated panel system was configured with two identical perforated panels and the perforation width was adjusted by the sliding movement of one panel over the other, fixed perforated panel. Furthermore, a prototype was built to reveal the possibility of a variable perforated panel system as mentioned above. The prototype was configured to adapt physical perforated panel model to different acoustical requirements of a multi-purpose hall. Multi-purpose halls are expected to respond to different acoustical requirements of several functions from speech to music. Therefore, while building the prototype, firstly, an “interface” to control the perforated panels is required. Secondly, commands coming from the interface are transferred to physical movement by an electronic and mechanical configuration. Finally, digital and physical control mechanisms are integrated with perforated panels and structural profiles, so the prototype of variable perforated panel system is obtained. After the panel configuration was clarified and realized by a prototype, the proposed perforated panel system was tested on a case as a variable acoustical solution. The amphitheater of METU Department of Architecture is chosen as a case since it is currently hosting different organizations for functions from lectures to musicals and concerts. In the following sections each step is explained in detail.

3.1.1. Perforated Panel Configuration

The perforated panel proposal needs to be controlled by one of the design features of perforated panels to obtain a variable acoustic solution in scope of this research. The perforation ratio, the width of perforations and the space between them are effective on the sound absorption characteristics of the perforated panels with air gap behind panels and porous absorber as a backing material. Alteration in width of perforations affects the distance between perforations and finally defines the perforation ratio. Therefore, by controlling the perforation ratio with width of perforations, the aimed variability can be obtained while conditions of the other design features like air gap, porous backing material and panel thickness are constant.

The variable perforated panel was proposed for use in rooms for acoustical design. Therefore, perforated panel samples were crafted from wooden panels, regarding common usage of wooden perforated panels in halls and auditoriums. Changes in perforation width and eventually in perforation ratio is provided by two identical panels and sliding movement. These two identical panels are produced from 8-mm and 3-mm thick raw MDF panels and placed such that panels are adjacent to each other with no additional gap. Some of the produced perforated panel samples for impedance tube measurements are presented in Table 3.1 with rock wool as the backing material. The opening size was tried to be controlled by sliding one of the identical perforated panels over the other stationary panel (Figure 3.1). The fixed panel which is facing the hall volume was made by the thicker MDF panel (8mm) to support the durability of the system. Slot perforation was preferred rather than circular to be able to control the shape of perforation while the width is changing. The range of perforation ratio was defined in a range between 2% and 20% as depicted from the literature review. Accordingly, the width of slot perforations changes from 2mm to 20mm to control perforation ratio (Figure 3.2). Five different modes of perforation with 2%, 4%, 8%, 12%, 16% and 20% perforation ratios are obtained depending on this alteration. The direct relation between the size of air gap and the amount of sound absorption performance of the perforated panel system, is revealed owing to the previous researches in literature, especially at low frequencies. In addition to that, contribution by the increase in thickness of porous material in air gap up to a certain level and effects of rock wool density as porous material were discussed by several studies as shared in literature. Therefore, considering former studies: 20 cm air gap was left behind the panels and within this gap 2 layers of 5 cm 50 kg/m^3 rock wool (10cm in total) are placed in panel configuration.

Table 3.1. *Samples of the perforated panel system and backing material*

<table>
<tr><td colspan="2">100mm diameter samples</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>28mm diameter samples</td><td>2 x 50mm 50 kg/m^3 rockwool</td></tr>
<tr><td></td><td></td></tr>
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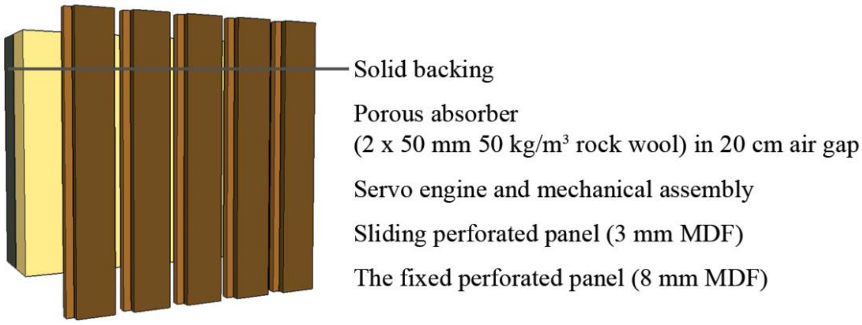


Figure 3.1. Schematic three-dimensional model of the perforated panel proposal (Eşmebaşı, Tanyer & Çalışkan, 2017)

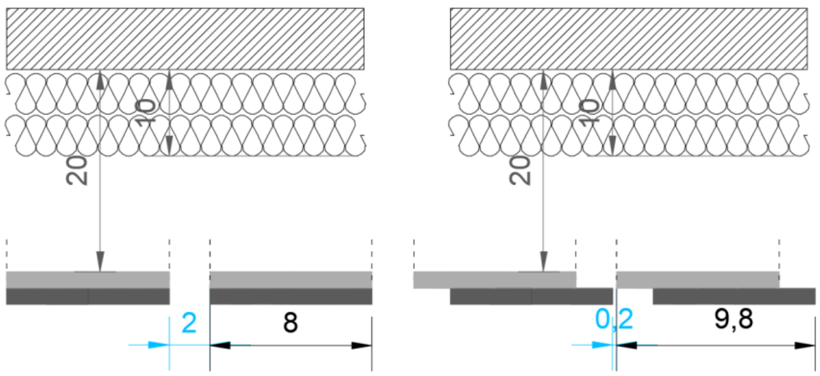


Figure 3.2. Schematic description of variability in perforations

3.1.2. Prototyping

The perforated panels can be applied on wall or ceiling surfaces as cladding. In literature, studies reveal that placement of porous material affects the sound absorption performance of perforated panels. Porous material which is placed directly after the perforated panels possesses higher sound absorption performance. However, placing porous material on wall or ceiling surfaces is preferable when convenience in application is considered. In addition to that, in specific to this case, sliding movement is suggested for perforated panels. Thus, application of porous material on fixed surfaces is more convenient in order to protect porous material from any hazard due to friction caused by movement of perforated panels.

The prototype is designed to reveal the possibility of variable perforated panel's realization. The construction phase of the prototype is configured in three steps. First, a control mechanism as a digital interface is designed to control sliding amount. The perforated panel proposal is aimed to answer different acoustical requirements of a multi-purpose hall; hence, proposed functions for the multi-purpose hall are represented as visual entities/modes in designed digital interface. These modes work like buttons to arrange panel positions according to previously defined angles for specific functions. Intended panel positions for different functions like speech, musical and concert are represented with these digital buttons. Moreover, a slider is provided by the same digital interface to enable the configuration of panels. This slider works like a manual potentiometer. Therefore, it is also possible to build this control mechanism physically with buttons and a potentiometer rather than using digital means.

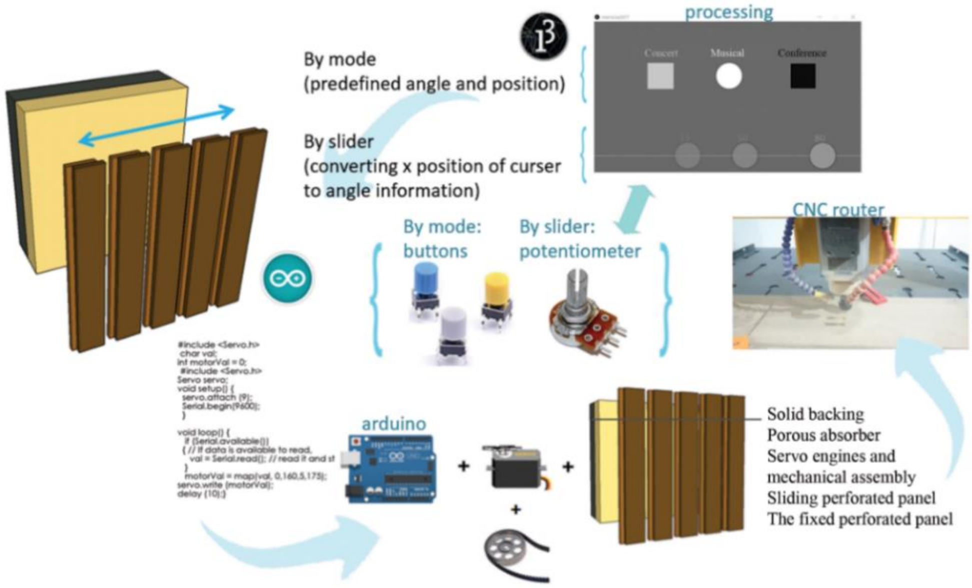


Figure 3.3. Schematic description of prototyping for perforated panel proposal

The electronic system is required to convert commands coming from the digital interface to physical movement. In second phase, the electronic system of the prototype is designed with Arduino board. Information provided via an interface designed in "Processing" transferred to physical movement by an Arduino board with the help of servo engines. Processing is a software sketchbook and a programming language, capable to generate images, computer graphics and provide motion and interaction (Reas & Fry, 2007). The rotational movement provided by servo engines is converted to lateral sliding movement by timing pulleys and belts. Open source software and easily accessible hardware are used to build the prototype, with a purpose to enable the prototype to be rebuilt and improved by concerned subjects. So, the experimental design of the prototype is open to improvement in further studies.

In the third and final step, 8-mm and 3-mm thick raw MDF panels are perforated by CNC router and laser cutting machine. The perforated panel facing to the hall volume (8 mm) is fixed by profiles. Mechanical system which is electronically controlled by Arduino board is combined with the moving perforated panel which is placed directly after the fixed first panel. Hence, following these three steps as descripted in Figure 3.3, the aim of revealing the realization possibility of proposed variable perforated panel system was achieved. (Eşmebaşı, Tanyer & Çalışkan).

3.1.3. METU Architecture Department Amphitheatre

The Amphitheatre and architecture faculty were built as a part of University campus project. The campus project of Middle East Technical University was designed by a national competition in 1961. Altuğ Çinici and Behruz Çinici won the first prize and designed the campus project including architecture faculty and its amphitheater ("50th anniversary exhibition," n.d.). The campus project has been awarded by Aga Khan Award ("Re-Forestation Programme of METU," n.d.). The buildings on the campus is awarded by the Getty Foundation owing to their architectural quality ("Keeping It Modern: 2017 Grants Awarded," 2017).

The Amphitheatre (Figure 3.4) as a part of the campus project and Architecture Faculty was designed with same modernist attitude. The reinforced concrete main structure was exposed, in reference to the principle of material honesty. Reinforced concrete walls (thickness varies in 25cm and 40cm) placed in almost square shaped floor plan. The dimensions of floor plan are 25.08 m to 26.2 m (Figure 3.5). The height of ceiling of the hall varies from 4.1 m to 5.8 m (Figure 3.6). The seating capacity of the hall is 357. The Amphitheatre was originally designed for lectures and speech functions (Hejjo, 1986). However, from conferences to musicals, Turkish music and classical music, the amphitheater serves to the university and the architecture faculty as a multi-purpose hall.

Figure 3.4. View from the interior of METU Architecture Faculty Amphitheatre

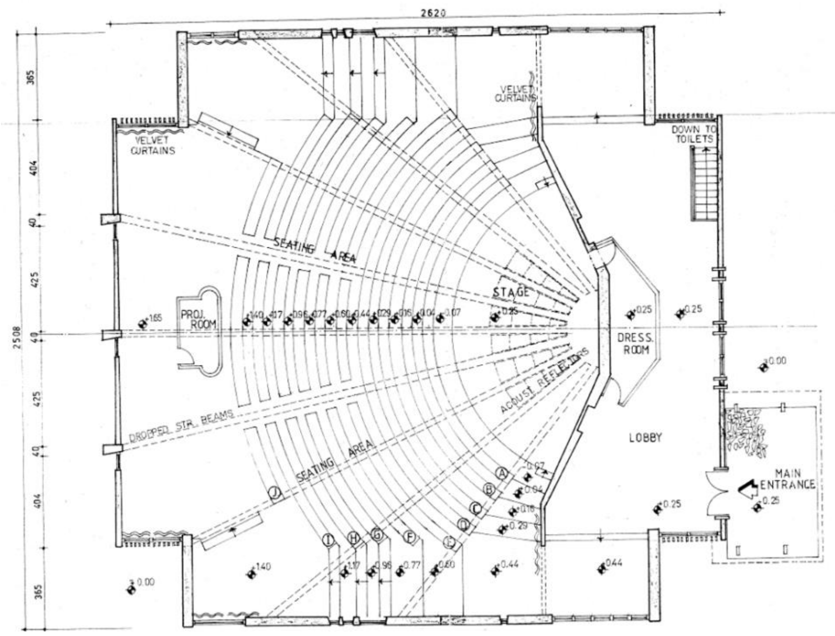


Figure 3.5. Plan of the Amphitheatre (Hejjo, 1986)

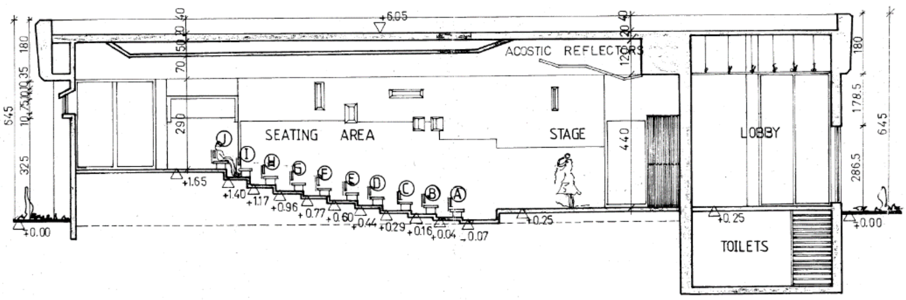


Figure 3.6. Longitudinal section of the Amphitheatre (Hejjo, 1986)

The 3D model of the amphitheater was modeled in Sketch-up modelling software and transferred to the acoustic simulation software, ODEON. Absorption coefficients of commonly used materials in auditoria are shared by Bies, Hansen & Campbell (2005), Barron (2009) and Long (2005). Sound absorption coefficients of finishing materials in the Amphitheatre are specified for room acoustic simulations regarding results of field measurements and sound absorption coefficients of materials presented in literature and material library of ODEON V.14.03 room acoustic software. The acoustical model for simulations was calibrated according to field measurements.

3.2. Research Method

Research methodology is configured in two main phases. In the first step, the perforated panel samples were produced by CNC routers and laser cutting machine. Furthermore, the perforated panel proposal was analyzed by impedance tube measurements and regression analysis. Sound absorption coefficients of the system in different panel positions were measured with impedance tubes on a standing wave system by SCS. The relation between change in sound absorption coefficients and perforation ratio depending on panel positions were examined with regression analysis. In the end of these sequences, the realization possibility of the perforated panel proposal providing variable sound absorption performance is proved.

In the second phase, the perforated panel proposal is assessed as a variable acoustic solution by field measurements and simulations in ODEON room acoustic software. Current acoustical condition of the Amphitheatre is displayed by field measurements.

In the first step sound absorption coefficients for variable perforated panel system obtained by impedance tube measurements. Furthermore, outcomes of the first step were assessed in simulations held by ODEON room acoustic software at the second step. Acoustical condition of the multi-purpose hall (METU Architecture Faculty Amphitheatre) was arranged for different functions by the help of perforated panel proposal. Hence, the potential of the perforated panel system was analyzed and investigated as a variable acoustic solution.

3.2.1. Sound Absorption Performance of the Variable Perforated Panel System

Sound absorption coefficients for variable perforated panel system were measured via Kundt's tubes / impedance tubes. Samples were prepared for each different phase of the variable perforated panel system. Circular samples were cut out from slotted panels for measurements. Impedance tube measurements is one of the fundamental methods with reverberant room to measure sound absorption coefficients.

Kristiansen & Vigran (1994) discussed the results of impedance tube measurements in circular cross-section for slotted panels in rather small and inhomogeneous samples by comparing with the transfer matrix method which simulates the experimentation assuming test samples of infinite extent. The slotted panels are composed of parallel beam series. For the measurement, a circular part is cut out from these serial repetitive pattern as indicated by the circle in the Figure 3.7. Finite element modelling is produced to make comparison with the measurement results. In conclusion, the calculations are assessed in good agreement with the measurement results despite of the concerns about measurements with small and rather inhomogeneous samples.

Standing wave tubes are excellent tools to develop absorbers and the fit between the measurement and calculation results support this claim. The coherent results of two experiments can be evaluated encouraging for the development of absorbers with various geometrical forms and slits which are not easy to estimate analytically (Kristiansen & Vigran, 1994).

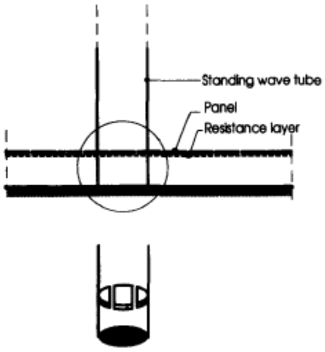


Figure 3.7. Measurement sample cut out from the real application of resonant absorber (Kristiansen & Vigran, 1994)

Perforated panel samples were manufactured from 8mm and 3mm raw MDF panels by CNC router and laser cutting machine (Figure 3.8) for the impedance tube measurements in the scope of this research. S.C.S Kundt impedance tubes and dBFA Suite 4.8.1 frequency analysis software were used in measurements performed by transfer function method according to ISO 10534-2 (1998) standards (Figure 3.9). The 200-mm air gap was left behind the perforated panels for impedance tube installation similarly to the proposal for real application of panels in a hall. Two layers of rock wool in 50 kg/m^3 density and 50mm thickness (100mm in total) was placed in the air gap as attached to the metal backing plate of tube. Samples were produced in 28-mm diameter for high frequency measurements and 100-mm diameter for low frequencies. Perforated panels were placed as the second one is directly after the first fixed perforated panel (Figure 3.10). The second perforated panel which is suggested to laterally slide to control the perforation width is produced for different panel positions to obtain 2%, 4%, 8%, 12%, 16% and 20% perforation ratios. The second panel was replaced for each scenario in the same setup of the experiment, and sound absorption coefficients of the system were measured in 1/3 octave bands.

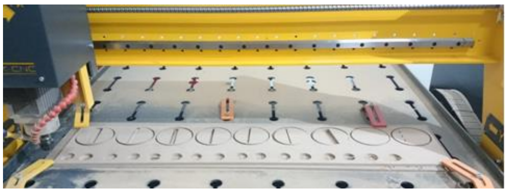


Figure 3.8. Manufacture of perforated panel samples by a CNC router

Figure 3.9. Impedance tubes for sound absorption coefficient measurements

Figure 3.10. Samples placed in impedance tube for sound absorption coefficient measurements

Changes in the width of perforations change the perforation ratio. However, for the proposed variable panel organization, perforation widths are controlled by two panels, therefore neck conditions and placements of panels are included in sound absorption mechanism of the system. Hence, despite of the relation between perforation width, ratio and the sound absorption performance is predictable, to make the uncertainty between proposed panel configuration and the aimed alteration in perforation ratio clear: the relation between sound absorption coefficients of the perforated panel system in each phase and panel positions were assessed statistically with regression analysis. The degree of relation between sound absorption coefficient and perforation ratio which is provided by perforation width controlled by two panels was discovered.

3.2.2. Perforated Panel Proposal as a Variable Acoustic Solution

Computational models and room acoustic simulation software are crucial parts of the acoustical design and assessment. With the help of the potent simulation software, it is possible to analyze and assess acoustical conditions of an actual space in prior design process before actual construction (Schmidt and Kirkegaard, 2004). Therefore, different scenarios in acoustical design can be assessed in limited time span thanks to simulation software. According to Bradley and Wang (2007), within these simulation software, hybrid methods of the image-source method, ray tracing and classical diffusion/scattering models such as ODEON, provide most accurate results. For the METU Architecture Faculty Amphitheatre as the case of this study, computer simulations need to be operated to compare the difference in the acoustical conditions depending on presence of proposed perforated panels. The response of the hall to variations in perforated panels can be easily assessed in a short time owing to the simulation software. Therefore, the acoustical model of the Amphitheatre was constructed, and simulations were employed by ODEON room acoustic software.

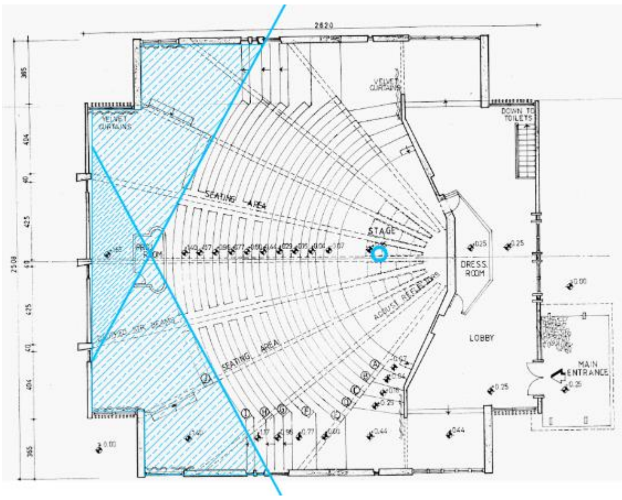


Figure 3.11. Wall surfaces suitable for sound absorber application

The detail level and accuracy of the model for simulation of an acoustical model is not the same as an architectural model. Modelling the room over a certain detail level causes complicated geometric models for simulation software like ODEON and has negative effect on the accuracy of the simulation results. After the acoustical model is imported to the simulation software, sound sources and receivers are defined. Impulse response and acoustical parameters of the space are simulated within the acoustical model (Bradley and Wang, 2007).

The acoustical model of the hall was calibrated according to the field measurement data. The current acoustical conditions of the hall are simulated and perforated panel proposal is placed on the wall and ceiling surfaces which are not effective for initial reflections (Figure 3.11, Figure 3.12).

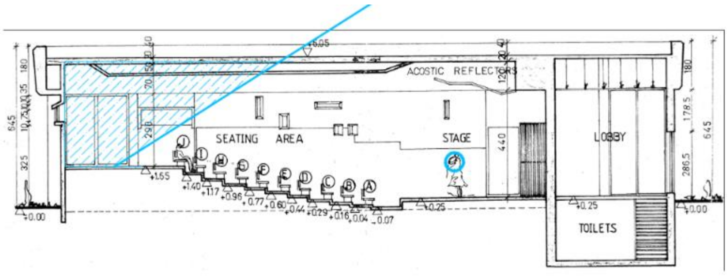


Figure 3.12. Ceiling surfaces suitable for sound absorber application

The acoustical model of the METU Architecture Department Amphitheatre was prepared with the help of AutoCAD and SketchUp software. It is composed of 677 plane surfaces. The model is prepared based on drawings representing latest status of the amphitheater shared by Hejjo (1986) in reference to drawings of Altuğ and Behruz Çinici. The waterproofness of the model was tested by ray tracing studies Figure 3.13. The acoustically effective volume of the space is ~2200 m^3. The hall has 357 seating capacity and acoustically active volume per person in the hall is ~6,2 m^3. The amount of the volume per person is suitable for multi-function halls.

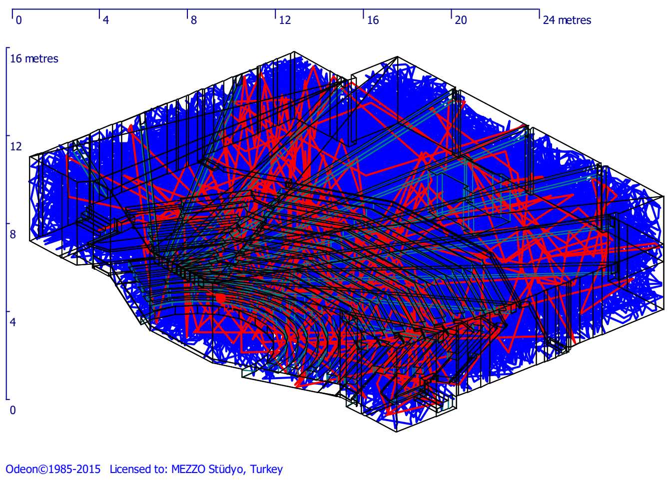


Figure 3.13. ODEON ray tracing view for the Amphitheatre

The omni-directional source was placed on stage as 1.5 m above the stage level representing the lecturer for simulations to estimate the reverberation time (Figure 3.14 & Figure 3.15). Acoustical parameters were assessed with distribution maps which is representing acoustical conditions at audience positions in the hall.

