ACOUSTICAL CHARACTERIZATION OF CLAY POTS IN OTTOMAN ARCHITECTURE THROUGH EXPERIMENTAL AND NUMERICAL ANALYSIS METHODS

A THESIS SUBMITTED TO

THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE

OF BILKENT UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF

MASTER OF SCIENCE

IN

ARCHITECTURE

By

Gülnihan Atay

July 2022

Acoustical Characterization of Clay Pots in Ottoman Architecture through Experimental and Numerical Analysis Methods
By Gülnihan Atay
July 2022

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

ACOUSTICAL CHARACTERIZATION OF CLAY POTS IN OTTOMAN ARCHITECTURE THROUGH EXPERIMENTAL AND NUMERICAL ANALYSIS METHODS

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Employment of clay pots as building elements is a common practice especially in the medieval structures throughout Europe and Near East. Despite the fact that their acoustical employment in historic structures is well known and dates back to the 1st century BC as observed in Vitruvius' writings, their true contribution to the acoustics of Medieval Architecture remains to be a subject of discussion. They are also present in Ottoman Architecture including Süleymaniye Mosque designed by Sinan the Architect Laureate. Although these elements placed in the dome of Süleymaniye are often interpreted to be utilized as Helmholtz resonators, a scientific account regarding their sound absorption performance is needed so as to understand whether they actually perform as cavity resonators. Therefore, the scientific investigation of their acoustical behaviour through analytical, experimental, and numerical analysis methods is necessitated. The objective of this study is to discuss the effect of clay pots on the sound energy decay pattern of Süleymaniye Mosque. The study begins with an archival research phase covering the versatile employments of clay pots as building elements that are not limited to their acoustical utilization. The study then proceeds with the impedance tube measurements conducted with the reproduced sample of an actual-sized clay pot employed in the structure. The results are then verified with finite element modelling (FEM) simulations. Finally, sound absorption coefficients, obtained from the latter are transferred into the ray tracing simulations so as to understand the pots' effect on reverberation times (T30) in the edifice. In the conclusion part, sound-absorption performance of clay pots and their possible contribution to the mosque acoustics are discussed. As a result of the study, the resonance frequency of the clay pots embedded into the central dome of Süleymaniye Mosque is found to be 50 Hz. Additionally, they are also proven to be effective at 500 Hz octave

band. Consequently, the ray tracing simulations exhibit a 2 seconds decrease in T30 values at 500 Hz octave band. This also proves the improvement of reverberation time at this octave band range, which was measured after the final restorations of Süleymaniye Mosque with repaired pots.

Keywords: Clay pots, Helmholtz resonator, Süleymaniye Mosque, architectural acoustics, sound absorption coefficient, mosque acoustics.