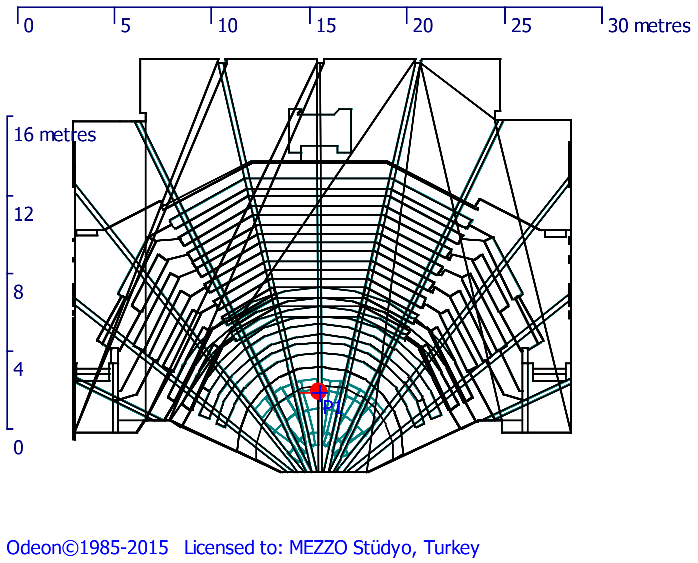


Figure 3.14. Source position in plan view of the Amphitheatre

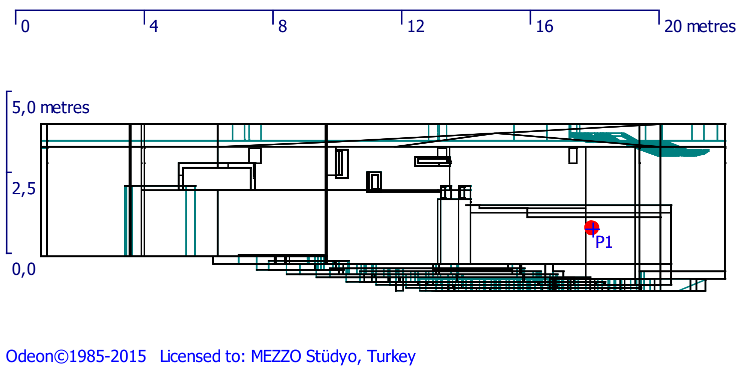


Figure 3.15. Source position in section view of the Amphitheatre

Finishing materials in the hall were defined in simulations regarding their sound absorption and scattering coefficients. Sound absorptive materials in the hall are represented in darker colors in 3D-OpenGL images Figure 3.16. Sound absorption coefficients of materials were reconsidered and adjusted according to results of field measurements conducted in the hall. This calibration process is widely common in academia and industry. Variables mostly like sound absorption and scattering coefficients are manipulated according to results of field measurements in calibration process. The difference in these results is caused by “test set-up discrepancies” and “difference in the material properties” (Bradley and Wang, 2007). The calibration process aims to match simulation results with measurement data of the actual space.

Figure 3.16. ODEON OpenGL view of the Amphitheatre

3.2.3. Room Acoustic Field Measurements

Acoustical field measurements for the Amphitheater are performed according to ISO 3382-1 (2009). Omnidirectional loudspeaker (B&K type 4292-L), power amplifier (B&K type 2734-A) and hand-held analyzer (B&K type 2250-A) were used in the measurements. DIRAC room acoustic software is used to collect data about impulse response and objective room acoustic parameters for each microphone position.

Field measurements were performed on 31st of August 2018 (Figure 3.17). The measurement date was arranged in accordance with the METU Office of Cultural Affairs and METU Theater Community, hence the Amphitheatre was to be unoccupied during the field measurements and background noise level was at minimum. Omni-directional sound source was located on stage 1.5m above the floor level. Distance between receivers was higher than 2m. Distance between microphone and nearest building element was more than 1m. Six microphone positions are proposed for halls up to 500 seating capacity. The proposed microphone number increases to 12 for halls with seating capacity of 2000. The seating capacity of the Amphitheatre is 357. To provide a precision, measurements were held at 12 microphone positions (Figure 3.18). Room acoustic features of the Amphitheater (EDT, T20-T30, C(80), STI) are obtained by DIRAC room acoustic software.

Figure 3.17. METU Architecture Faculty Amphitheatre, room acoustic field measurement photographs taken on August 31st, 2018

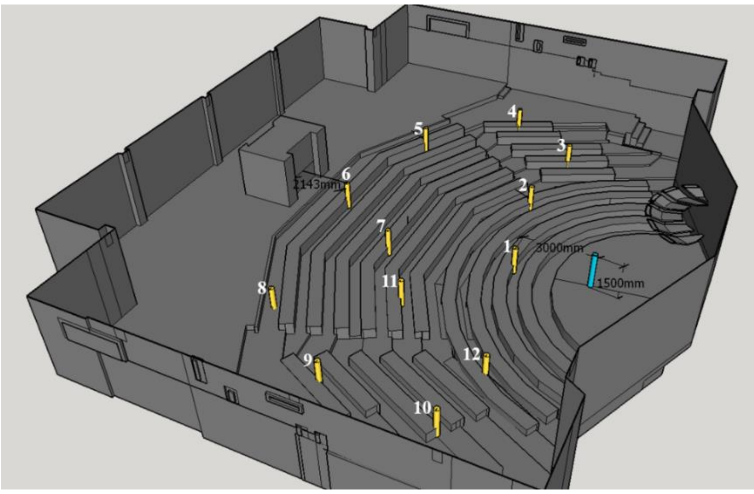


Figure 3.18. Representation of source and microphone positions in the hall

CHAPTER 4

RESULTS AND DISCUSSION

This chapter covers impedance tube measurement results and findings of the regression analysis on the relation between sound absorption coefficients and panel positions of the perforated panel proposal. In the light of the obtained results, sound absorption characteristic of perforated panel proposal in low, mid and high frequencies and the variance in sound absorption coefficients of the perforated panel proposal in different panel positions were analyzed.

In following steps, the capability of the perforated panel proposal as a variable acoustic solution is discussed. Acoustical conditions of the METU Architecture Faculty Amphitheatre were described with objective room acoustic parameters as reverberation time (T30), early decay time (EDT), clarity (C(80)), speech transmission index (STI) and distribution of A-weighted sound pressure level (SPL(A)). Room acoustic parameters and target values were presented according to proposed functions for the hall. The acoustical design of the hall was adapted for different scenarios by the help of variable perforated panels system. Acoustical conditions in the hall are simulated by ODEON room acoustic software and outcomes of the simulations were explained for different panel positions. The room acoustic simulations are calibrated according to the field test performed in the Amphitheatre and the results of the field measurements representing the current acoustical situation in the hall are shared. Hence, the competence of the perforated panel proposal as variable acoustic solution was discussed by room acoustic simulations.

4.1. Sound Absorption Data and Discussion

The effects of air gap and porous backing material on sound absorption performance of perforated panels especially at low frequencies are covered in literature. The perforated panel proposal in this study was configured according to the cumulative knowledge owing to previous studies in literature. Furthermore, the perforated panel proposal is tested with different air gap, porous material thickness and perforation ratios to support these deductions from literature. Sound absorption characteristic of different configurations at low frequencies was analyzed before the final decision about the air gap and porous material thickness for the proposal. These tests are performed by impedance tubes with 100mm diameter samples for low frequencies. Therefore, sound absorption coefficients of samples were presented up to 1 kHz that impedance tubes allow for low frequency measurements.

On Table 4.1 several perforated panel sets are prepared with the same perforation ratio but with different slot width, air gap, porous material layer and panel thickness. Effects of these design parameters on sound absorption at low frequencies were compared. Panels were manufactured from 8mm and 3mm MDF panels with same perforation ratio arranged by sliding one of the panels. Distance of the air space behind the panels varies as 50mm, 100mm and 200mm. 50-mm thick porous material (rock wool) of density 50kg/m^3 was proposed to be placed in air gap as attached to the wall. Furthermore, the difference between placing one layer (50 mm) or double layer (2 x 50 mm) porous material (50kg/m^3 rock wool) in 200 mm air gap was analyzed. Thickness of the fixed panel, facing the hall interior, was increased from 3 mm to 8 mm to strengthen the perforated panel proposal. Effects of panel thickness on sound absorption coefficients of the system are also presented.

The comparison has settled 12% perforation ratio as optimum. Sound absorption performance of the backing material becomes dominant for higher perforation ratios. Several perforated panel configurations with the same 12% perforation were compared in Table 4.1. The comparison is repeated for 2% perforation ratio and 2-mm slot width on D, E, F and G samples to observe the effect of air gap on sound absorption at low frequencies clearly (Table 4.2). Perforated panel samples with same air gap and porous material but different perforation ratios (2% and 12%) were compared in Table 4.3.

Table 4.1. *Panel samples have same perforation ratio (12%) but different slot width, air gap distance, porous absorber layer and panel thickness*

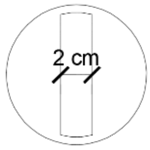
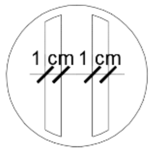
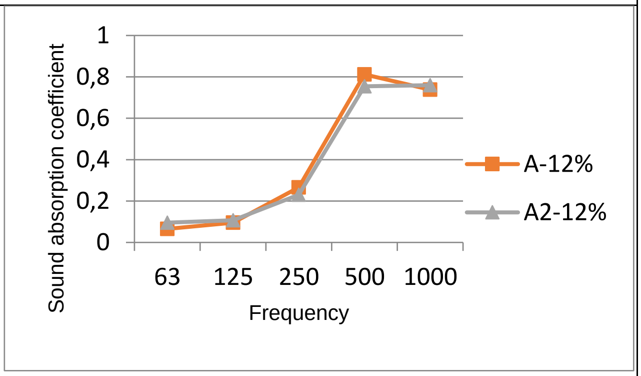
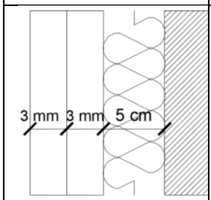
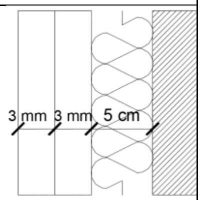
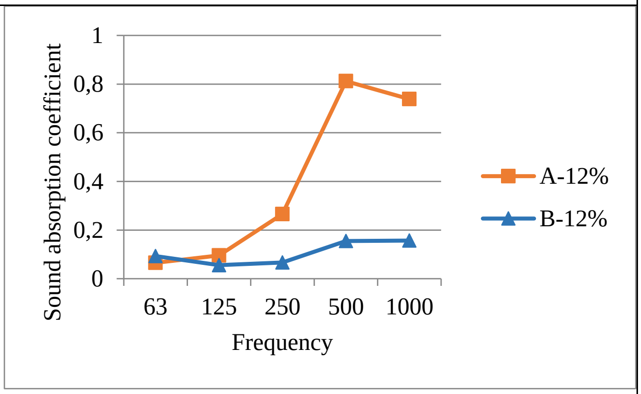
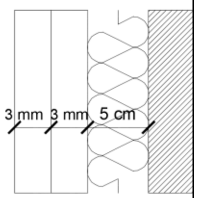
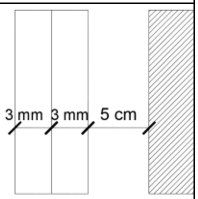
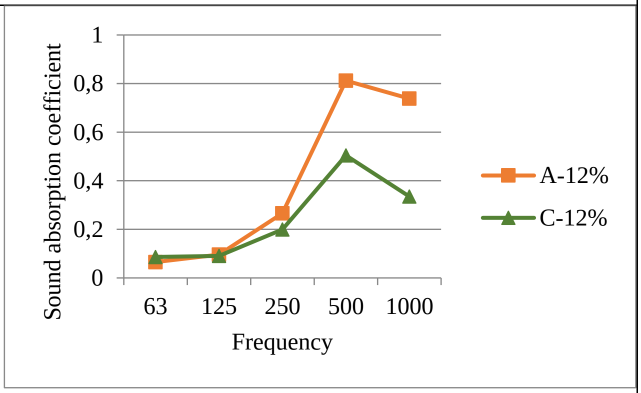
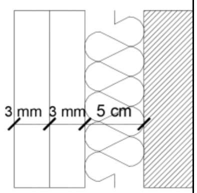
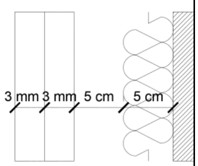
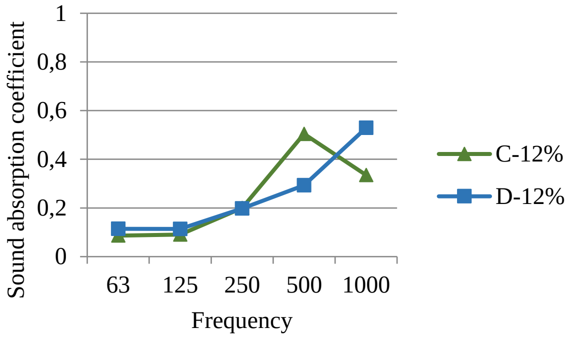
Slot width		
A 	A2 	
		
Porous absorber		
A	B	
 3mm panels + 5 cm backing material	 3mm panels + 5 cm air gap without backing material	
Air gap		
A	C	
 3mm panels + 5 cm backing material	 3mm panels + 5 cm backing material in 10 cm air gap	

Table 4.1 (continued)

<table>
<tr><td>C</td><td>D</td><td rowspan="2">
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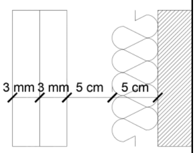
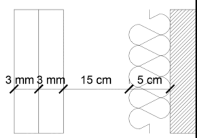
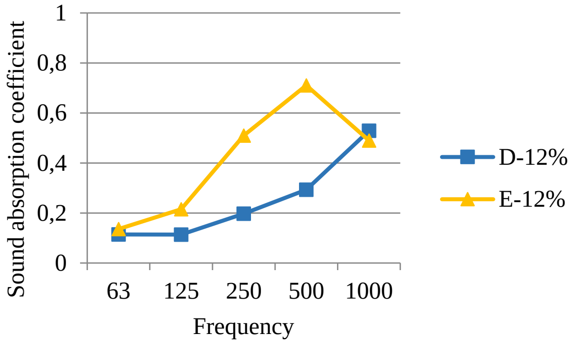
<tr><td>

3mm panels + 5 cm backing material in 10 cm air gap</td><td>

3mm panels + 5 cm backing material in 20 cm air gap</td></tr>
<tr><td colspan="3">Porous absorber layer</td></tr>
<tr><td>D</td><td>E</td><td rowspan="2">
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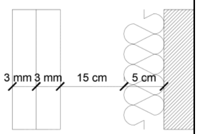
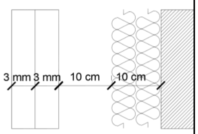
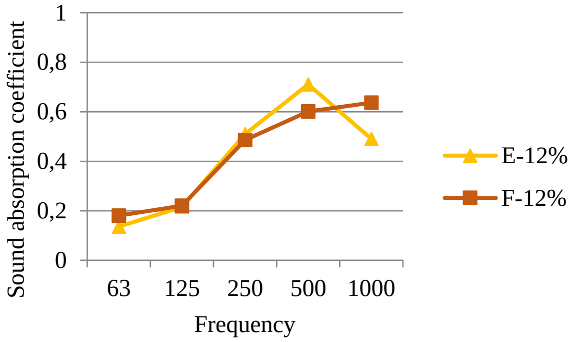
<tr><td>

3mm panels + 5 cm backing material in 20 cm air gap</td><td>

3mm panels + 2x5 cm backing material in 20 cm air gap</td></tr>
<tr><td colspan="3">Panel thickness</td></tr>
<tr><td>E</td><td>F</td><td rowspan="2">
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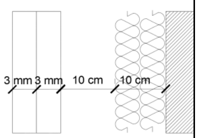
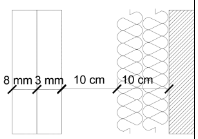
<tr><td>

3mm panels + 2x5 cm backing material in 20 cm air gap</td><td>

8mm and 3mm panels + 2x5 cm backing material in 20 cm air gap</td></tr>
</table>

Table 4.2. *Panel samples have same perforation ratio (2%) but different air gap distance, porous absorber layer and panel thickness*

<table>
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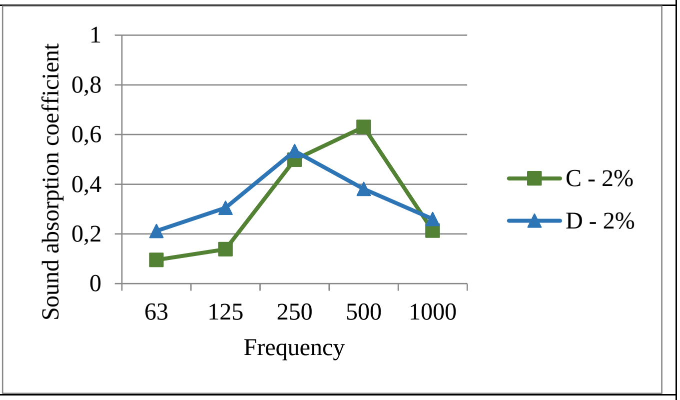
<tr><td>C</td><td>D</td><td rowspan="2">
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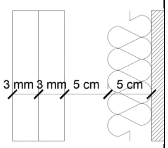
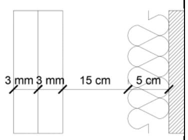
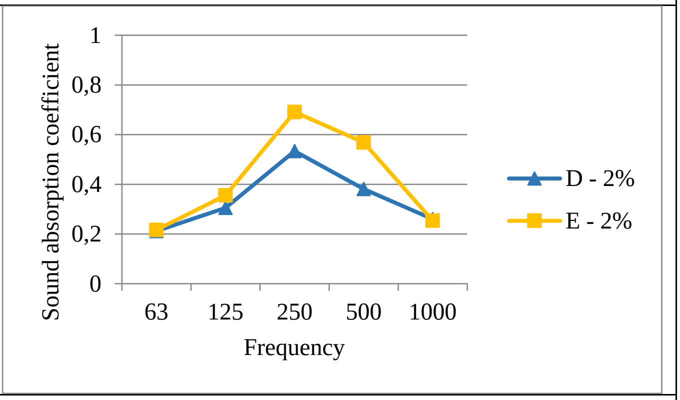
<tr><td>

3mm panels + 5 cm backing material in 10 cm air gap</td><td>

3mm panels + 5 cm backing material in 20 cm air gap</td></tr>
<tr><td colspan="3">Porous absorber layer</td></tr>
<tr><td>D</td><td>E</td><td rowspan="2">
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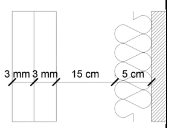
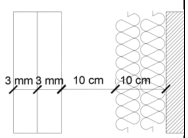
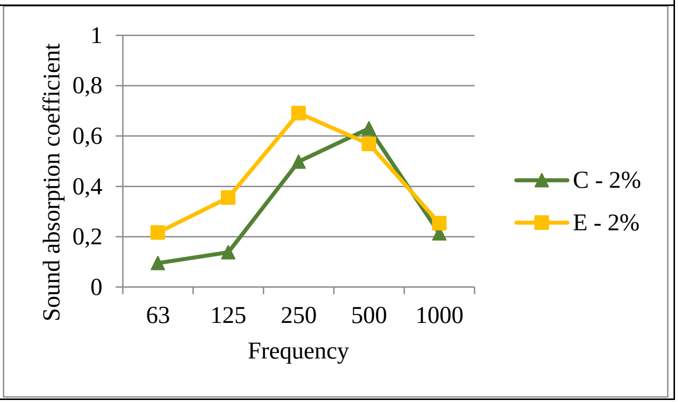
<tr><td>

3mm panels + 5 cm backing material in 20 cm air gap</td><td>

3mm panels + 2x5 cm backing material in 20 cm air gap</td></tr>
<tr><td colspan="3">Air gap & Porous absorber layer</td></tr>
<tr><td>C</td><td>E</td><td rowspan="2">
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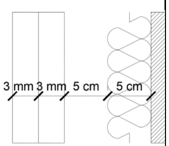
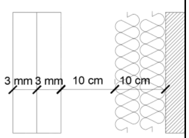
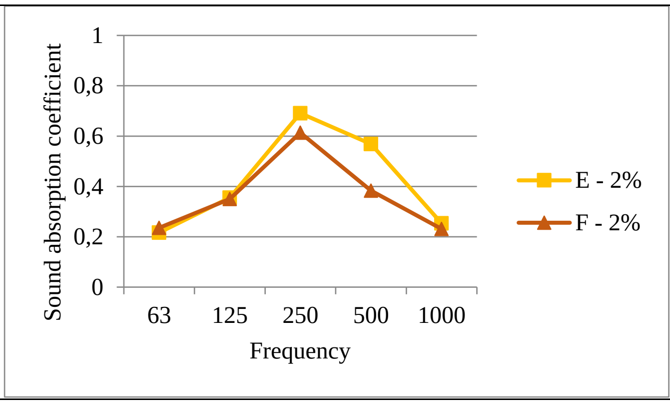
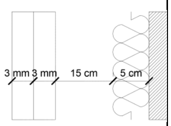
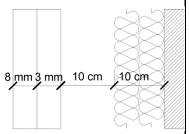
<tr><td>

3mm panels + 5 cm backing material in 10 cm air gap</td><td>

3mm panels + 2x5 cm backing material in 20 cm air gap</td></tr>
</table>

Table 4.2 (continued)

Panel thickness		
E	F	
 3mm panels + 2x5 cm backing material in 20 cm air gap	 8mm and 3mm panels + 2x5 cm backing material in 20 cm air gap	

The perforated panel with 2% perforation ratio and 2-mm rather narrow slot width was expected to provide higher sound absorption at low frequencies compared to the panel with 12% perforation ratio. Hence, the effects of air gap and porous material with different slot widths as 2mm and 12 mm were determined. Final configuration for the perforated panel proposal is established at the end of these analyses.

The findings of these measurements as shared in Table 4.1, Table 4.2, and Table 4.3 support the outcomes of the literature review. 2mm slot width provides higher sound absorption at low frequencies than wider 12mm slot width. The sound absorption performance of the porous absorber as backing material becomes determinative about sound absorption characteristic of perforated panel proposal for 12-mm slot width and 12% perforation ratio. Increase of the air space contributes the sound absorption at low frequencies for the perforated panel proposal with 2-mm slot width, in accordance with the Helmholtz resonator principles. Additional layer of porous absorber improves the sound absorption performance of the perforated panel proposal. Sound absorption coefficients varies at mid frequencies 500 Hz and 1000 Hz due to two layers of porous absorber (2x50mm 48-52 kg/m^3 rock wool) in comparison of 2% and 12% perforation ratios. In addition to that, the variable perforated panel proposal is capable to provide the highest sound absorption at different frequencies like 250 Hz and 1000 Hz in different panel positions with two layers of porous absorber.