ÖZET

OSMANLI MİMARİSİNDE KULLANILAN SEBULARIN DENEYSEL VE SAYISAL ANALİZ YÖNTEMLERİ İLE AKUSTİK ÖZELLİKLERİNİN BELİRLENMESİ

Gülnihan Atay
Mimarlık, Yüksek Lisans
Tez Danışmanı: Zühre Sü Gül
Temmuz 2022

Sebuların üst yapı elemanları olarak kullanımı özellikle orta çağ yapılarında sıklıkla karşılaşılan bir uygulamadır. Tarih sayfalarındaki bahsi milattan önce 1. yüzyıla kadar dayanan bu çömlek kapların Romalı mimar Vitruvius'un eserlerinde bahsettiği üzere akustik kontrol amaçlı mekâna yerleştirilen yapı elemanları olduğu önerisi güçlü olmakla birlikte elemanların yapı içerisindeki ana işlevleri belirsizliğini korumaktadır. Mimar Koca Sinan'ın eserlerinde çokça gözlemlenen bu uygulamanın yapıların akustiğine sağladığı katkının analitik, deneysel ve sayısal benzetim çalışmalarıyla incelenmesi, bu elemanların yapıda bilinçli olarak boşluklu rezonatör olarak kullanılıp kullanılmadığının bilimsel tespiti için önem arz etmektedir. Bu çalışmanın amacı, Süleymaniye Cami'nde yer alan sebuların hacim içerisindeki ses enerjisinin kontrolüne katkısını tartışabilmektir. Çalışma, toprak çömleklerin Anadolu mimarisinde akustik kontrolle sınırlı kalmayan çeşitli kullanım amaçlarının incelendiği bir arşiv araştırması ile başlar. Süleymaniye özelinde devam eden incelemeler, caminin kubbesinde tespit edilen sebuların özgün ölçülerinde tekrar üretimini ve bu üretim üzerinden gerçekleştirilen empedans tüpü ölçümlerini içerir. Çalışma, sebuların etkili olduğu frekans aralıklarının tespit edildiği sonlu eleman metodu benzetimleri ile devam eder. Sebuların deneysel ve sayısal yöntemlerle elde edilen ses yutma katsayıları yapının ses alanına etkilerini anlayabilmek amacıyla karşılaştırmalı ışın izleme metodu benzetimlerine aktarılır. Böylece sebu kullanımının mekânın çınlama süresine katkısı incelenir. Analiz sonucunda sebuların rezonans frekansı 50 Hz bulunmuş, etkili oldukları bir diğer baskın frekans aralığının ise 500 Hz oktav bandı olduğu belirlenmiştir. Sebuların 500 Hz oktav bandında çınlama süresinde 2 saniyelik düşüş meydana getirdikleri benzetim çalışmaları ile ortaya konulmuştur. Bu durum, Süleymaniye Cami'nde gerçekleşen son restorasyon

çalışmalarından sonra sahada yapılan çınlama süresi ölçümlerinde 500 Hz oktav bandında gerçekleşen iyileşmeyi desteklemektedir.

Anahtar sözcükler: Sebu, Helmholtz resonatörü, Süleymaniye Cami, mimari akustik, ses yutma katsayısı, cami akustiği.

Acknowledgement

First and foremost, the author would like to express her deepest gratitudes to her supervisor, Zühre Sü Gül, for her guidance and support along the research. Her cheerful presence, understanding and patience was an essential element that made the completion of this work possible during the compelling times of pandemics. She is greatly appreciated not only for her academic advisory but also for her valuable mentorship. The doors she opens for her students are much appreciated and valued.

Dr. Onursal Önen is thankfully acknowledged for his technical contribution and support for the finite element modeling phase of the research. He has become an essential contributor to this project with his knowledge and critical reviews which steered the course of the project for the better. I thankfully appreciate his patience and guidance along the research.

The author also would like to convey her gratitude to Professor Mehmet Çalışkan for his invaluable technical guidance, support and the most needed insight he provided throughout the project.

The author would like to acknowledge architect Nilgün Olgun; the site chief of the Süleymaniye Mosque restoration, architect Çiğdem Saruhan; the site chief of the Yeni Mosque restoration, architect Sevgi Gemici and the restoration team of Yeni Mosque as well as Dr. Ahmet Vefa Çobanoğlu, member of the science committee of the current Sultan Ahmet Mosque restoration, for their contribution to the study by providing the information from the recent restoration works. Architect İbrahim Hakkı Yiğit, architect Acar Avunduk, Dr. Aras Neftçi and Dr. Aliye Öten are also thankfully acknowledged for their help, time and sincere interest to the study.

My thanks are extended to my colleagues from Mezzo Stüdyo team for their interest and support for this research. Mezzo Stüdyo is also thankfully acknowledged for providing the impedance tubes and the required laboratory environment for the measurements. The author also expresses her sincere thanks to Galip Körükçü for his part in the production of the sample clay pot based on the given dimensions of the original resonators.

Last but not least, it would not be possible to complete this thesis without the unconditional support, love and patience from my family. With an excitement and interest that is almost equal to mine, they have always been the main source of my enthusiasm and perseverance. Finally, I am thankful for the irreplaceable companionship of my brother, Atakan Atay, who kindly guide me with the every aspect of my life.