Table 4.3. *Comparison of 2% and 12% perforation ratios for panel samples have different air gap distance, porous absorber layer and panel thickness*

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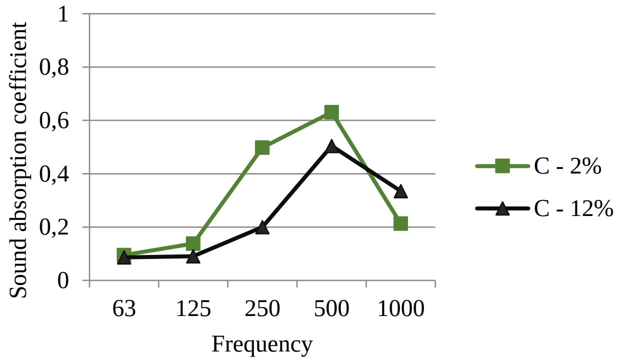

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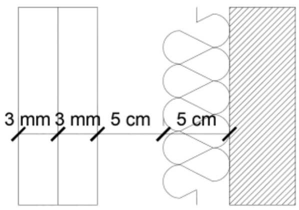
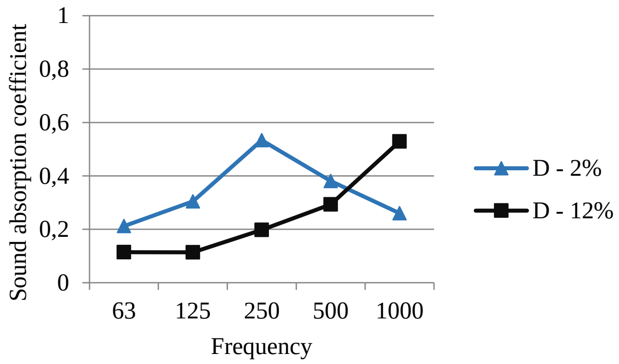


3mm panels + 5 cm backing material in 10 cm air gap
</td></tr>
<tr><td>D – 2%</td><td>D – 12%</td><td rowspan="2">


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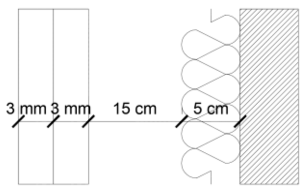
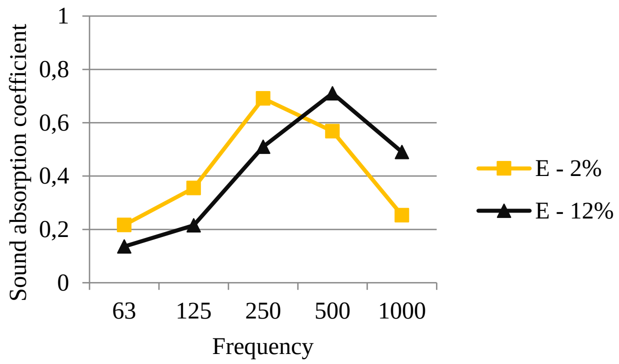


3mm panels + 5 cm backing material in 20 cm air gap
</td></tr>
<tr><td>E – 2%</td><td>E – 12%</td><td rowspan="2">


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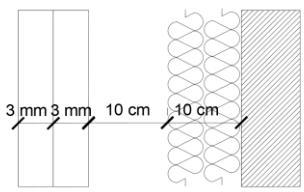
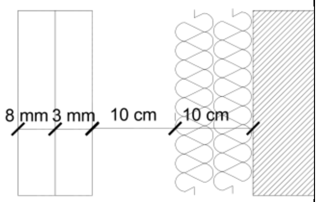
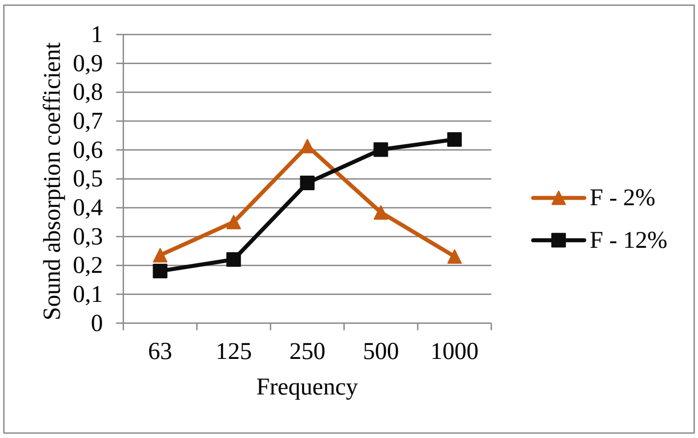


3mm panels + 2x5 cm backing material in 20 cm air gap
</td></tr>
</table>

Table 4.3 (continued)

F – 2%	F – 12%	
 8mm and 3mm panels + 2x5 cm backing material in 20 cm air gap		

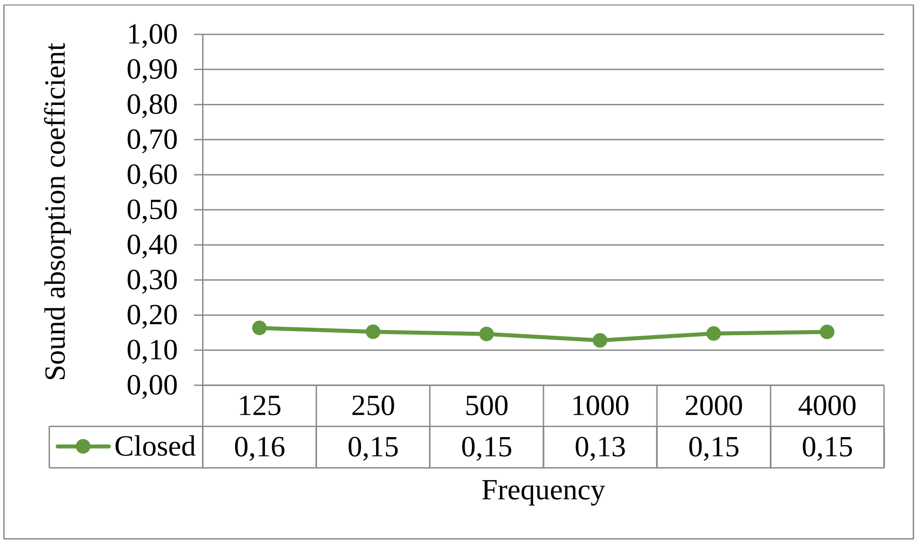


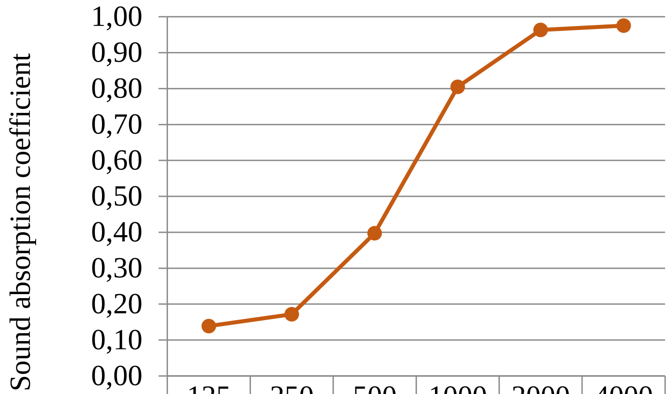
Figure 4.1. Sound absorption coefficients of perforated panel system in closed position

Thickness of panels in presented graphs is 3mm except the sample “F”. The lightweight panels can be preferred for the proposed sliding movement. Moreover, it is possible to perforate thinner 3-mm thick MDF panels with laser cutting machines. On the other hand, 8-mm thicker panels are not suitable for conventional laser cutting machines and need to be manufactured by CNC routers. However, the fixed first panel is decided to be manufactured by 8-mm thick MDF panels to strengthen the panel system, as presented in comparisons with the sample “F”. Sound absorption coefficients for perforated panels in closed position are shown in Figure 4.1 for 1/1 octave bands. While the panels are closed, scattering effect is expected owing to niches created by overlapping of two panels. Hence, the system is expected to be effective at high frequencies even if it is closed.

4.1.1. Perforated Panel Proposal Sound Absorption Measurement Data

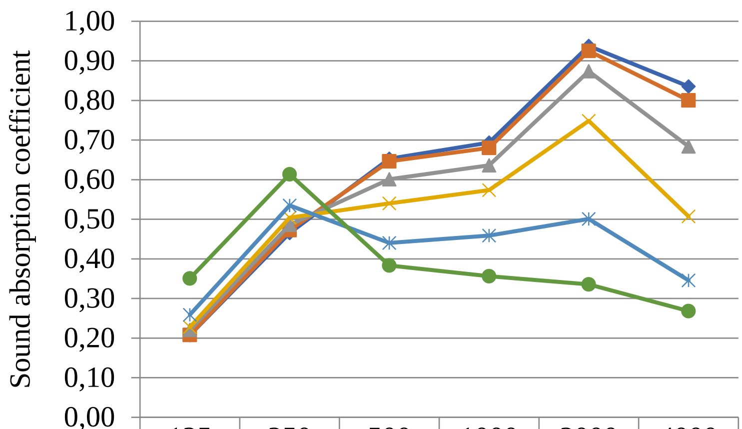
The comparison of 2% and 12% perforation ratios for the perforated panel sample with 20-cm air gap and two layers of porous absorber display highest sound absorption at different frequencies depending on the panel position (Table 4.1, Table 4.2, Table 4.3) the perforated panel proposal was configured with two porous absorber layers (50mm 48-52 kg/m3 rock wool) in 20 cm air gap to obtain variation in sound absorption characteristics for different panel positions. The sliding perforated panel was manufactured from 3mm MDF panel. The thinner panel is suitable for sliding movement and can be easily processed by laser cutting machines. On the other hand, the fixed first panel was produced from 8mm MDF panel by CNC routers to make the perforated panel system more durable.

Sound absorption coefficients of porous material used in a system as a backing material are presented in Figure 4.2.



	125	250	500	1000	2000	4000
2x 5 cm rockwool (50 kg/m3)	0,14	0,17	0,40	0,80	0,96	0,98

Figure 4.2. Sound absorption coefficients of 2 x 5 cm 48-52 kg/m^3 rock wool.



	125	250	500	1000	2000	4000
20%	0,21	0,47	0,65	0,69	0,94	0,84
16%	0,21	0,47	0,65	0,68	0,93	0,80
12%	0,22	0,49	0,60	0,64	0,87	0,68
8%	0,23	0,50	0,54	0,57	0,75	0,51
4%	0,26	0,54	0,44	0,46	0,50	0,35
2%	0,35	0,61	0,38	0,36	0,34	0,27

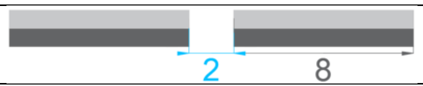
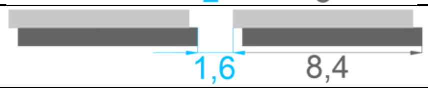
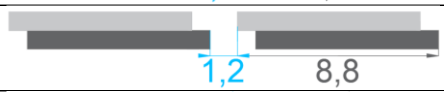
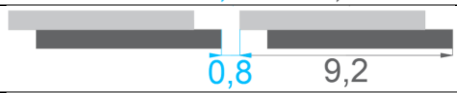
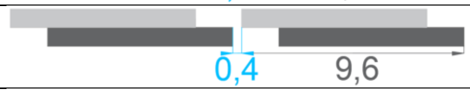
Figure 4.3. Sound absorption coefficients of perforated panel system with 20-cm air gap and 2 x 5 cm 48-52 kg/m^3 rock wool.

Sound absorption performance of porous absorber is determinative for samples with high perforation ratios and slot widths. Hence, samples with a perforation ratio higher than 12%, perform a similar sound absorption characteristic. The maximum variance in sound absorption was observed at high frequencies 2000 Hz and 4000 Hz in 1/1 octave bands. Resonance frequency was observed at 250 Hz, for 2% perforation ratio and 2 mm neck width (Table 4.3). Decreasing slot width and perforation ratio increases the sound absorption at low frequencies as expected. Sound absorption characteristic of the proposal displays a diversity especially in low and mid frequencies. The aimed variable perforated panel proposal was obtained.

4.1.2. Regression Analysis Result

The perforated panel proposal aimed to regulate perforation ratio with two panels have same perforation ratio 20% unlike common perforated panels which are manufactured by punching holes to obtain a specific perforation ratio. Therefore, factors like panel placement and shifting neck conditions become parts of sound absorption characteristic of the perforated panels system. Aimed perforation ratios as 20%, 16%, 12%, 8%, 4% and 2% depend on panel positions. Hence, in scope of this research, the relation between the panel position, and sound absorption performance of the system needs to be analyzed regarding to aimed perforation ratio although the relation between perforation ratio and sound absorption coefficient has been proved. Perforated panel positions are arranged to provide opening with a width changing from 20 mm to 2 mm. For each position, the relation between aimed perforation ratio and sound absorption performance is analyzed to reveal the comprehensive pattern between the phases of perforated panel proposal and sound absorption performances (Table 4.4). The sound absorption performance of the system is represented by Noise Reduction Coefficient (NRC) value which is the average of sound absorption coefficients at 250 Hz, 500 Hz, 1000 Hz and 2000 Hz.

Table 4.4. *NRC value and perforation ratio for different panel positions*

Noise Reduction Coefficient	Perforation ratio	Schematic description of panel positions
0,69	20%	
0,68	16%	
0,65	12%	
0,59	8%	
0,49	4%	
0,42	2%	

Curve estimation analysis in SPSS (Statistical Package for the Social Sciences) for linear, quadratic and cubic regressions are represented in Figure 4.4. Non-linear regression analysis with a cubic function was observed as a proper method for analysis (Table 4.8, Table 4.9,

Table 4.10, Table 4.11). According to curve estimation process; as R value of the curve was equal to 1,00 meaning that the function is accurate for predicting values, while the significance level is 0,001 (<0,05), thus, there should be no inconvenience in terms of statistical significance. (See Table 4.5 and

Table 4.6) The obtained formula and curve are perfectly fitting the relation between NRC values of perforated panel proposal and perforation ratios (Table 4.7).

NRC value = 0,341 + 4,289 * (PR) + (-16,421) * (PR^2) + 18,135 * (PR^3) (NRC: Noise Reduction Coefficient value, PR: Perforation Ratio)

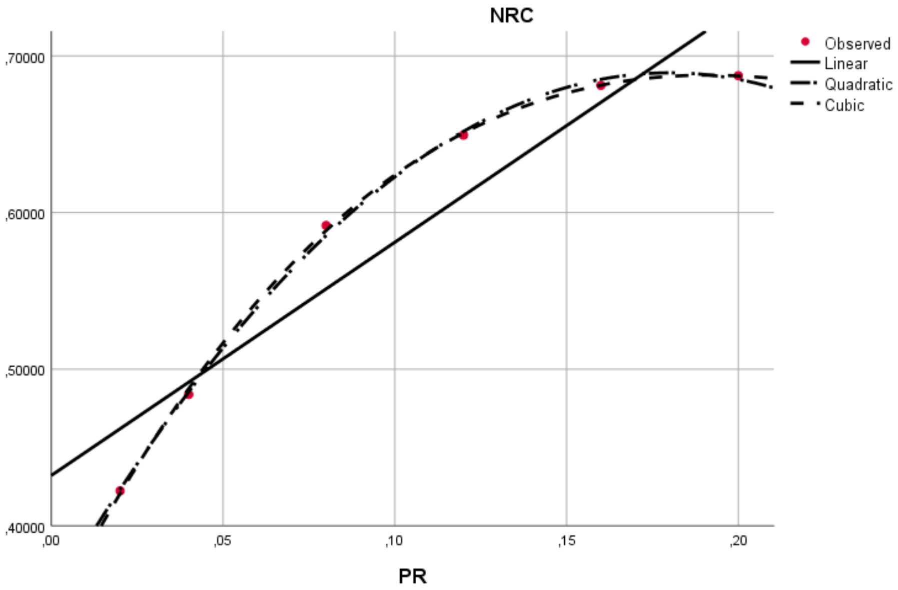


Figure 4.4. Representation of curve estimation by SPSS.

Table 4.5. *Model summary for curve estimation – cubic*

R	R Square	Adjusted R Square	Std. Error of the Estimate
1,000	1,000	0,999	0,004
The independent variable is PR (Perforation Ratio).			

Table 4.6. *Analysis-of-variance (ANOVA) table for curve estimation - cubic*

	Sum of Squares	df	Mean Square	F	Sig.
Regression	0,061	3	0,020	1372,570	0,001
Residual	0,000	2	0,000		
Total	0,061	5			
The independent variable is PR (Perforation Ratio).					

Table 4.7. *Coefficients for curve estimation – cubic*

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
PR	4,289	0,344	2,718	12,461	0,006
PR ** 2	-16,421	3,627	-2,314	-4,527	0,045
PR ** 3	18,135	10,818	0,518	1,676	0,236
(Constant)	0,341	0,008		41,149	0,001

Table 4.8. *Non-linear regression - Iteration History*[b]

Iteration Number[a]	Residual Sum of Squares	Parameter			
		b0	b1	b2	b3
1.0	0,000	0,341	4,289	-16,421	18,135
1.1	0,000	0,341	4,289	-16,421	18,135
2.0	0,000	0,341	4,289	-16,421	18,135
Derivatives are calculated numerically.					
a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.					
b. Run stopped after 3 model evaluations and 2 derivative evaluations because the relative reduction between successive parameter estimates is at most PCON = 1,000E-8.					

Table 4.9. *Non-linear regression - Parameter Estimates*

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
b0	0,341	0,008	0,306	0,377
b1	4,289	0,344	2,808	5,770
b2	-16,421	3,627	-32,028	-0,815
b3	18,135	10,818	-28,410	64,679

Table 4.10. *Non-linear regression - Correlations of Parameter Estimates*

	b0	b1	b2	b3
b0	1,000	-0,935	0,869	-0,816
b1	-0,935	1,000	-0,981	0,948
b2	0,869	-0,981	1,000	-0,991
b3	-0,816	0,948	-0,991	1,000

Table 4.11. *Non-linear regression - Analysis-of-variance (ANOVA)* [a]

Source	Sum of Squares	df	Mean Squares
Regression	2,121	4	0,530
Residual	0,000	2	0,000
Uncorrected Total	2,121	6	
Corrected Total	0,061	5	
Dependent variable: NRC			
a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 1,000.			

4.1.3. Perforated Panel Proposal Sound Absorption Performance Discussion

Perforated panel proposal was configured with 20-cm air gap distance to increase the sound absorption performance at low and mid-frequencies based on previous tests and literature review. Porous absorber layers as backing material are effective on sound absorption performance of the system. Two layers of 50-mm thick 50 kg/m^3 rock wool are placed as attached to the wall to obtain highest sound absorption at different frequencies for different panel positions. As a result of this, the highest sound absorption is obtained at 250 Hz for 2% and 4% perforation ratios. For higher perforation ratios and slot widths, the highest sound absorption is observed at 2000 Hz at 1/1 octave bands. For 12% and higher perforation ratios sound absorption characteristics of panel positions are similar. Sound absorption characteristics of porous material become determinative for sound absorption performance because of the wider slot width (12mm and higher). The maximum difference in sound absorption values between panel positions was observed at 2000 Hz.

The relation between sound absorption and panel position was investigated. Defined perforation ratios were obtained with two identical panels having same 20% perforation ratio. The relation between NRC values (average of sound absorption coefficients at 250 Hz, 500 Hz, 1000 Hz and 2000 Hz) and proposed perforation ratios was analyzed by non-linear regression analysis in SPSS. Furthermore, according to results of curve estimations, the cubic curve perfectly fits the obtained results, hence, by the formula, it is possible to estimate NRC values for perforation ratios which are not measured like 18%, 14%, 10% and 6%. Hence, according to obtained results: the aimed perforated panel proposal providing a sound absorption variety is achieved.

4.2. Room Acoustic Measurement and Simulation Data and Discussion

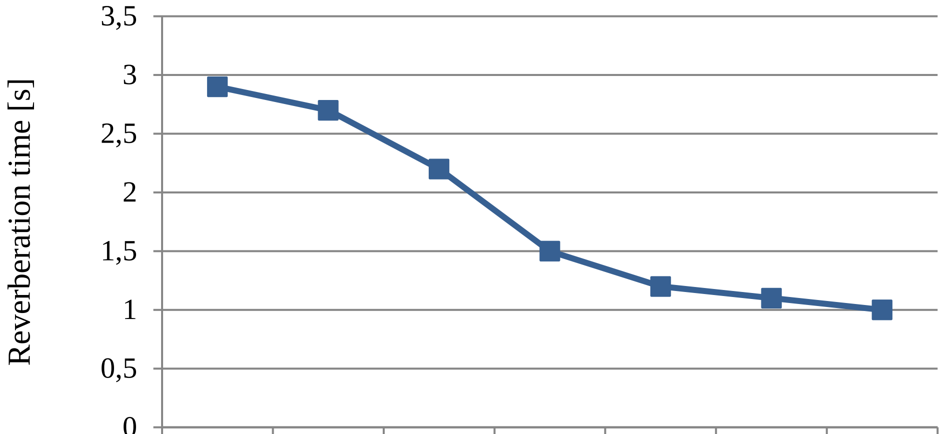
Findings of room acoustic measurements and simulations are presented under this section. Current acoustical condition of the hall is represented with objective room acoustic parameters. Reverberation Time (T30), Sound Pressure Level distribution in the hall (SPL(A)), Clarity (C(80)) and Speech Transmission Index (STI) values are presented to discuss adaptation of the hall to different functions as conference, musical and concert.

The hall is accommodating functions in a variance from lectures to concerts of music clubs of the University. The Amphitheatre serving as a multi-purpose hall with ~2200m^3 acoustically effective volume. The seating capacity of the hall is 357.

Perforated panels were arranged to provide proper acoustical conditions in the hall. Primarily, high reverberation times at low frequencies and the unbalanced current condition of the hall are taken as the reference, and acoustical conditions of the hall are aimed to be improved.

4.2.1. METU Empty Amphitheatre Field Measurement Data

This section covers measured room acoustic features for the METU Architecture Faculty Amphitheater in the absence of audience. Measurements were held hours in between 16.00 (pm) – 18.00 (pm) on 31st of August 2018. The sound source is expected to produce a peak sound pressure level in the hall 35-45 dBA higher than the background noise to measure T20 and T30 respectively. Requirements of the source can be lower if special sound signals like sine sweeps or pseudo-random noise (MLS) which can provide improved signal-to-noise ratio, are used according to ISO 3382-1 (2009). Swept sine signal is used in measurements. Before the measurements, background noise levels for the amphitheater were measured as 33.3 dBA (LAeq). Background noise level is suitable for intelligibility and proposed functions for the Amphitheatre.



	63	125	250	500	1000	2000	4000
T30[s]	2,9	2,7	2,2	1,5	1,2	1,1	1

Figure 4.5. Current acoustical condition of the Amphitheatre, reverberation time (T30)

INR values in between 63 Hz and 4000 Hz for each microphone positions, are higher than 35 dBA. Reverberation time, Early Decay Time and Clarity were all measured and presented in 1/1 octave bands with impulse response to noise ratio (Table 4.12, Figure 4.5). Measured Speech Transmission Index values vary in between 0,53(fair) and 0,63 (good) for 12 different receiver positions. Reverberation time values presented in Figure 4.5, are the average values of measurements at 12 different receiver positions.

Table 4.12. *INR, EDT, T20 and T30 field test results for the Amphitheatre*

Mic. Position	Parameter	Frequencies (Hz)						
		63	125	250	500	1000	2000	4000
1	INR	39	39	40	45	56	63	56
	EDT	2,27	2,18	1,89	1,48	0,97	0,89	0,69
	T20	2,23	2,49	1,92	1,43	1,13	1,08	0,92
	T30	2,19	2,46	1,78	1,50	1,20	1,12	0,97
	C(80)	-1,16	-3,5	1,66	4,2	5,04	5,62	7,53
2	INR	39	38	37	43	55	63	55
	EDT	2,26	2,16	1,87	1,45	0,97	0,87	0,69
	T20	2,25	2,49	1,93	1,42	1,10	1,06	0,92
	T30	2,16	2,47	2,10	1,50	1,19	1,11	0,96
	C(80)	-1,2	-3,54	1,68	4,22	4,78	5,18	7,5
3	INR	37	36	37	42	54	60	55
	EDT	3,03	2,15	2,26	1,58	1,18	1,10	0,93
	T20	2,46	2,68	2,19	1,45	1,23	1,12	0,99
	T30	2,39	2,66	2,26	1,50	1,23	1,15	1,01
	C(80)	0,55	0,13	-1,19	1,3	3	2,57	4,01
4	INR	35	36	36	42	54	60	55
	EDT	2,11	1,96	2,37	1,65	1,34	1,17	1,01
	T20	2,71	2,96	2,37	1,47	1,09	1,15	1,01
	T30	3,35	2,83	2,37	1,50	1,16	1,14	1,04
	C(80)	-1,27	-3,15	-2,17	1,38	0,59	1,12	3,2
5	INR	35	38	37	42	54	60	54
	EDT	2,80	2,65	2,13	1,61	1,30	1,23	1,06
	T20	3,31	2,35	2,21	1,47	1,24	1,14	1,02
	T30	2,76	2,61	2,23	1,57	1,22	1,14	1,01
	C(80)	-5,14	-3,83	-3,85	-0,33	1,96	1,48	2,91
6	INR	37	37	37	43	53	60	54
	EDT	2,57	2,85	2,19	1,54	1,19	1,18	1,00
	T20	2,87	2,79	2,16	1,41	1,20	1,13	0,99
	T30	3,62	2,64	2,28	1,31	1,22	1,11	1,00
	C(80)	-4,63	-1,87	-2,42	0,48	0,68	1,96	3,56
7	INR	35	37	37	42	54	60	55
	EDT	2,86	1,94	1,97	1,32	1,21	1,08	0,96
	T20	2,74	2,95	1,85	1,40	1,19	1,18	0,99
	T30	3,12	2,76	2,26	1,53	1,22	1,17	1,00
	C(80)	0,44	-1,78	-0,61	2,5	2,69	3,49	5,31
8	INR	37	38	37	42	55	60	56
	EDT	2,76	2,34	2,61	1,38	1,16	1,18	0,93
	T20	2,42	2,46	2,10	1,57	1,15	1,16	1,00
	T30	2,37	2,54	2,22	1,58	1,16	1,13	1,00
	C(80)	2,39	-1,92	-0,6	2,03	3,1	2,08	5,34
9	INR	35	37	38	41	54	60	54
	EDT	2,88	2,88	2,12	1,49	1,28	1,17	1,03
	T20	3,33	2,53	1,98	1,44	1,15	1,11	1,00
	T30	2,66	2,85	2,19	1,52	1,21	1,11	1,03
	C(80)	-2,83	-3,05	-2,16	0,35	1,28	2,49	3,26

Table 4.12 (continued)

10	INR	36	36	38	42	53	60	54
	EDT	2,36	3,00	2,28	1,37	1,30	1,27	1,07
	T20	3,32	2,87	1,97	1,48	1,25	1,14	1,02
	T30	2,60	2,70	2,23	1,54	1,24	1,14	1,03
	C(80)	-3,45	-2,17	-4,59	1,56	1,84	1,46	2,64
11	INR	35	36	36	41	54	60	54
	EDT	2,37	2,21	2,06	1,44	1,28	1,14	1,05
	T20	2,99	2,71	2,32	1,57	1,16	1,18	1,03
	T30	3,37	2,80	2,31	1,60	1,22	1,18	1,13
	C(80)	-2,67	-2,83	-0,96	2,01	3,04	2,48	2,6
12	INR	36	38	38	43	55	62	56
	EDT	2,42	2,24	2,08	1,37	1,32	0,93	0,90
	T20	3,12	2,35	2,07	1,42	1,20	1,18	0,94
	T30	2,98	2,55	2,03	1,45	1,22	1,16	0,99
	C(80)	-1,92	-0,59	-0,39	1,64	3,92	5,94	7,25

4.2.2. Simulation Results of METU Amphitheatre

Acoustical conditions in the Amphitheatre was simulated and presented for the current situation. Perforated panel proposal was applied to wall and ceiling surfaces which are not effective for direct specular reflections. Acoustical analysis was performed for the unoccupied condition of the Amphitheatre. However, the fully occupied condition is also simulated for the conference and concert function, to contribute the examination of the perforated panel proposal. The Amphitheatre was adapted to conference, musical and concert functions according to criteria presented in Table 4.13 by the help of perforated panel proposal in these simulations. Hence, the reliability of perforated panel proposal as a variable acoustic solution is tested and acknowledged by the simulation results.

Interior view of the hall is presented in OpenGL view (Figure 4.6) which is imported from ODEON room acoustic software. Sound absorption characteristics of finishing surfaces are indicated with colors; darker colors are representing sound absorber surfaces. Reverberation Time (T30) (Figure 4.8, Figure 4.9, Figure 4.10, Figure 4.11), Clarity (C(80)) (Figure 4.12, Figure 4.13, Figure 4.14, Figure 4.15) Speech

Transmission Index (STI) (Figure 4.16, Figure 4.17) and Sound Pressure Level difference (SPL(A)) (Figure 4.18, Figure 4.19) are presented for the current situation of the Amphitheatre.

Table 4.13. *Room acoustic design parameters and criteria for different functions proposed for the Amphitheatre*

Acoustical Parameters	Criteria
Conference	
Reverberation Time, T(30) (500 Hz – 1kHz average)	< 0,95 s
Speech Transmission Index, STI	> 0,6
Musicals	
Reverberation Time, T(30) (500 Hz – 1kHz average)	>0,95, <1,15
Clarity, C(80)	>+0, <+8
Lateral Fraction, LF(80)	<0,1
Speech Transmission Index, STI	>0,6
Concert (Chamber Music)	
Reverberation Time, T(30) (500 Hz – 1kHz average)	>1,15, <1,35
Clarity, C(80)	<-2, <+4
Lateral Fraction, LF(80)	>0,1

Table 4.14. *Sound absorptive materials and architectural configurations for different functions proposed for the Amphitheatre*

Material location	Materials for different functions proposed for the hall			
	Conference-Unoccupied	Conference-Occupied	Musical-Unoccupied	Concert-Unoccupied
Perforated panel proposal on back wall and back ceiling surfaces	2% (241 m^2) 20% (145 m^2)	2% (5 m^2) 4% (267 m^2) 8% (71 m^2) 12% (43 m^2)	2% (174 m^2) closed (212 m^2)	2% (161 m^2) closed (225 m^2)
Stage covering	6mm MDF panel with air space	6mm MDF panel with air space	Cotton curtain (500g/m^2)	6mm MDF panel with air space

In current situation, the reverberation time is 1,36 s for the average of 500 Hz and 1000 Hz (Figure 4.7), that is, mid-frequency reverberation time. The value is desired to be longer for the classical music, but for the chamber music, current reverberation time values in high frequencies are in limits. However, reverberation times at low frequencies 2,65s and 2,19s for 125 Hz and 250 Hz respectively are radically high and unbalanced situation between reverberation times in 1/1 octave bands is observed.

Porous materials are ineffective to decrease reverberation times at low frequencies. Hence, perforated panels with low perforation width and perforation ratio need to be applied in the hall (Table 4.14). Therefore, the primary aim of the studies about adaptation of the hall for different functions, is providing a balance in reverberation times in 1/1 octave bands.

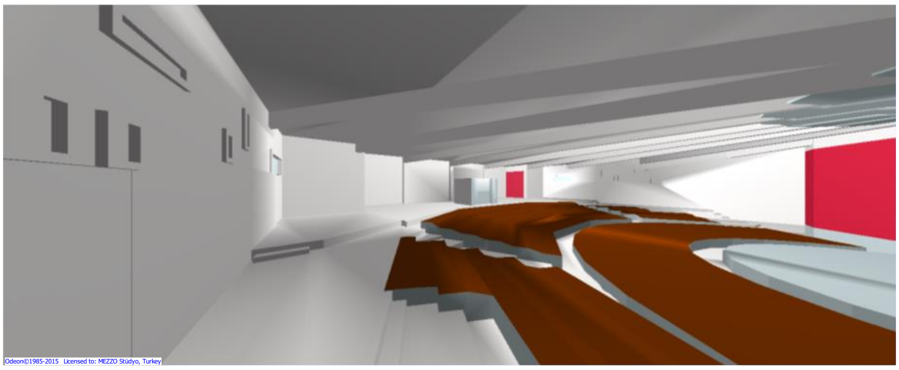


Figure 4.6. OpenGL view (interior view exported from ODEON room acoustic software)-current situation

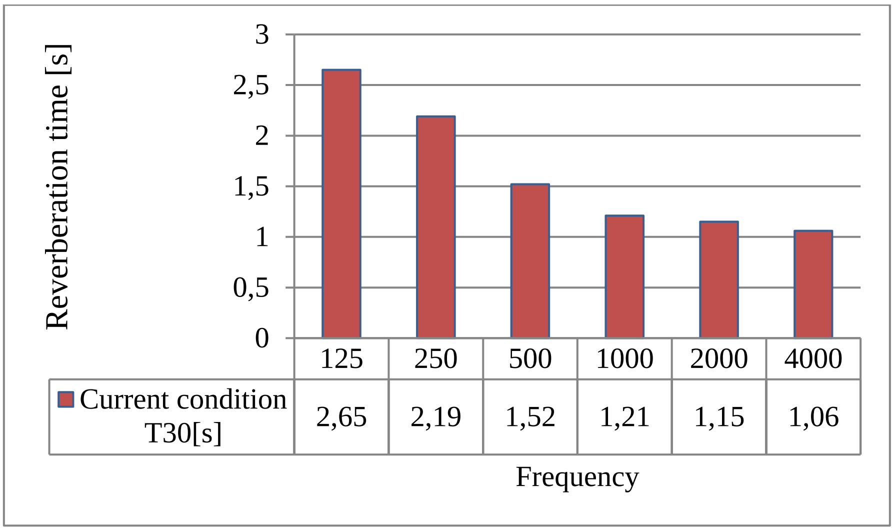


Figure 4.7. Estimated global reverberation times-current situation

According to simulation results STI value is higher than 0,48 and Clarity value is positive for all seats in the hall as represented with distribution graphs and maps. The sound pressure distribution in the hall is less than 10 dB as expected with reference to room volume (2200 m3). Room acoustic design parameters and criteria for different functions are presented in Table 4.13.

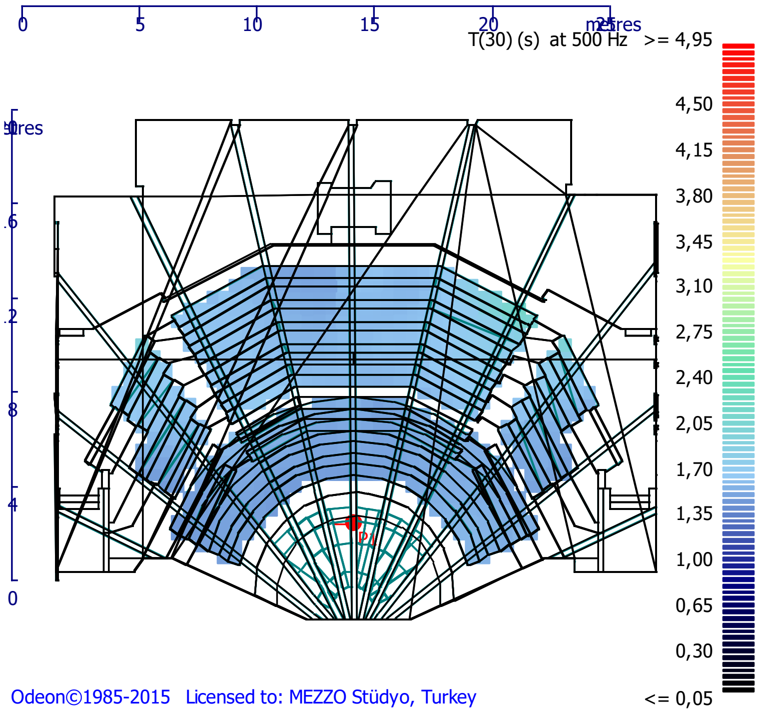


Figure 4.8. Reverberation time (T(30)) distribution map for 500 Hz -current situation

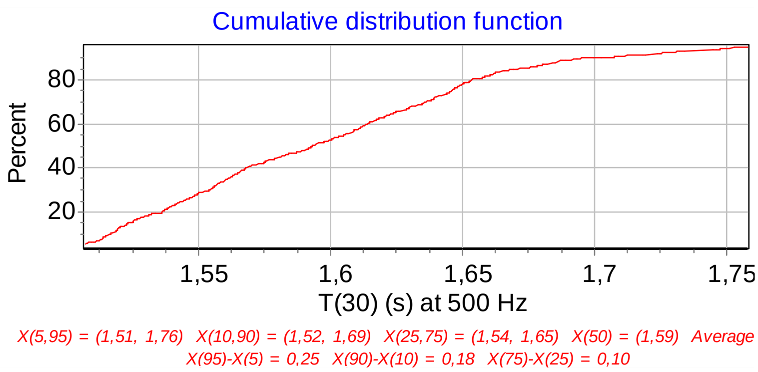


Figure 4.9. Reverberation time (T(30)) distribution graph for 500 Hz -current situation

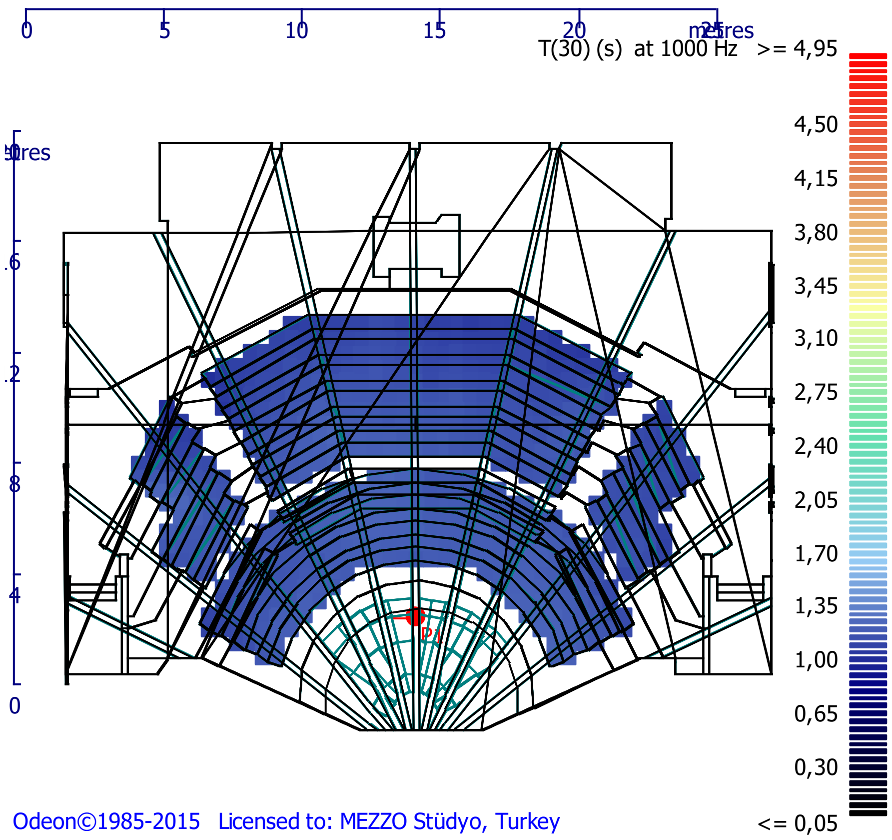


Figure 4.10. Reverberation time (T(30)) distribution map for 1000 Hz -current situation

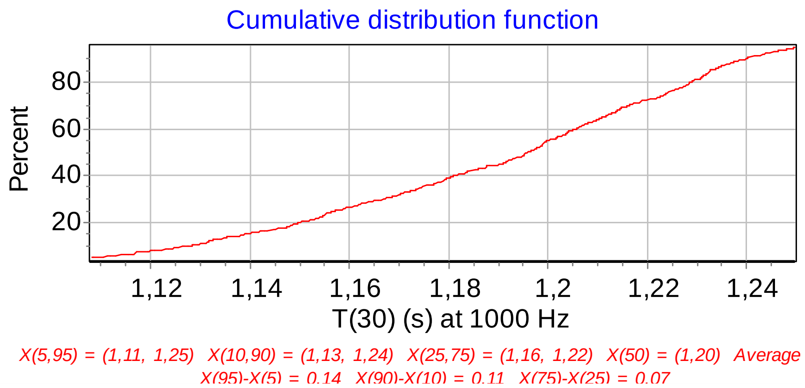


Figure 4.11. Reverberation time (T(30)) distribution graph for 1000 Hz -current situation

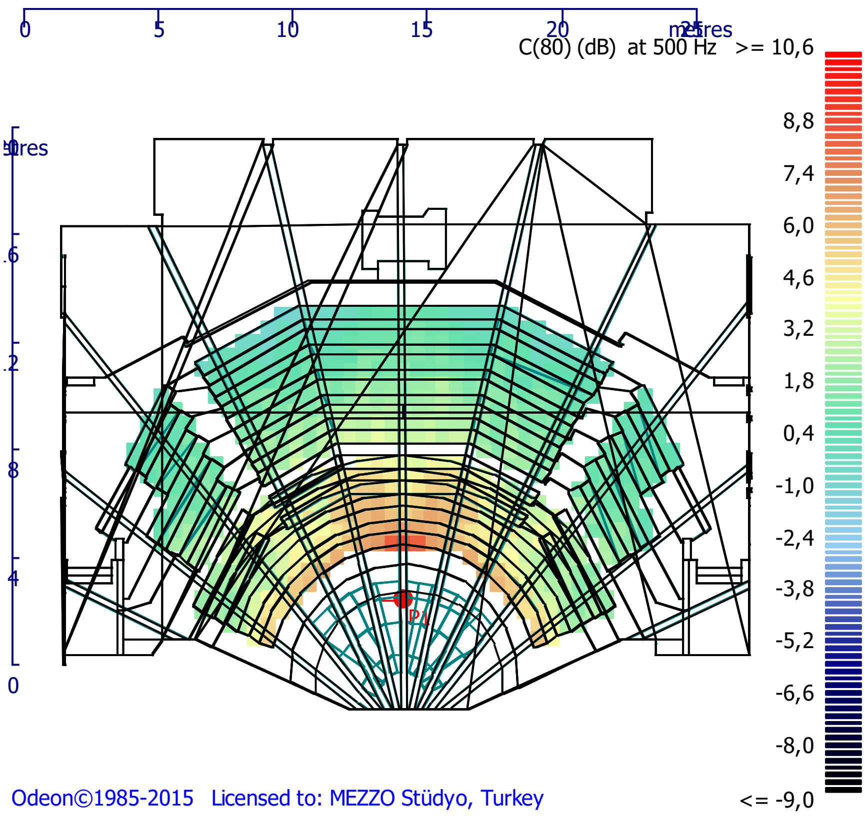


Figure 4.12. Clarity (C(80)) distribution map for 500 Hz -current situation

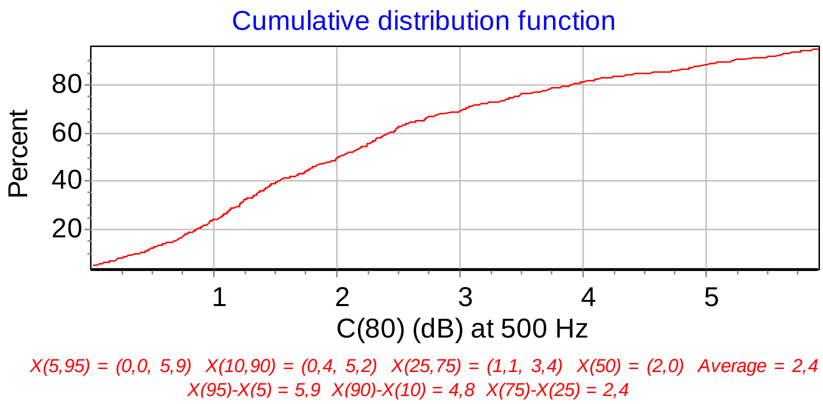


Figure 4.13. Clarity (C(80)) distribution graph for 500 Hz -current situation

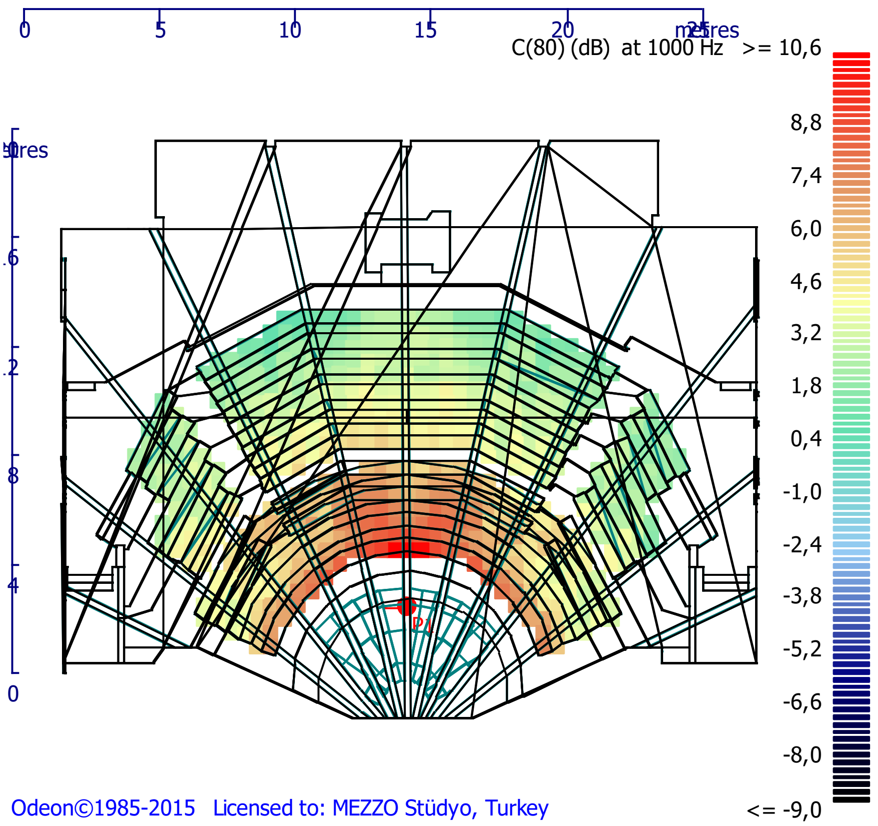


Figure 4.14. Clarity (C(80)) distribution map for 1000 Hz -current situation

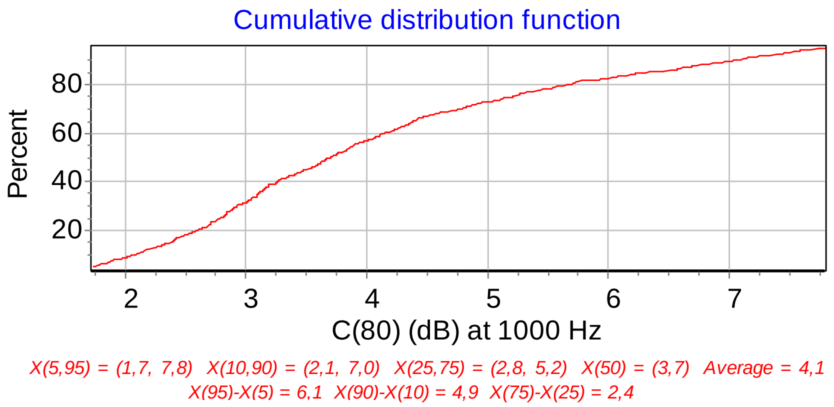


Figure 4.15. Clarity (C(80)) distribution graph for 1000 Hz -current situation

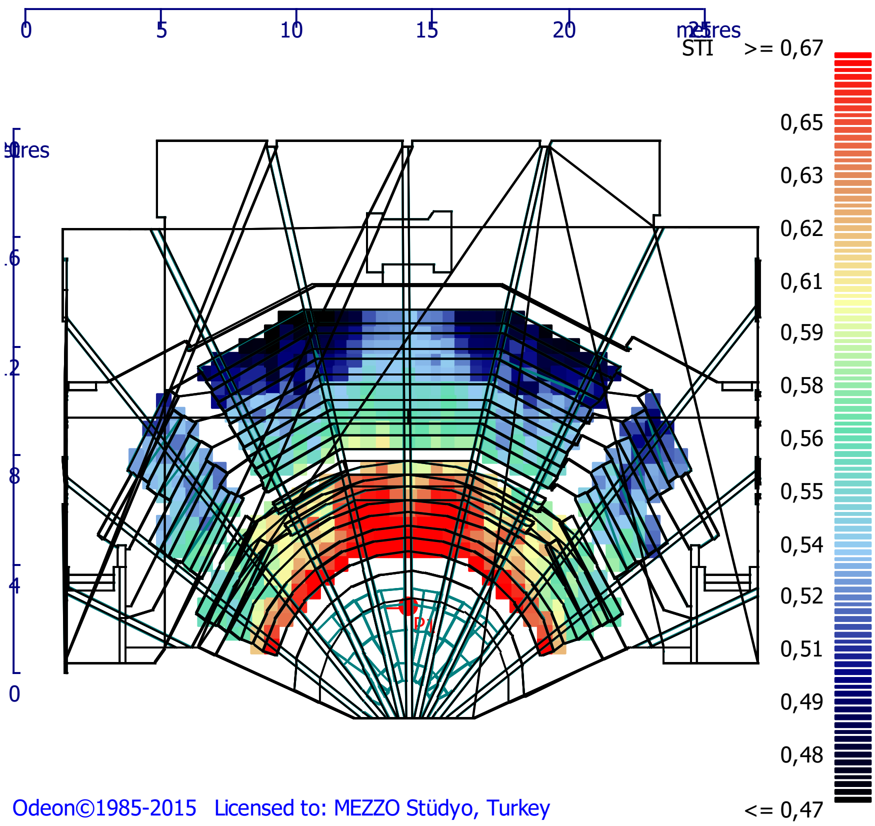


Figure 4.16. Speech Transmission Index (STI) distribution map -current situation

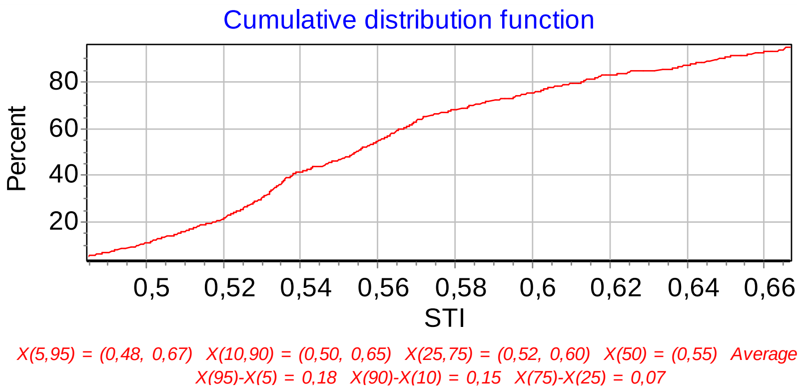


Figure 4.17. Speech Transmission Index (STI) distribution graph -current situation