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Chapter 1

Introduction

1.1 Problem Statement

The field of acoustics has a long-standing interest on so called Helmholtz resonators found embedded in the walls of historic structures. "De Architectura" written by the Roman architect and engineer Vitruvius in the 1^{st} century BC is recognized as one of the oldest records of such acoustical association. In Book 5, he discusses the acoustical employment of the bronze and earthen vessels called "echea" found in the ancient Greek theaters in which he argues their utilization for the amplification of sound [1]. Following the antiquity, the widespread employment of clay pots as acoustical elements is reappeared during medieval period in which they were observed especially in the religious architecture of Europe, Near East and last but not least, Anatolia. Although the existing historical texts leave no doubt for the deliberate acoustical intention behind their medieval implementation, their true contribution to the acoustics of the space remains to be a subject of a scholarly discussion. Therefore, the present study focuses on the employment of *sebu* (clay pot) in Ottoman Architecture in Anatolia and assess their acoustical performance in Süleymaniye Mosque, a 16^{th} century edifice that contains 224 clay pots on its great dome.

Based on the available texts on their implementation in medieval structures, Arns & Crawford [2] infer that the medieval motives behind their usage were either the adaptation of the sounding-vessel concept of Vitruvius, or solely a symbolic implementation that is "representative of the belief in the role of musical tones in elevating the soul." On the other hand, Valière & Palazzo-Bertholon [3] indicate the lack of concrete evidence of their connection with Vitruvius altough they acknowledge his influence on medieval practice. Despite the acoustical utilization of clay pots found in medieval architecture is mainly linked with the amplification of sound since the antiquity, alternative interpretations regarding their functionality are present. With the development of theoretical framework of Helmholtz resonance later in the 19^{th} century, their employment as cavity resonators which control low frequency sound energy within the space became one of the main arguments.

Present studies investigating the supposedly-acoustic-pots found in medieval liturgical architecture in Europe mainly examine the related historic texts that belong to the given structures and investigate the intention behind their deliberate addition to the architecture. Other group of researches aim to identify the resonance frequency of such pots through experimental and numerical analysis. On the other hand, few of them survey the sound absorption coefficient of the pots in their effective frequency range. The limited number of the pots found in European examples, however, hinder the examination of their true contribution to the acoustics of the space. The abundant number of pots found in the dome of Süleymaniye Mosque when compared to its European contemporaries, makes the case a significant subject to understand the true acoustical behaviour of the pots. Apart from their acoustical properties, clay pots are already known to be serving for versatile functions including structural, infrastructural and ventilational purposes in Ottoman Architecture [4]. Their acoustical implementation, however, is mainly observed in mosque structures. Despite the abundant number of studies examining the acoustics of the Ottoman era and modern day mosques, none scientifically examine the acoustical behaviour of the pots and their effect on the sound energy decay pattern of the structure. In fact, the clay pots found in the superstructure of Ottoman Architecture in Anatolia is often interpreted

to be employed as Helmholtz resonators without sufficient scientific investigation. Therefore, the present literature exhibits a significant reseach gap in the field and a comprehensive study covering the sound absorption performance of the clay pots found in Ottoman Architecture and their contribution to the sound energy decay pattern of the space is necessary. Comprehension of the empirical acoustical practice of the medieval era is prominent, as understanding the working principles of acoustic pots may elucidate the transformation of the building knowledge during its transfer through geography and time. Hereby, the problematic of the study is that, altough the acoustical employment of clay pots are mainly accepted, their precise contribution to the sound energy decay pattern in the medieval structures in Europe and Anatolia remains to be specified.

1.2 Aim & Scope of the Thesis

Consequently, the present study aims to assess the sound absorption capacity of the clay pots found in the dome of Süleymaniye Mosque so as to understand whether these pots are originally employed as cavity resonators. The subject of the study is selected as Süleymaniye Mosque, a 16th century edifice in İstanbul owing to its historical significance, vast volume and the abundant number of pots it contains on its grand dome. The acoustical behaviour of clay pots are aimed to be documented through impedance tube measurements and finite element modeling. The acoustics of the edifice with functioning clay pots is then virtually reconstructed with ray tracing simulations.