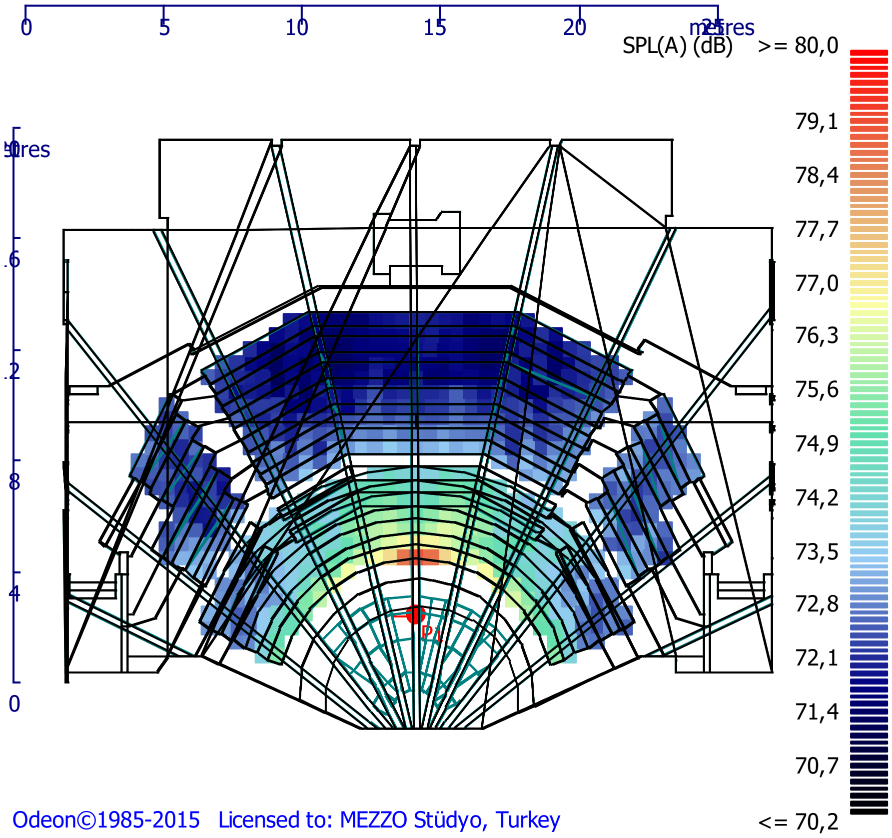


Figure 4.18. Sound pressure level distribution map (SPL(A)) -current situation

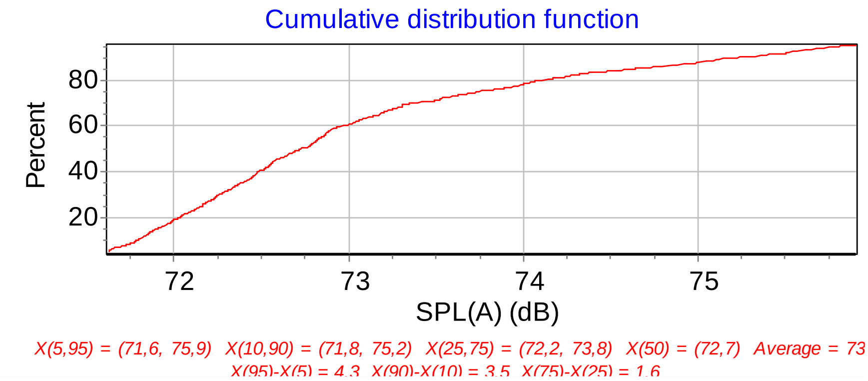


Figure 4.19. Sound pressure level distribution graph (SPL(A)) -current situation

4.2.2.1. Conference

For conference use, panels at back and side walls of the hall were arranged to 20% perforation ratio in total area of 145 m^2. Moreover, 240 m^2 of perforated panels at ceiling surfaces were arranged with 2% perforation ratio and 2mm slot width to control the reverberation time at low and mid frequencies. This measure provides higher sound absorption at 250 Hz. Darker red colors in OpenGL view are representing perforated panels with 20% perforation ratio. Panels have 2% perforation ratio are indicated in purple color in the same OpenGL view (Figure 4.20). Hence, reverberation time was decreased to 0,94 s (500 Hz – 1kHz average) for the conference function (Figure 4.21, Figure 4.22, Figure 4.23, Figure 4.24, Figure 4.25) and intelligibility is improved for the hall. STI level is higher than 0,62. In other words; speech intelligibility rating is GOOD for each audience position in the hall (Figure 4.26, Figure 4.27).

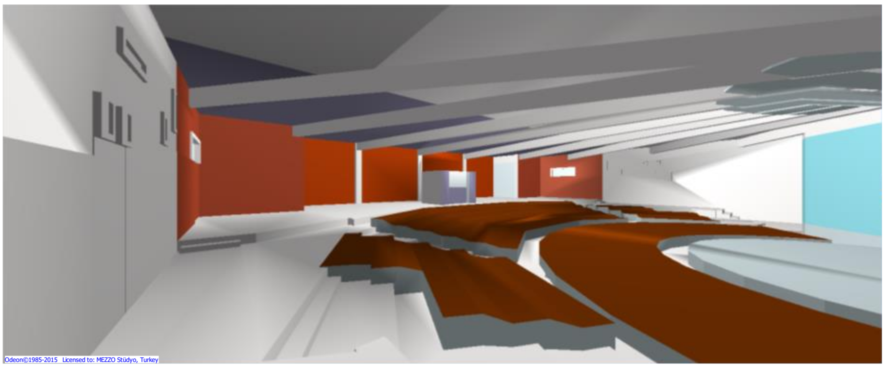


Figure 4.20. OpenGL view – conference proposal

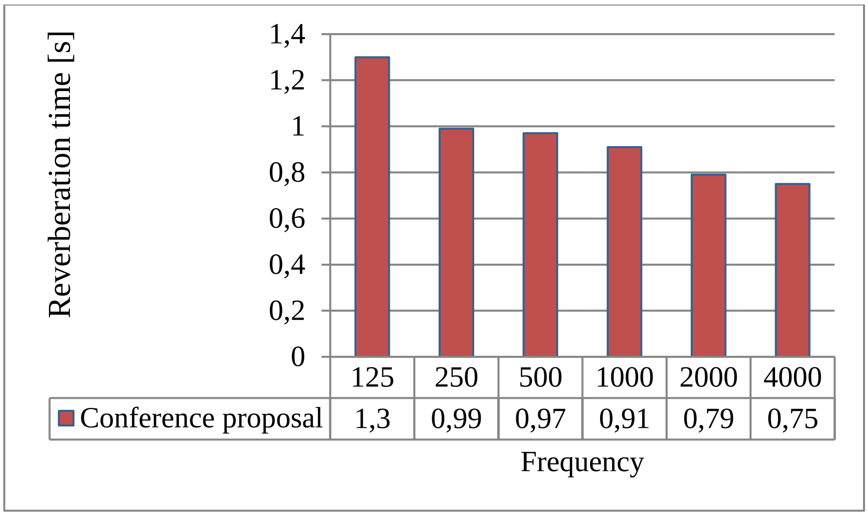


Figure 4.21. Estimated global reverberation times – conference proposal

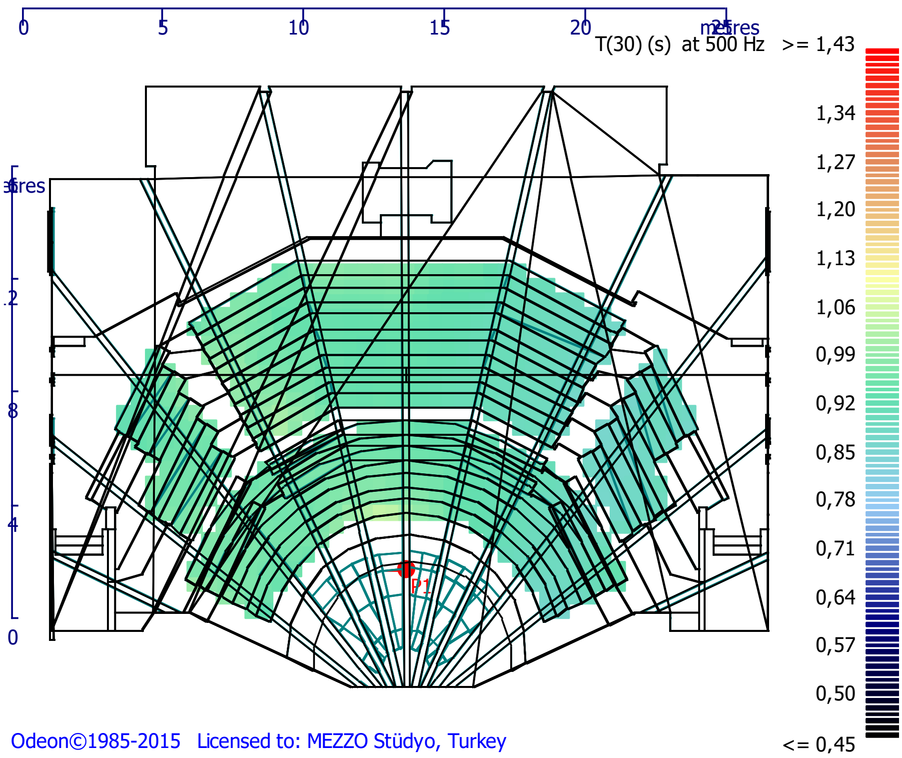


Figure 4.22. Reverberation time (T(30)) distribution map for 500 Hz– conference proposal

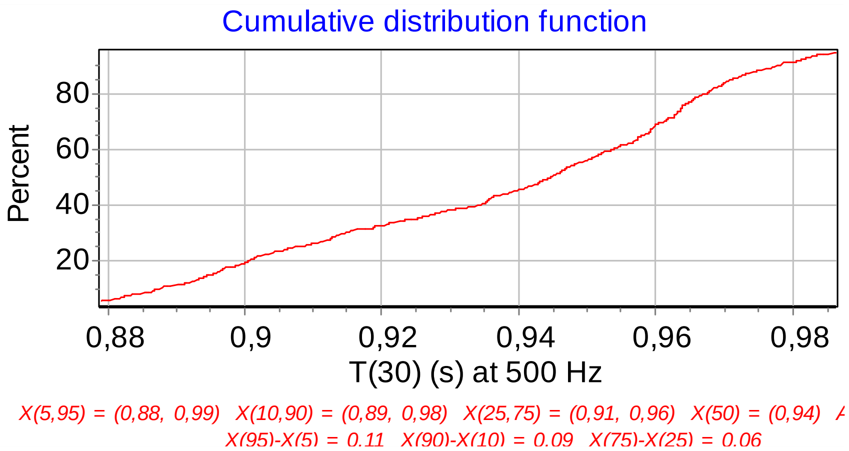


Figure 4.23. Reverberation time (T(30)) distribution graph for 500 Hz– conference proposal

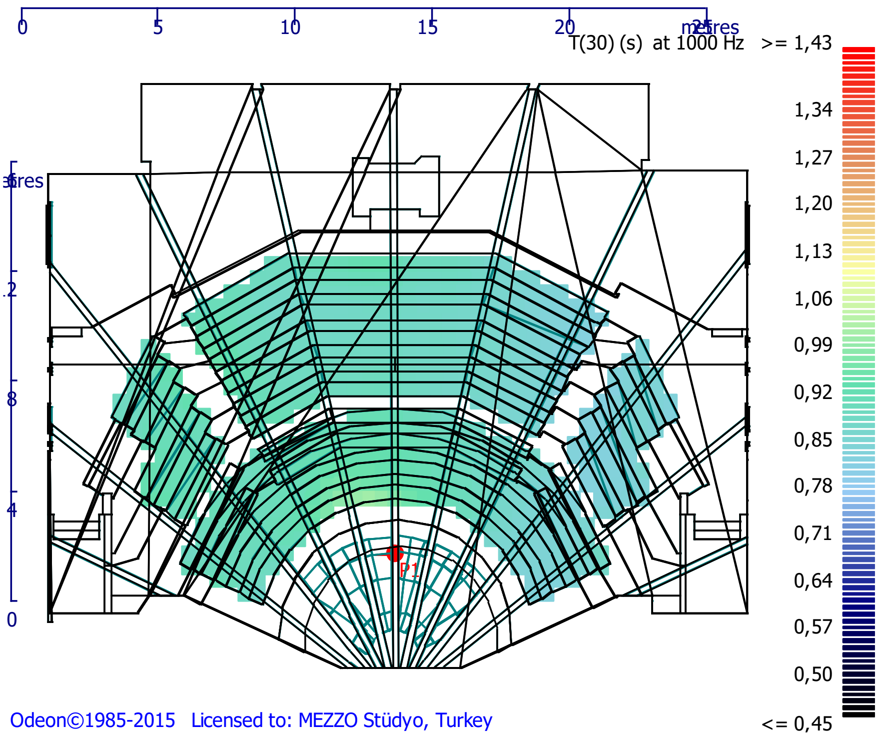


Figure 4.24. Reverberation time (T(30)) distribution map for 1000 Hz– conference proposal

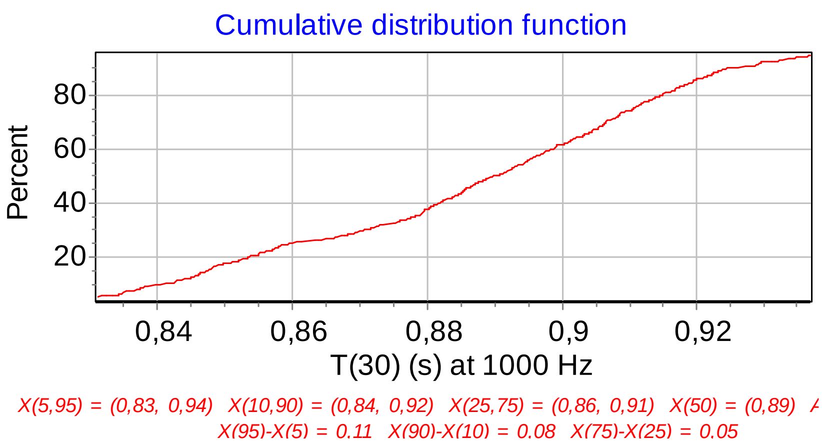


Figure 4.25. Reverberation time (T(30)) distribution graph for 1000 Hz– conference proposal

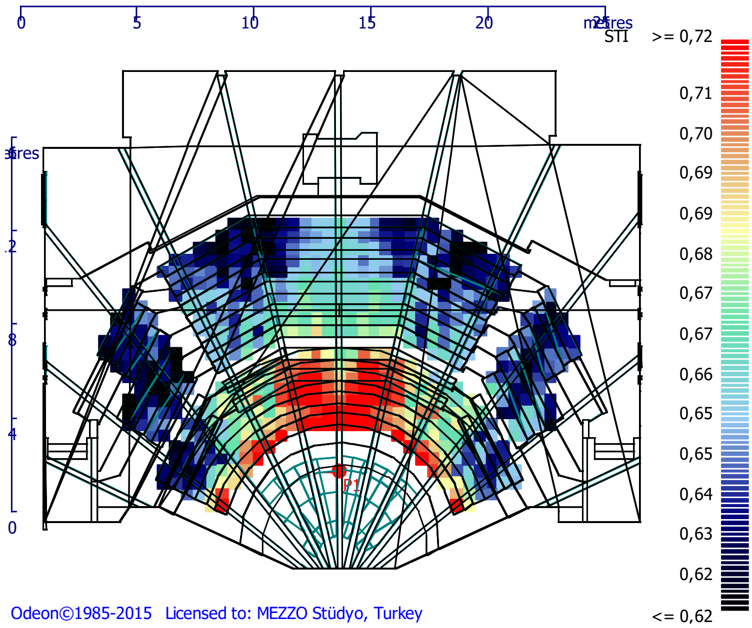


Figure 4.26. Speech Transmission Index (STI) distribution map– conference proposal

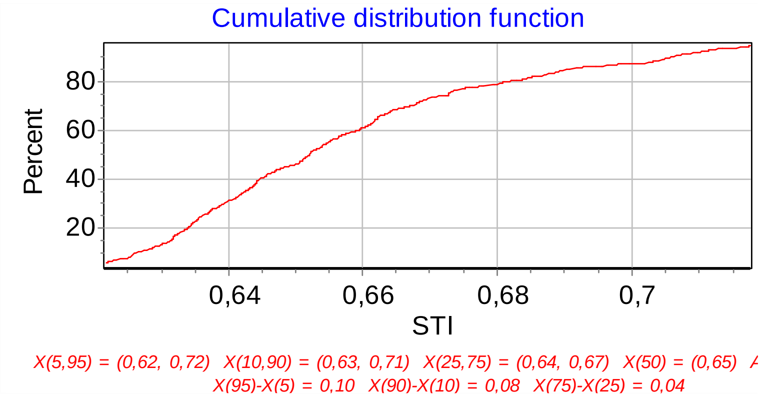


Figure 4.27. Speech Transmission Index (STI) distribution graph– conference proposal

4.2.2.2. Conference use in fully occupied condition

According to simulation results, averaged (500Hz and 1000 Hz) reverberation time for the conference use when the hall is unoccupied is 0,94 s. To keep the reverberation time constant in condition of the hall is fully occupied, perforation ratio of perforated panels was decreased. For the unoccupied conditions, perforation ratio of panels was arranged to 20%. Perforation ratios of perforated panels were decreased for side wall to 12%, for ceiling surfaces to 4% and for the back-wall surfaces to 8% as represented with different colors in Figure 4.28. Hence, increased sound absorption area by the existence of audience is balanced with decreasing in sound absorption of perforated panels. Reverberation time was obtained as 0,93 s for the average of 500 Hz and 1000 Hz as intended in both occupied and unoccupied conditions for the conference function (Figure 4.29).

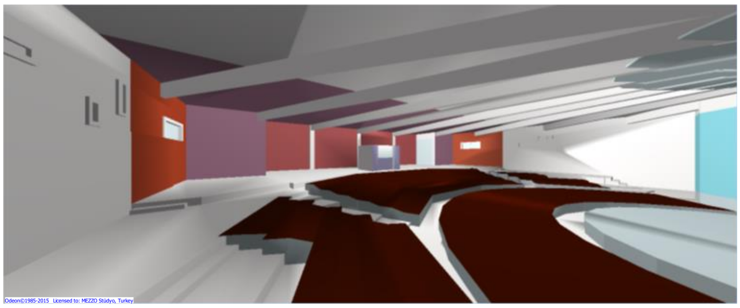


Figure 4.28. OpenGL view of the Amphitheatre in fully occupied condition– conference proposal

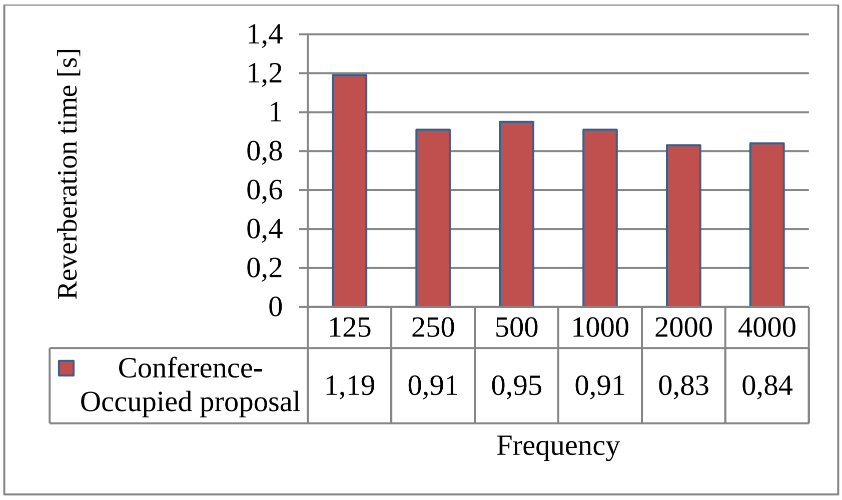


Figure 4.29. Estimated global reverberation times -occupied condition-conference proposal

4.2.2.3. Musical

For the proposed function, musicals, perforated panels on the side walls were closed. Half of the perforated panels on ceiling and back-wall surfaces were arranged to 2% perforation ratio, while the other half of them were closed. Closed and 2%perforated panels were staggered (Figure 4.30). Beside the Reverberation Time (T(30)) (Figure 4.32, Figure 4.33, Figure 4.34, Figure 4.35), objective room acoustic parameters as

Clarity (C(80)), Lateral fractions (LF(80)) and STI level are controlled. Reverberation time for the average of 500 Hz and 1000 Hz is calculated as 1,06 s (Figure 4.31).

Perforated panels with 2% perforation ratio provide utmost sound absorption for 250 Hz. Some of the panels were arranged to 2% ratio regarding to current acoustical condition of the hall. With curtains on the stage and perforated panels in the hall, averaged reverberation time at mid-frequencies was decreased to 1,06s which can be considered as low or short for musicals. On the other hand, reverberation times at low frequencies were decreased and balanced conditions were obtained.

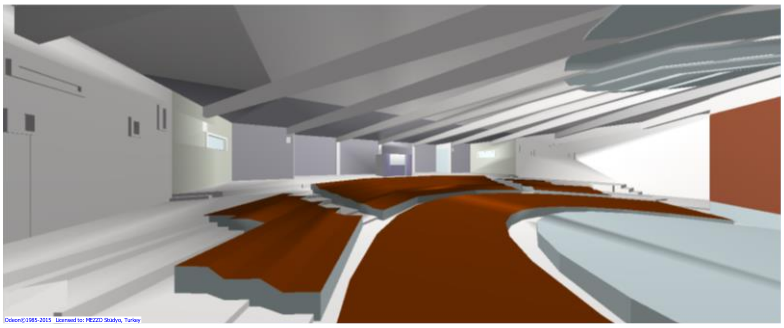


Figure 4.30. OpenGL view – musicals - proposal

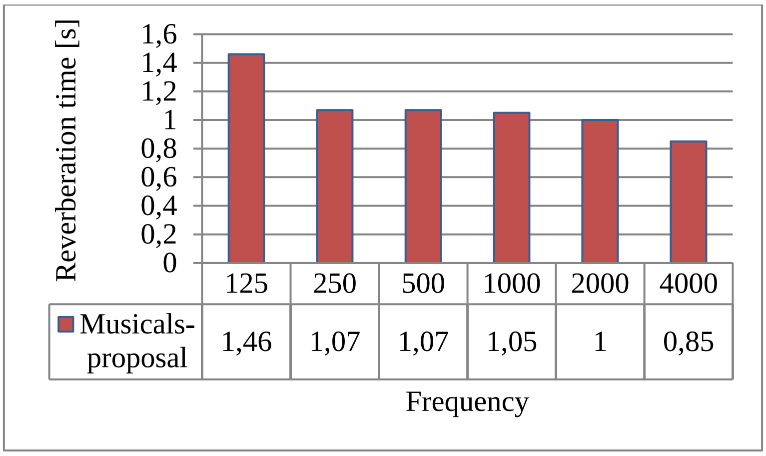


Figure 4.31. Estimated global reverberation times– musicals - proposal

The aimed proper clarity is obtained for musicals. For all of the seats, energies of reflections that occur during first 80ms after the direct sound is more than the reverberance after 80ms (Figure 4.36, Figure 4.37, Figure 4.38, Figure 4.39). Lateral fraction is affected by the form of the Amphitheatre. Therefore, LF(80) value decreases for seats around the stage and middle of the Amphitheatre far from the surrounding surfaces. Nevertheless, LF(80) was obtained more than 0,15 ratio for each of the seats (Figure 4.40, Figure 4.41, Figure 4.42, Figure 4.43). STI values were more than 0,58 according to distribution maps and graphs (Figure 4.44, Figure 4.45). Intelligibility was provided with GOOD rating for musicals.

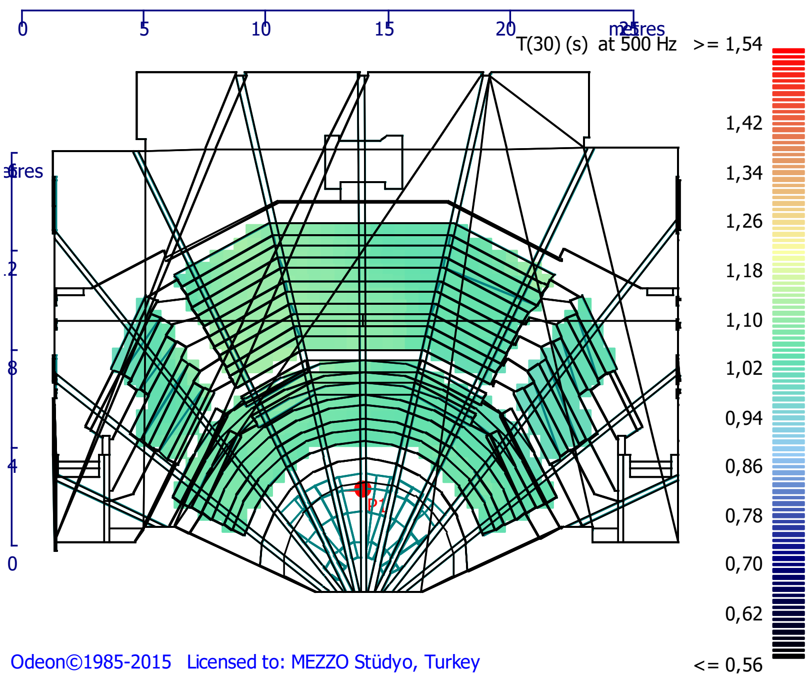


Figure 4.32. Reverberation time (T(30)) distribution map for 500 Hz-musicals - proposal

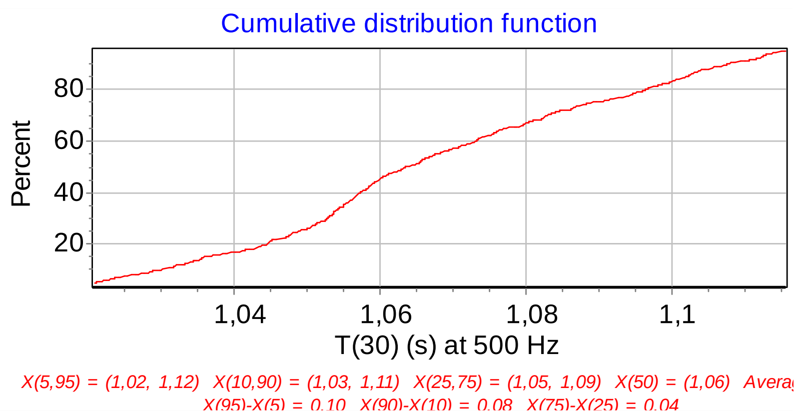


Figure 4.33. Reverberation time (T(30)) distribution graph for 500 Hz-musicals - proposal

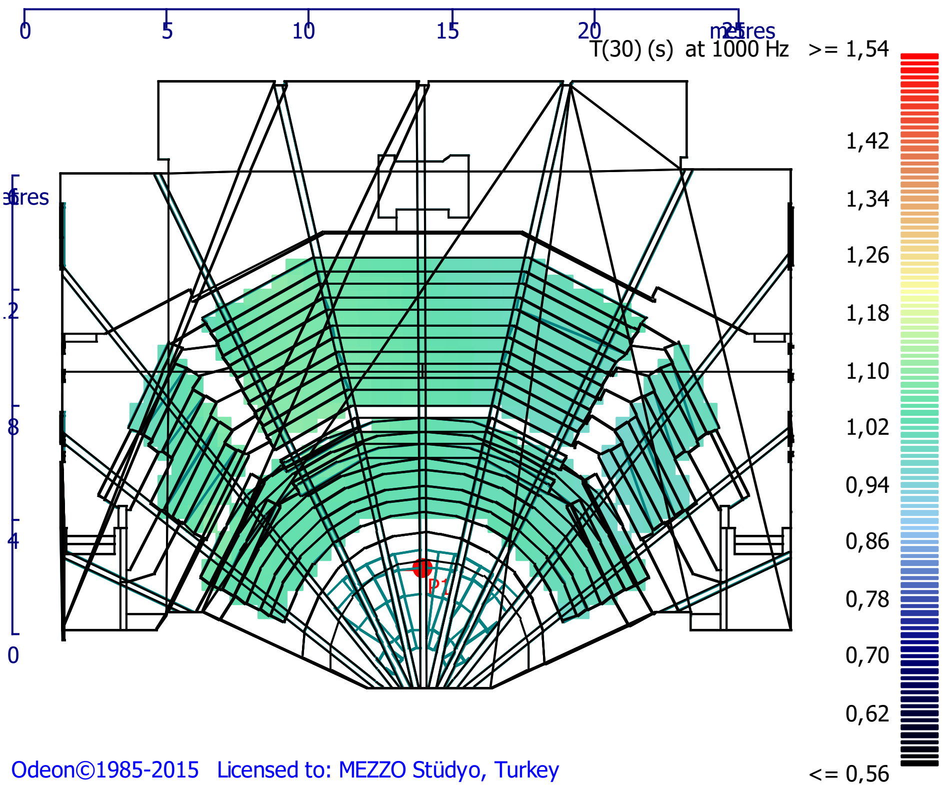


Figure 4.34. Reverberation time (T(30)) distribution map for 1000 Hz-musicals - proposal

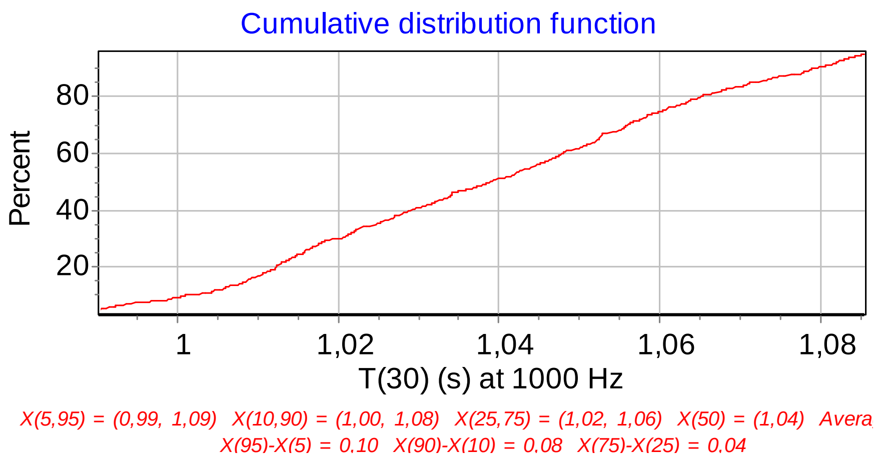


Figure 4.35. Reverberation time (T(30)) distribution graph for 1000 Hz-musicals - proposal

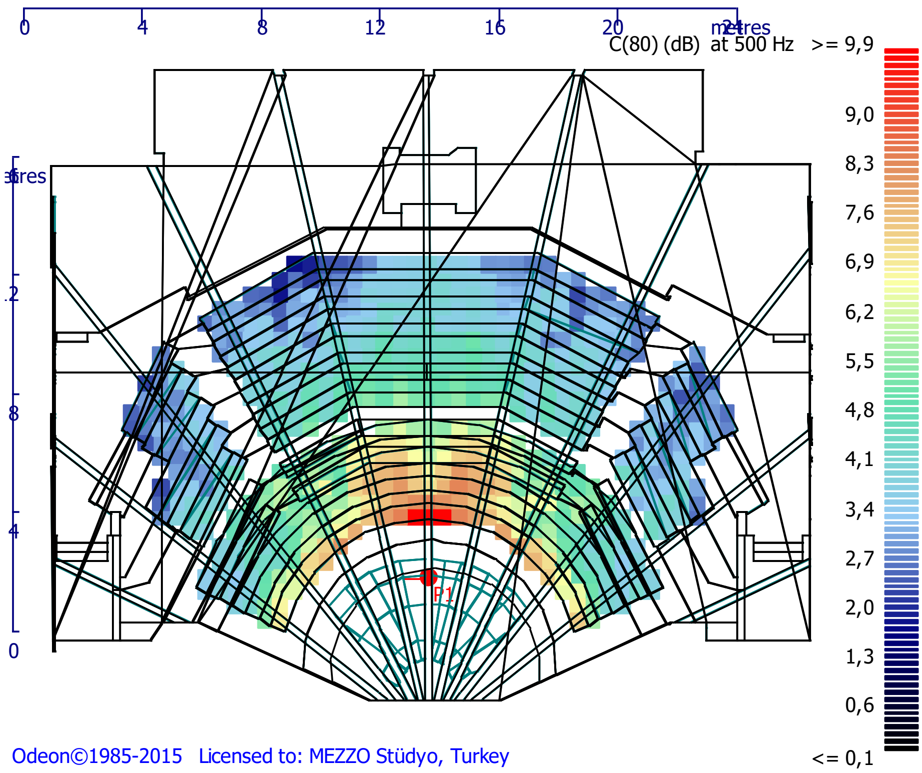


Figure 4.36. Clarity (C((80)) distribution map for 500 Hz-musicals - proposal

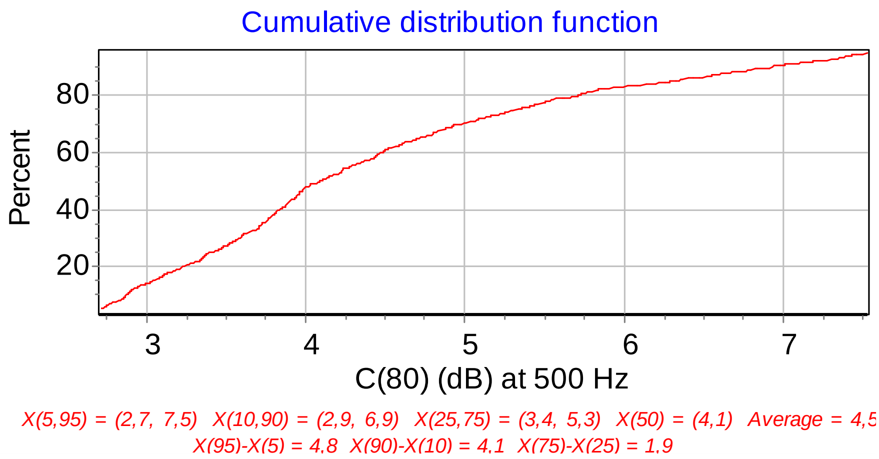


Figure 4.37. Clarity (C(80)) distribution graph for 500 Hz-musicals - proposal

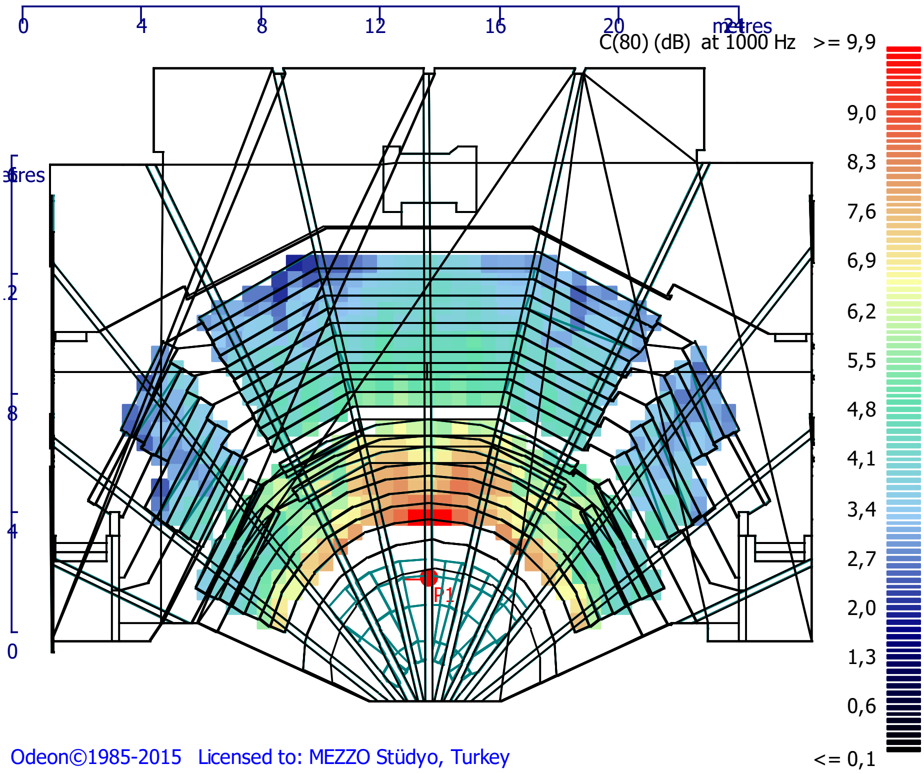


Figure 4.38. Clarity (C(80)) distribution map for 1000 Hz-musicals - proposal

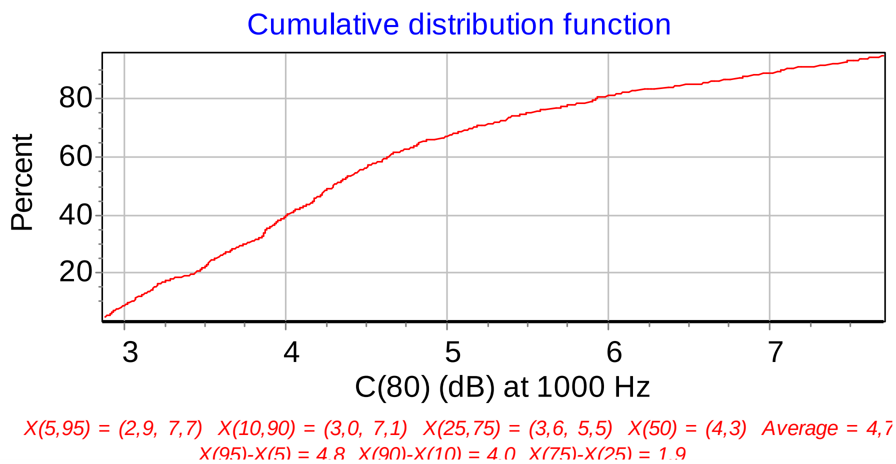


Figure 4.39. Clarity (C(80)) distribution graph for 1000 Hz-musicals - proposal

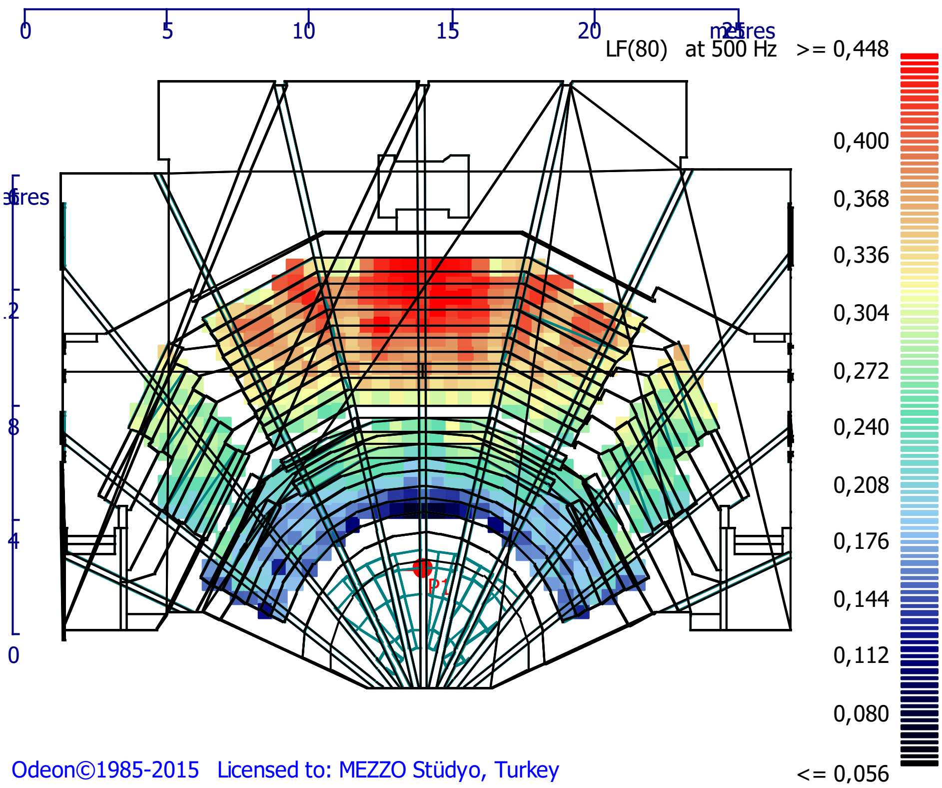


Figure 4.40. Lateral fraction (LF(80)) distribution map for 500 Hz-musicals - proposal

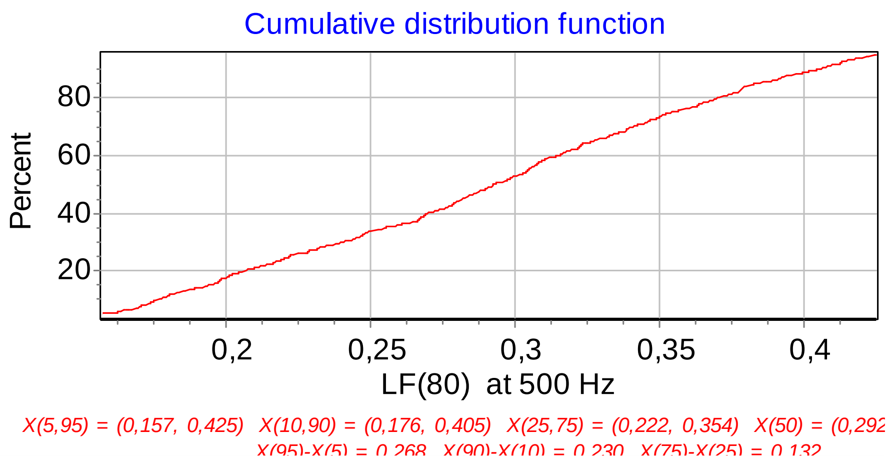


Figure 4.41. Lateral fraction (LF(80)) distribution graph for 500 Hz-musicals - proposal

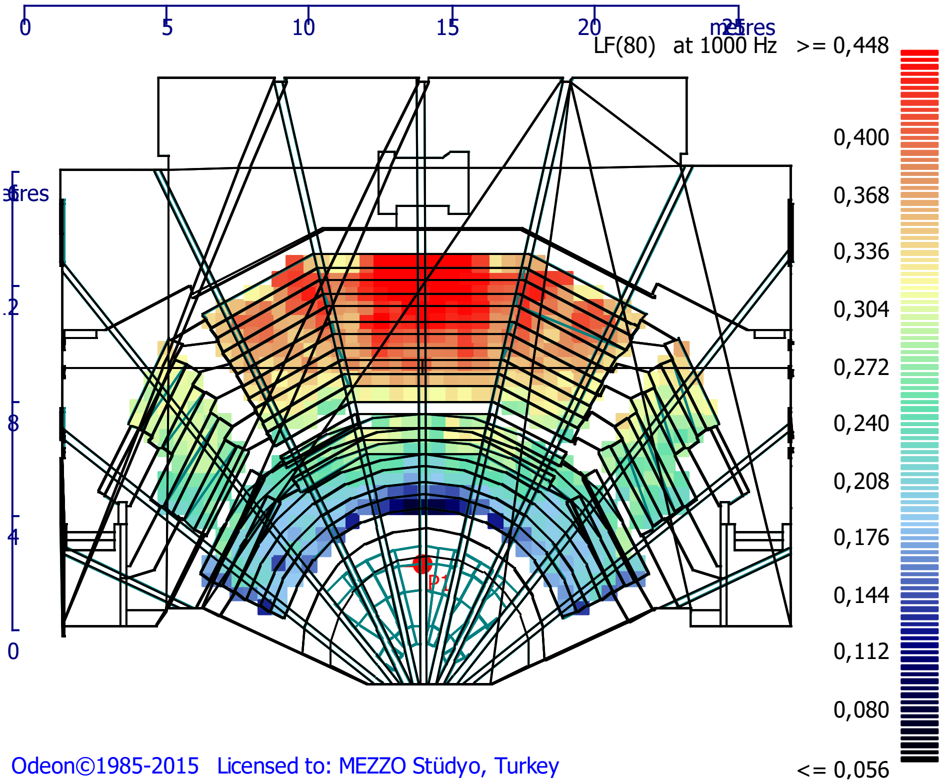


Figure 4.42. Lateral fraction (LF(80)) distribution map for 1000 Hz-musicals - proposal

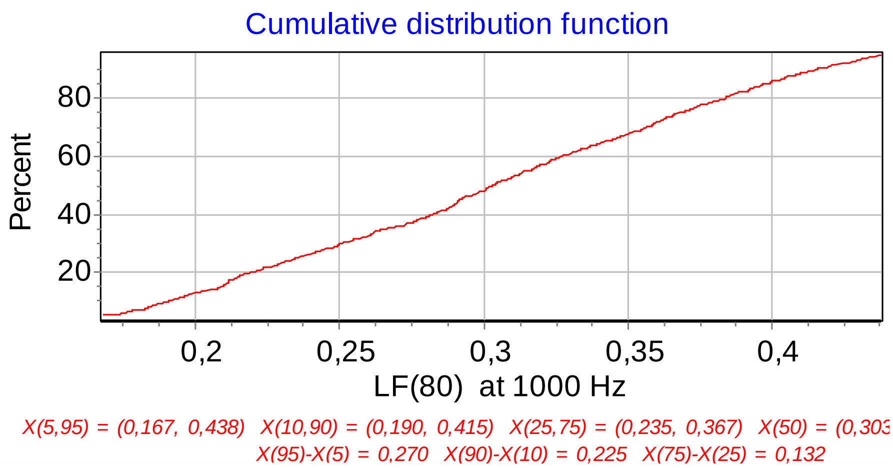


Figure 4.43. Lateral fraction (LF(80)) distribution graph for 1000 Hz-musicals - proposal

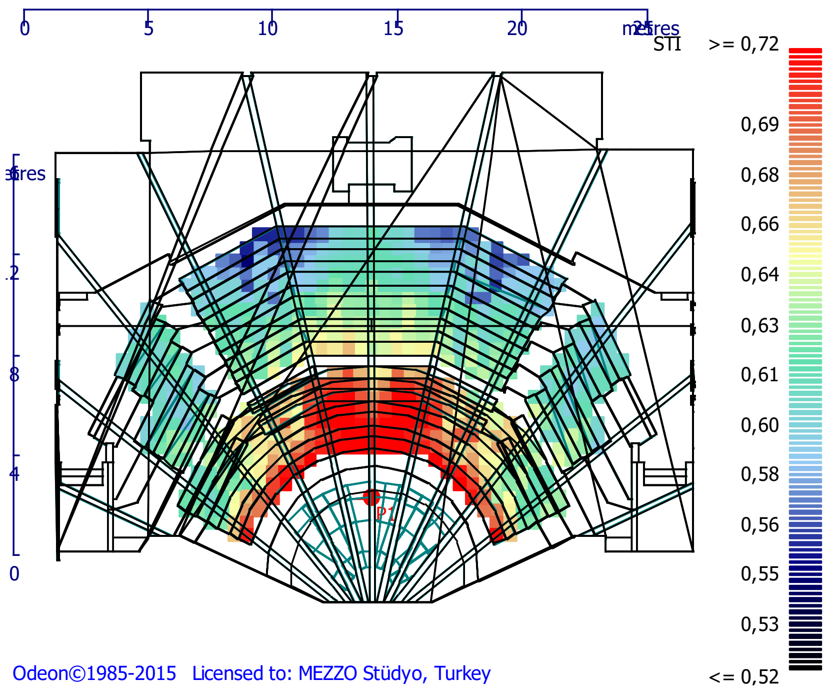


Figure 4.44. Speech transmission index (STI) distribution map -musicals - proposal

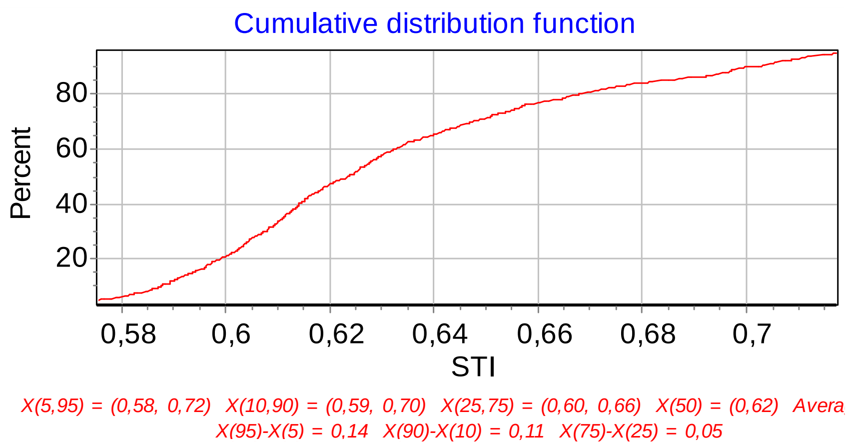


Figure 4.45. Speech transmission index (STI) distribution graph -musicals - proposal

4.2.2.4. Concert

For the concert use, 225 m^2 of the perforated panels at the ceiling and side-wall surfaces were closed and 161 m^2 of panels at back wall are opened with 2% perforation ratio. Back wall was chosen for the application of 2% perforation ratio to prevent echo and acoustical defects (Figure 4.46). Reverberation Time (T(30)) (Figure 4.48, Figure

4.49, Figure 4.50, Figure 4.51), Clarity (C(80)) and Lateral Fraction (LF(30)) values are presented for concert function. Reverberation time for the concert use was obtained as 1,28 s for the average of reverberation times in 500 Hz and 1000 Hz (Figure 4.47). C(80) values are more than +1, in consideration with reverberation time, positive clarity values were expected (Figure 4.52, Figure 4.53, Figure 4.54, Figure 4.55). Level of lateral fraction is affected by the hall geometry. For concert use, proper lateral fraction (LF(80)) which is higher than 0,2 was obtained for the hall (Figure 4.56, Figure 4.57, Figure 4.58, Figure 4.59). Reverberation time is low for a concert use however in comparison with the current condition of the hall reverberation times at low frequencies were decreased and acoustical defects and echoes in the hall were prevented.

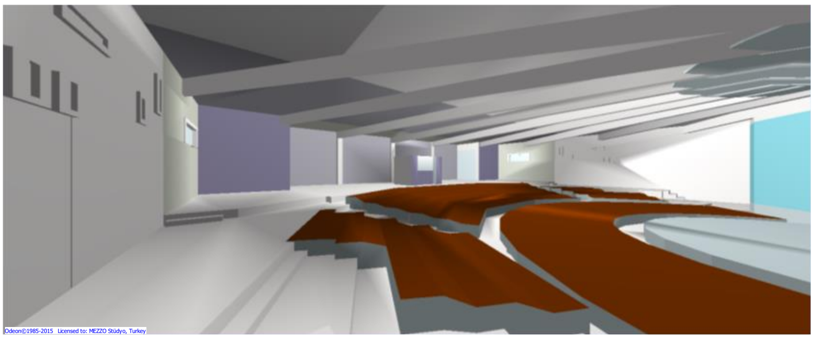


Figure 4.46. OpenGL view of – concert - proposal

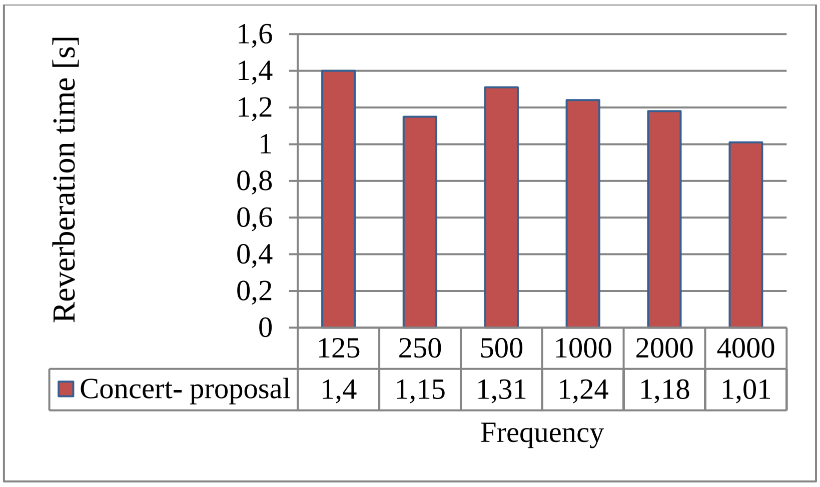


Figure 4.47. Estimated global reverberation times – concert - proposal

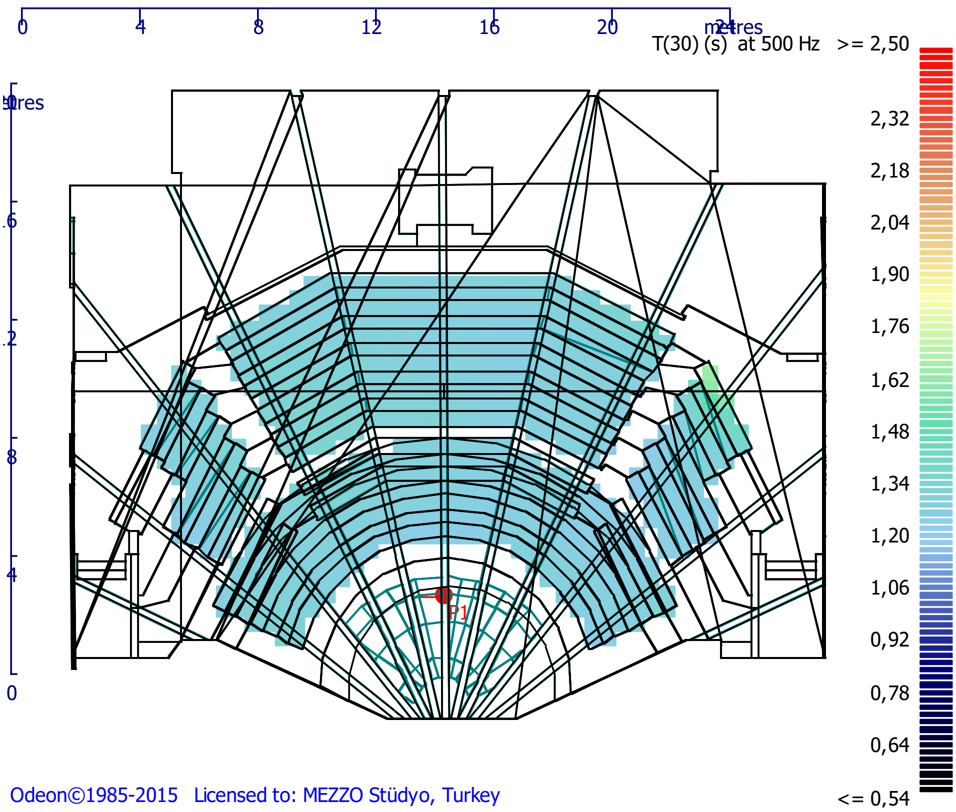


Figure 4.48. Reverberation time (T(30)) distribution map for 500 Hz -concert - proposal

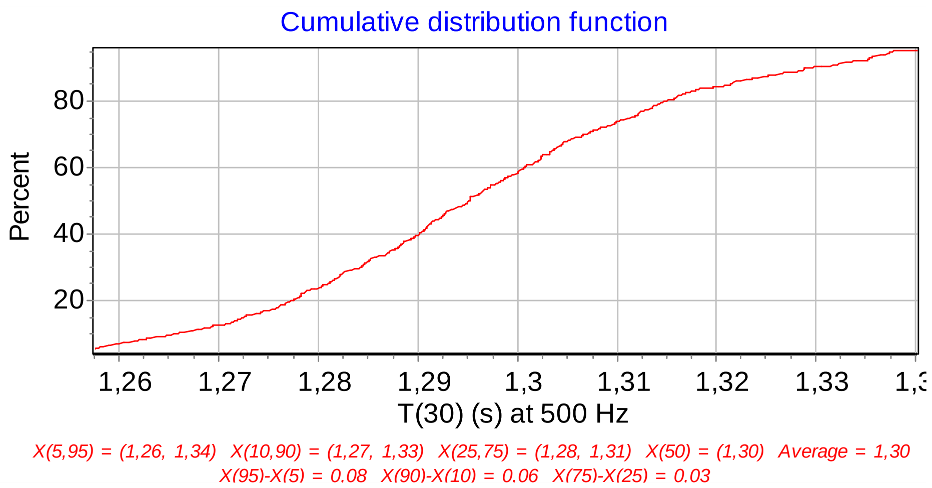


Figure 4.49. Reverberation time (T(30)) distribution graph for 500 Hz -concert - proposal

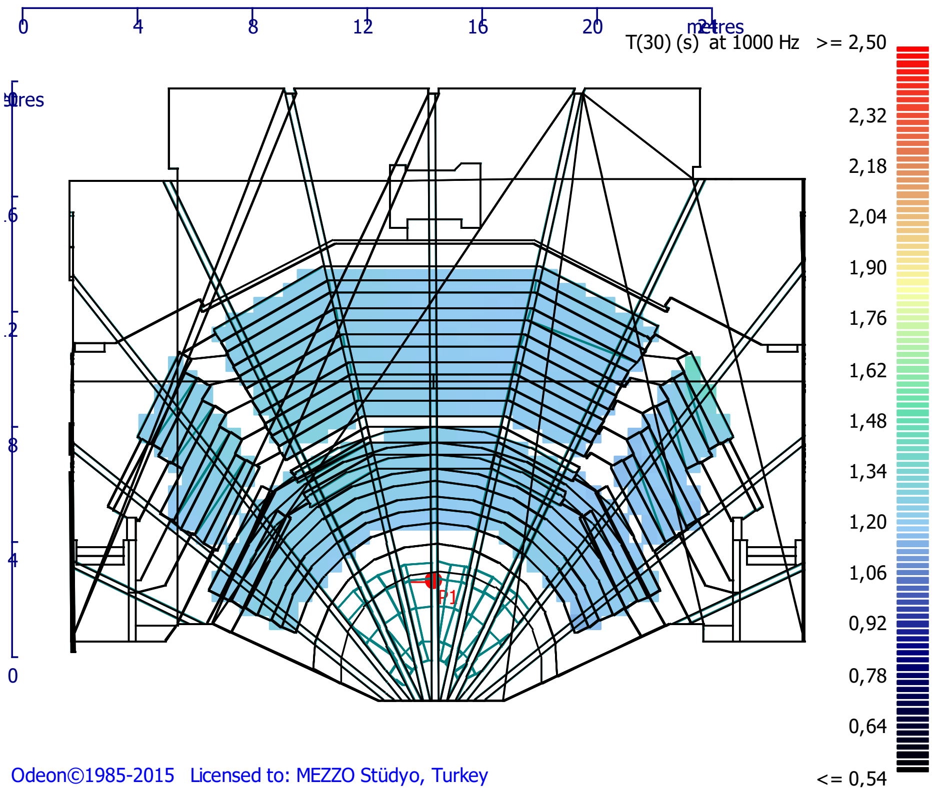


Figure 4.50. Reverberation time (T(30)) distribution map for 1000 Hz -concert - proposal

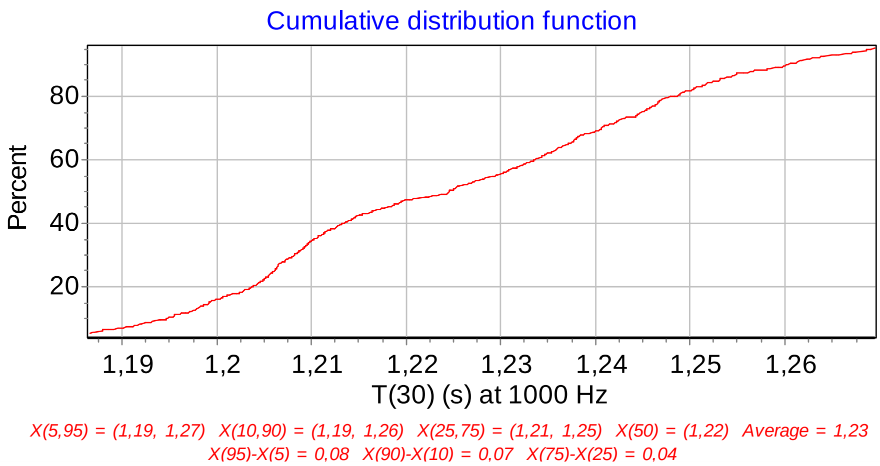


Figure 4.51. Reverberation time (T(30)) distribution graph for 1000 Hz -concert - proposal

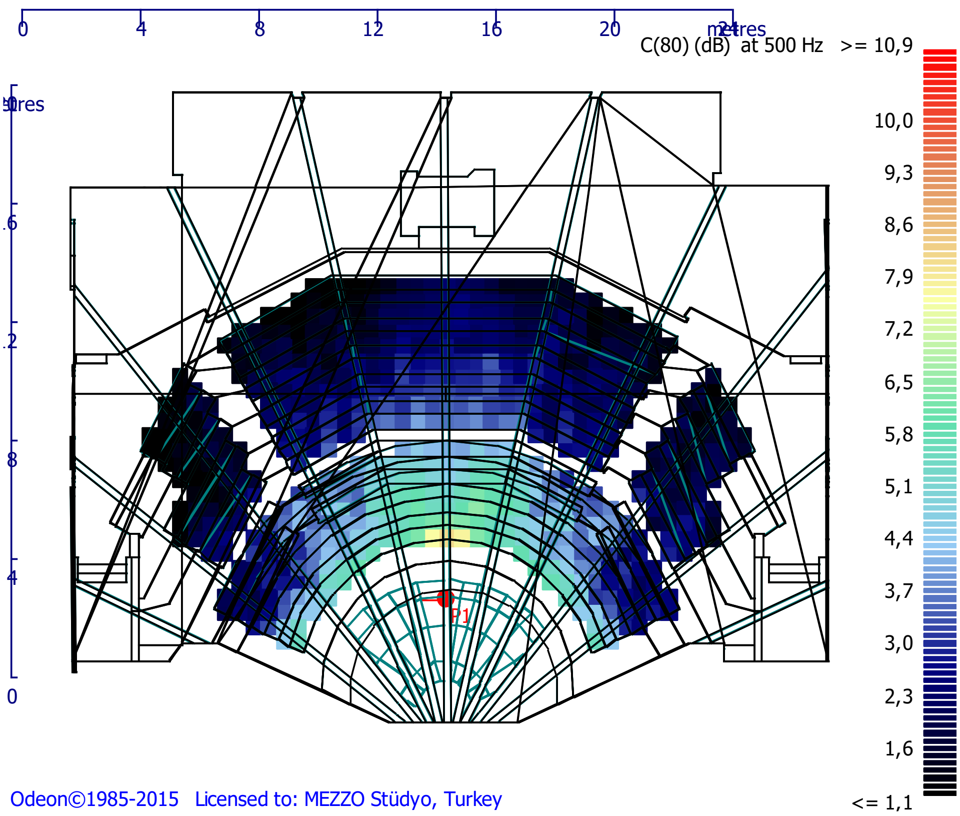


Figure 4.52. Clarity (C(80)) distribution map for 500 Hz -concert - proposal

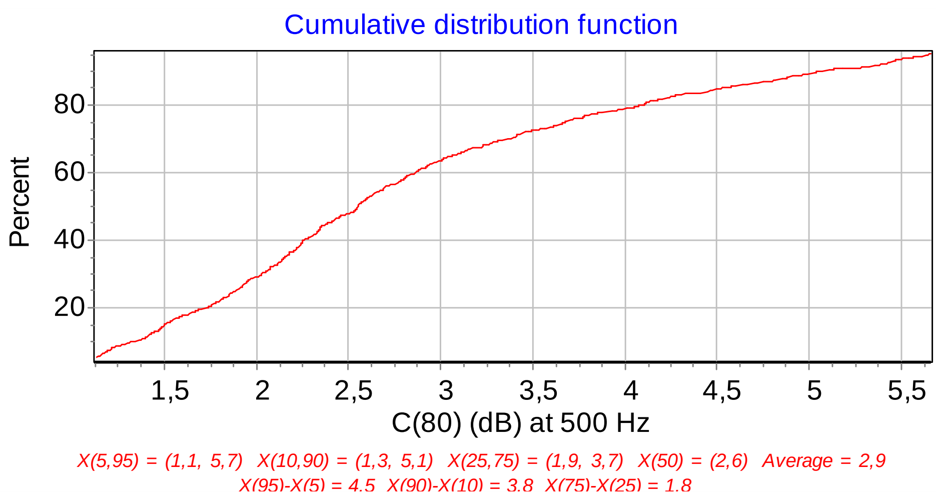


Figure 4.53. Clarity (C(80)) distribution graph for 500 Hz -concert - proposal

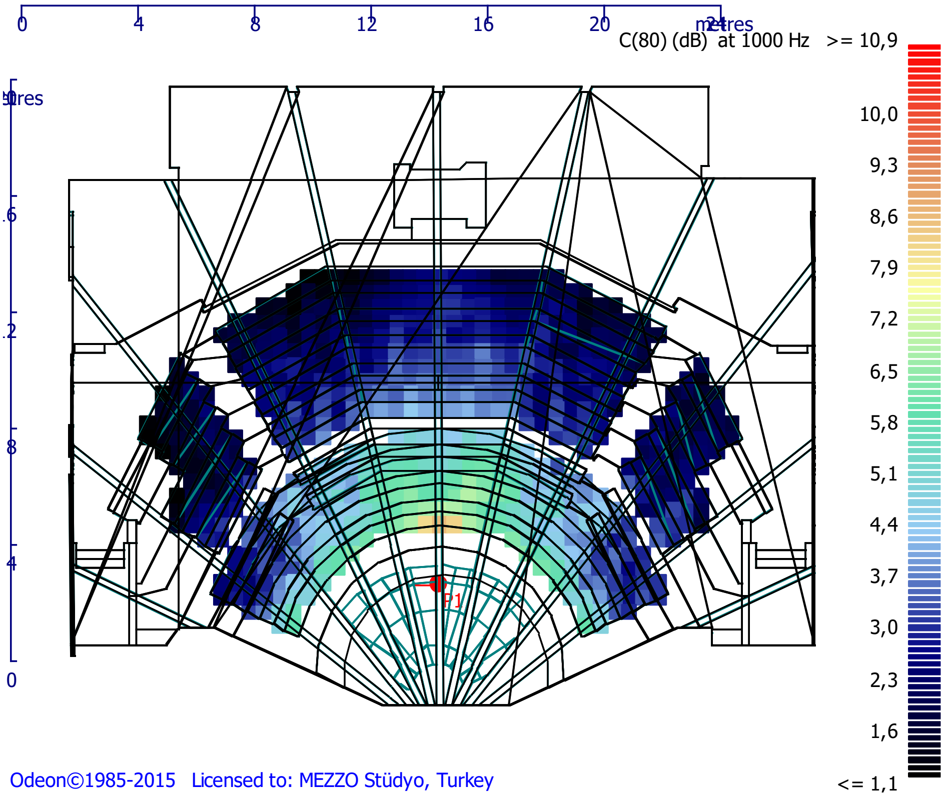


Figure 4.54. Clarity (C(80)) distribution map for 1000 Hz -concert - proposal

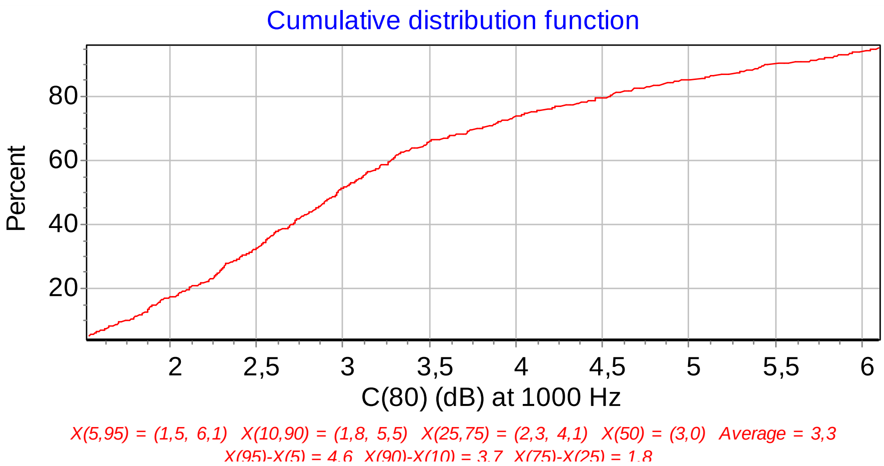


Figure 4.55. Clarity (C(80)) distribution graph for 1000 Hz -concert - proposal

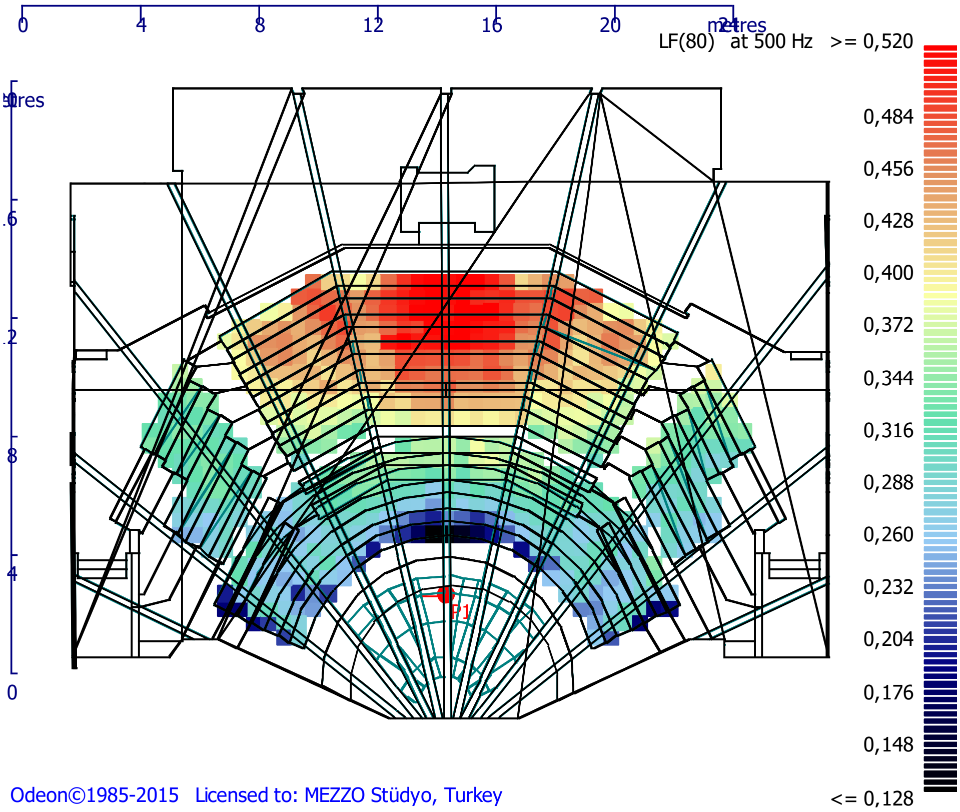


Figure 4.56. Lateral fraction (LF(80)) distribution map for 500 Hz -concert - proposal

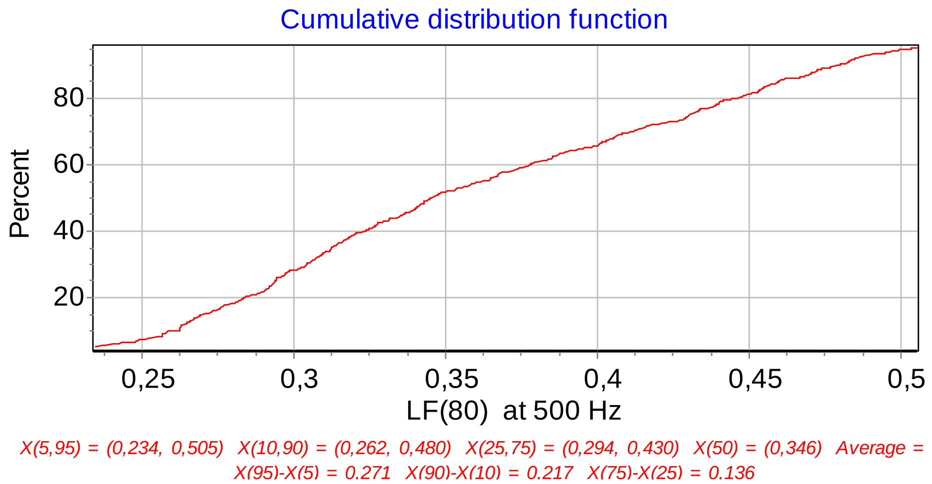


Figure 4.57. Lateral fraction (LF(80)) distribution graph for 500 Hz -concert - proposal

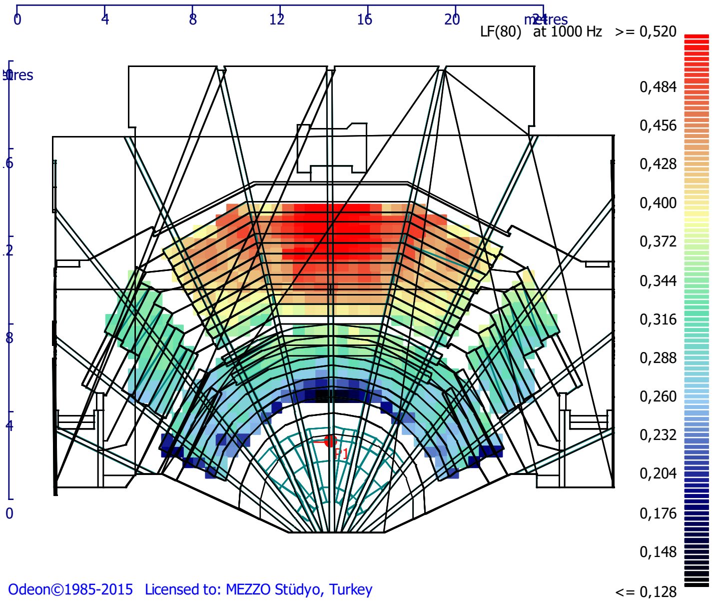


Figure 4.58. Lateral fraction (LF(80)) distribution map for 1000 Hz -concert - proposal

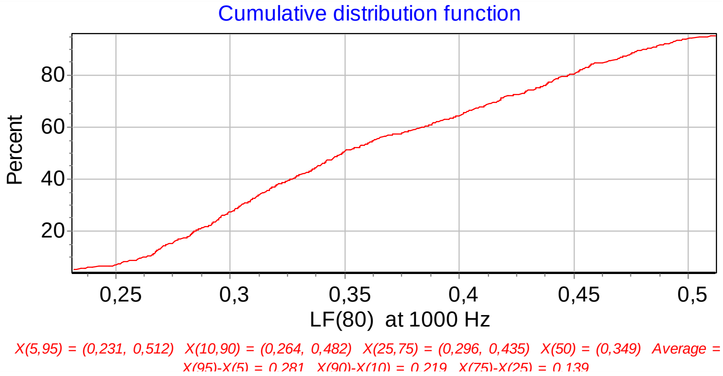


Figure 4.59. Lateral fraction (LF(80)) distribution graph for 1000 Hz –concert - proposal

4.2.2.5. Concert use in fully occupied condition

In consider with the current acoustical conditions of the hall, to decrease reverberation times in low frequencies, perforated panels at back-wall surfaces were arranged in 2% perforation ratio and 2mm slot width, to prevent echo. Perforation ratio of perforated panels were kept constant for the fully seated case of the hall (Figure 4.60). Hence, increased sound absorption area by the presence of audience decreases the reverberation time. Decrease in reverberation time at low frequencies create more suitable condition for the possible electro-acoustic systems (Figure 4.61).

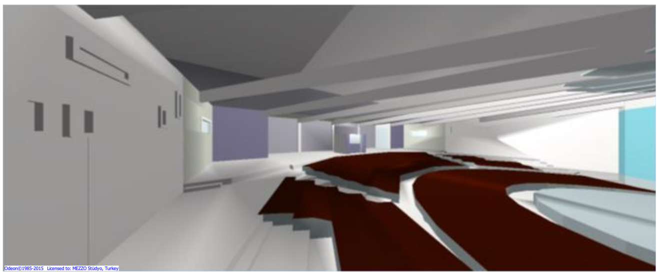


Figure 4.60. OpenGL view of the Amphitheatre in fully occupied condition– concert - proposal

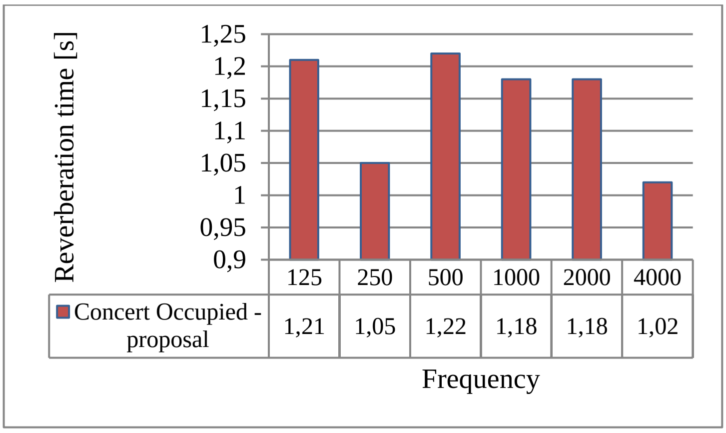


Figure 4.61. Estimated global reverberation times-occupied condition-concert - proposal

4.2.3. Room Acoustic Analysis Discussion

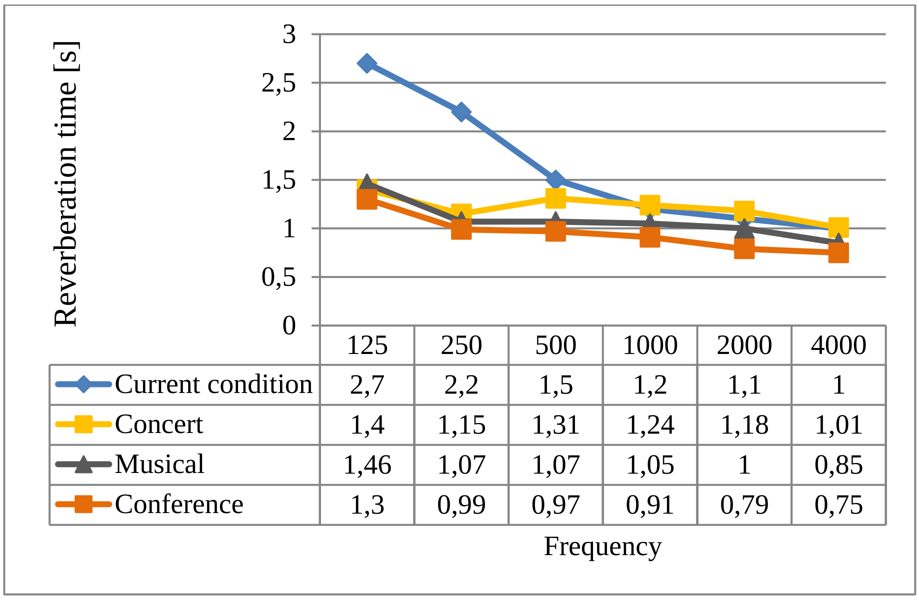
Current acoustical condition of the hall is not suitable for lectures or concerts that the Amphitheatre is assigned with. Reverberation times at low frequencies of 125 Hz and 250 Hz are as high as 2,65 s and 2,19 s. The acoustical condition of the Amphitheatre needs to be improved and reverberation times in 1/1 octave bands need to be balanced. To decrease reverberation times at low frequencies, variable perforated panels in the hall were arranged to 2mm slot width and 2%perforation ratio. Perforated panel proposal was tested as a variable acoustic solution. According to simulation results, despite of the difficulties in current acoustical conditions of the hall, it is possible to adapt the Amphitheatre to different functions as conference, musical, concert (chamber music) and differences in size of audience by the perforated panel proposal. The contribution by the perforated panel proposal in the hall reveals the potential of the proposal as a variable acoustic solution. To overcome the acoustical problems at low frequencies, conventional variable acoustic solutions designed with porous materials will not be helpful, because of the lack of sound absorption capability of porous absorbers at low frequencies. Findings of simulations are summarized in Table 4.15.

Table 4.15. *Acoustical design parameters and simulation results for different functions*

Acoustical Parameters	Criteria	Hall averages
Current Situation		
Reverberation Time, T(30) (500 Hz – 1kHz average)	-	1,36 s
Speech Transmission Index, STI	-	0,53 - 0,63
Conference		
Reverberation Time, T(30) (500 Hz – 1kHz average)	< 0,95 s	0,94 s
Speech Transmission Index, STI	> 0,6	0,62 – 0,72
Musicals		
Reverberation Time, T(30) (500 Hz – 1kHz average)	>0,95, <1,15	1,06 s
Clarity, C(80)	>+0, <+8	>3
Lateral Fraction, LF(80)	<0,1	>0,15
Speech Transmission Index, STI	> 0,6	0,58 – 0,72
Concert (Chamber Music)		
Reverberation Time, T(30) (500 Hz – 1kHz average)	>1,15, <1,35	1,28 s
Clarity, C(80)	<-2, <+4	>1
Lateral Fraction, LF(80)	>0,1	>0,2

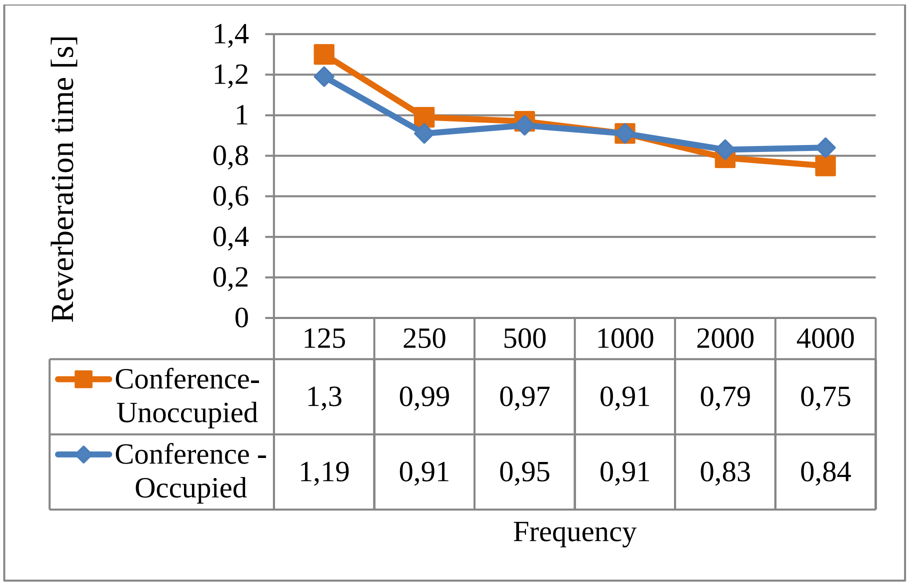
Room acoustic simulations were performed to test the capability of perforated panel proposal to change the acoustical conditions of a hall. Reverberation time for current situation of the hall and acoustical proposals for conference, musical and concert were compared in Figure 4.62. The perforated panel proposal achieves to alter the acoustical conditions of the hall as a variable acoustic solution according to represented comparison in Figure 4.62.

Acoustical conditions proposed for conference use in unoccupied condition of the hall were aimed to be provided for in fully occupied case, to test the capability of the perforated panel proposal. Panels which have 20% perforation ratio for the unoccupied case, were arranged in different perforation ratios. Hence, increased sound absorption area by the existence of the audience was tried to be balanced. Perforation ratios were decreased to 12%, 8% and 4%. Comparison of reverberation times for unoccupied and occupied conditions of the hall is presented in Figure 4.63. Proper acoustical conditions for the conference use were provided for both occupied and unoccupied cases.



Frequency	125	250	500	1000	2000	4000
Current condition	2,7	2,2	1,5	1,2	1,1	1
Concert	1,4	1,15	1,31	1,24	1,18	1,01
Musical	1,46	1,07	1,07	1,05	1	0,85
Conference	1,3	0,99	0,97	0,91	0,79	0,75

Figure 4.62. Comparison of reverberation times for current condition and acoustical proposals: conference, musical and concert functions for unoccupied hall



Frequency	125	250	500	1000	2000	4000
Conference-Unoccupied	1,3	0,99	0,97	0,91	0,79	0,75
Conference - Occupied	1,19	0,91	0,95	0,91	0,83	0,84

Figure 4.63. Comparison of reverberation times for unoccupied and occupied conditions for conference

CHAPTER 5

CONCLUSION

In this chapter, the research is summarized with reference to literature review, material and methods of the research. In the following sections, summary of the research and main results are shared, and limitations of the study are mentioned. For further studies, open ends of the study are presented. In conclusion, the perforated panel proposal as a variable acoustic solution has proven to be a viable solution. It can be concluded that objectives of the research are satisfied:

- Design parameters of a perforated panel were examined and a perforated panel proposal providing variability in sound absorption characteristic was obtained.
- The proposal was tested on a case, and competence of the proposal about creating sufficient variation in room acoustic conditions was proved.

5.1. Summary of the Research

In scope of this research, a perforated panel proposal was produced, and tested as a variable acoustic solution. Design parameters of perforated panels were analyzed by studies in literature. Variable perforated panel system is proposed, in consider with the cases in literature like adaptable Helmholtz resonators and research by Randeberg (2002) and Fuchs (2000) on perforated panel systems designed with two macro perforated panels. Effects of features like perforation, hole width, panel thickness, air gap and backing material were investigated by literature review and Kundt's tube measurements. Configuration of the variable perforated panel proposal was finalized. Perforated panels were produced by CNC routers and laser cutting machines from 8 mm and 3 mm raw MDF panels. Sound absorption coefficients of perforated panel proposal were measured. Variance in sound absorption performance of the perforated panel system in different positions was revealed by the measurement results. The relation between perforation ratio and sound absorption performance of the panel proposal was displayed by non-linear regression analysis. Cubic equation which represents the relation between panel position and noise reduction coefficient was presented. A prototype of the perforated panel proposal was produced by an Arduino board and controlled by a digital interface. The digital interface represents proposed functions for a hall like conference, musical and concert. The panel proposal was expected to adapt these functions. Furthermore, capability of the perforated panel proposal as a variable acoustic solution is tested on a case: METU Architecture Department Amphitheatre. Current acoustical condition of the Amphitheatre is documented by field measurements. Acoustical model of the Amphitheatre was prepared and imported to ODEON room acoustic software. The model was calibrated according to the field measurements. The Amphitheatre was adapted to conference, musical and concert functions and results of room acoustic simulations were presented. Findings of computer simulations suggested that it is possible to alter acoustical conditions of a hall by the variable perforated panel proposal. Hence, the aim of the research, perforated panel proposal as a variable acoustic solution was achieved.

5.2. Main Results

Design features of perforated panels were examined by impedance tube measurements. Perforated panel proposal was designed by considering the result of these experiments. Prototype of the perforated panel proposal is schematized, and perforated panel proposal was obtained. In next step, impedance tube measurements reveal the sound absorption performance of the proposal for different panel positions. The relation between panel positions and sound absorption performance of the system was described by a cubic equation with the help of non-linear regression analysis. The claim of the proposal to be a variable acoustic solution was tested by a case. Current acoustical conditions of the METU Architecture Department Amphitheatre were documented and presented by field measurements. The variable perforated panel proposal was placed on wall and ceiling surfaces of the Amphitheatre virtually in

ODEON room acoustic simulations. Simulation results show that the perforated panel proposal is capable to be a variable acoustic solution. Main results of these measurements and simulations were summarized under this section.

5.2.1. Perforated Panel Configuration and Prototyping

Variable perforated panel system is composed of two identical panels. While one of this panels is stationary, the other panel which is immediately behind is sliding. Opening ratio and width are arranged by this sliding movement. Slot perforation was preferred rather than circular perforation to avoid distortion of the shape of perforation. Porous sound absorber material, which is behind the panels, was placed on wall surface for operational reasons to prevent the material from dry friction caused by sliding of panels.

The perforated panel proposal was configured with 8-mm and 3-mm perforated panels, 20-cm air gap and two layers 5-cm thick 50 kg/m^3 rock wool. Effects of air gap, porous absorber and panel thickness were tested to decide this configuration. Increasing the distance of air space improves the sound absorption at low and mid frequencies. Tests which were performed with panels have 2% perforation ratio pointed the effect of air gap clearly. Application of double layer porous absorber improves the sound absorption performance of the system for low, mid and high frequencies. Thickness of the sliding panel is 3 mm. Thickness of the stationary panel is increased to 8 mm to strengthen the system for the final panel configuration. 3-mm MDF panels were perforated by laser cutting machines. CNC routers need to be used for 8-mm panels because of the thickness being higher than 5 mm. Hence, perforation shape, placement and thickness of porous material, panel thickness and air gap distance are all specified after prototyping studies and impedance tube measurements.

5.2.2. Sound Absorption Measurement of Variable Perforated Panel Proposal

Final configuration of the perforated panel proposal was tested for 20%, 16%, 12%, 8%, 4% and 2% perforation ratios. The highest sound absorption was obtained at 250 Hz for 2% and 4% perforation ratios; on the other hand, the maximum sound absorption is obtained at 2000 Hz for higher perforation ratios. For 12% and higher perforation ratios, the sound absorption characteristic of porous absorber becomes dominant because of the wider slot width. The maximum variance in sound absorption is 0,6 and obtained at 2000 Hz. Hence, variable sound absorption characteristic of the perforated panel proposal is proved by these test results. The relation between panel positions and sound absorption performance is expressed by a cubic equation obtained after regression analysis.

5.2.3. Field Measurements of The METU Architecture Department Amphitheatre

Variable perforated panel proposal is tested on a case: METU Architecture Department Amphitheatre. Field measurements were held for the Amphitheatre to identify current acoustical conditions of the hall and calibrate the following simulation studies. The Amphitheatre is used for various purposes from lectures to musicals and concerts by student clubs of the university. The hall is in almost square form and interior surfaces of the Amphitheatre is mostly fair-faced concrete surfaces. Measured reverberation times for 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz are respectively; 2,7s, 2,2s, 1,5s, 1,2s, 1,1s and 1,0s. Variable perforated panel system is proposed to produce proper acoustical conditions in the hall for different functions and for varying amount of audience absorption.

5.2.4. Room Acoustic Simulations

Perforated panel system was placed on wall and ceiling surfaces of the Amphitheatre virtually for room acoustic simulations. The Amphitheatre as a multi-purpose hall was adapted to conference, musical and concert functions. Acoustical conditions of the hall were changed by the perforated panel proposal. Reverberation time for the current condition of the hall (1,36s as average of reverberation times at 500 Hz and 1000 Hz) was decreased to 0,94s for conference use. Average of the reverberation times at 500 Hz and 1000 Hz were obtained as 1,28s for concert use and 1,06s for musicals. Perforation width of the variable perforated panels decreased to 2mm to obtain higher sound absorption at low frequencies. Hence, long reverberation times at low frequencies in current condition of the hall were reduced and balanced acoustical conditions for different functions were obtained. Proper acoustical conditions and similar reverberation times in 500 Hz and 1000 Hz were obtained for both unoccupied (0,97s and 0,91s) and fully occupied (0,95s and 0,91s) conditions of the hall in the conference use. The proposal reveals its capability to tune a hall for different acoustical requirements as a variable acoustic solution.

5.3. Limitation of the Study

Sound absorption measurements for perforated panel proposal and prior panel configurations were performed with impedance tubes. Samples which were prepared for impedance tube measurements, were assumed to represent a homogeneous part of the absorber. On the other hand, studies in literature claim that impedance tube measurements with rather small and inhomogeneous samples are also capable to provide good agreement with sound absorption predictions and calculations for perforated panels. Impedance tube is remarked as an excellent tool to develop new absorbers and it is capable to provide sound absorption coefficient measurements of perforated panels with various perforation shapes which is difficult to calculate. Nevertheless, as a limitation of this study, sound absorption coefficient measurements can be performed in reverberation chamber with larger samples representing rather more homogeneous part of the perforated panel proposal. The proposal was tested on a case METU Architecture Department Amphitheatre by room acoustic simulations. If the proposal would be produced for real application, it can be tested by field measurements. The proposal can be improved and industrialized as a variable acoustic solution in further studies. Hence, the subject of the research, perforated panel proposal can be part of the acoustical designs in practice.

5.4. Further Studies

The perforated panel proposal was designed with slot perforation rather than circular to control the shape of perforation more accurately. Effects of design parameters of perforated panels; slot width, perforation ratio, air gap, porous backing material and panel thickness were examined and presented. The perforated panel proposal which is the subject of the research was designed with two identical perforated panels. Therefore, another parameter occurred: the distance between perforated panels. In scope of this research, the distance between panels was eliminated and panels were placed as attached each other. In further studies, the distance between panels can be assessed as another design parameter beside; slot width, perforation ratio, air gap, porous backing material and panel thickness. However, increase in distance between panels causes concerns about the maintenance. Demountable architectural details can be designed to overcome maintenance problems and clean the gaps of the system. In further studies, porous absorber can be removed, and sound absorption performance of the system designed with two macro-perforated panels can be investigated without a backing material.

The perforated panel proposal was examined in terms of variance in sound absorption characteristics and its capability as a variable acoustic solution. A prototype of this proposal was built. Control panel was designed digitally by Processing software and the main electronic assembly was built with Arduino board. Servo engines were used to drive panels to provide physical movement. Timing belt and pulley were the main supplementary mechanical equipment to provide sliding movement. However, the prototype needs to be improved for real applications. Its structural profiles and mechanical assembly require standardization to be a part of the real construction process. Furthermore, designed interface to control the prototype, represents proposed functions for the multi-purpose hall like conference, musicals and concert. Each function is matched with proper angle to control the servo engine. The angle is defined according to room acoustic simulations. However, the prototype can be designed as a self-adaptive module and combined with a measurement system including microphone. Moreover, the panel position can be arranged regarding to the measured and aimed reverberation times simultaneously.

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