The research questions adressed in the present study are as follows:

1. Do clay pots perform any acoustical behaviour in the edifice? If they do, how do they contribute to the interior sound field of Süleymaniye Mosque?

2. What is the effective frequency range of the clay pots?

3. Do clay pots embedded inside the main dome of Süleymaniye Mosque reduce

the reverberation times in their effective frequency range?

4. If the clay pots perform as Helmholtz resonators, what are their sound absorption coefficients in their effective frequency range?

5. What are the locations and the organization of the pots found in Süleymaniye Mosque and do their placement contribute to their acoustical performance?

6. Which functions do clay pots serve as building elements in the world?

The hyphothesis of the present study is that the pots perform as Helmholtz resonators and have a notable effect on the reverberation times of the edifice. One reason that supports their acoustical employment is that Sinan, the Architect Laureate of Ottoman Empire, is often known to utilize building elements to serve for multi-functional purposes. It is a historically common practice to utilize clay pots as infill materials in the walls and the upperstructures with load-lessening purposes. Nonetheless, the fact that the openings of the clay pots found in the central dome of Süleymaniye Mosque face the interior space strengthen the hyphothesis of their acoustical implementation in the structure.

The selected methodology is composed of two main bodies. First, the qualitative data regarding their history and diversive employments in Ottoman Architecture; their number, placement and disposition in the selected structures are collected in the inital archival research phase of the study. A literature survey covering the European examples of acoustic clay pots also form a basis for a discussion covering the employment of acoustic pots in the world history regarding their functionality and distribution in the geography.

Then, the empirical data regarding the sound absorption performance of the clay pots found in the central dome of Süleymaniye Mosque is acquired through aforementioned experimental and numerical analysis methods. After that, the obtained alpha values are utilized for the ray tracing simulations and their impact on the sound energy decay pattern of the mosque is finally evaluated based on a comparative evaluation of the T30 parameters. Subsequently, the contribution of

clay pots in control of the sound energy in the edifice are discussed.

1.3 Structure

This thesis is structured under six chapters as follows:

The first chapter establishes the framework of the research topic including the problem statement, aim and scope of the thesis. The research gap in the field is defined, and the objectives of the present study are exhibited.

Chapter two is composed of several subchapters including an historical overview of clay pots employed as different building elements involving their acoustical utilization. The following subchapter covers the previous experimental and numerical investigations of acoustic clay pots in medieval structures and their effect to the acoustics of the space. Definitions of the related acoustical terminology referred throughout the thesis are also provided in this chapter.

In the third chapter, the main subject of the study -Süleymaniye Mosque- is introduced. The architectural features covering interior finishing materials and the geometrical form of the edifice that affect the acoustics of the space are depicted. The detailed information regarding the number, size and disposition of the clay pots found in the central dome of Süleymaniye Mosque are given in this chapter. The required background information regarding the previous acoustical field tests and the restoration works held in the edifice are also introduced in a chronological order so as to prepare a basis for the upcoming discussion section in Chapter 5.

In the fourth chapter, data collection and analysis methods covering the experimental and numerical procedures are described. The experimental stage including the measurement of sound absorption coefficients of a life-sized reproduction of a *sebu* found in the dome of Süleymaniye Mosque through an impedance tube is detailed. The latter procedure involves the verification of initial results of the

impedance tube measurements through finite element modeling of the *sebu*. The acquired sound absorption coefficients are then transferred to the ray tracing simulations so as to understand their effect on the sound energy decay pattern of the mosque.

In the fifth chapter of the thesis, final results are presented. The outcomes of the experimental and numerical analysis are compared. The fundamental frequency of the *sebu* calculated using the well-known Helmholtz formula is also consulted so as to set a benchmark for experimental and numerical results. Finally *sebus'* resultant effect on the sound-energy decay pattern of Süleymaniye Mosque is discussed on the basis of reverberation times acquired from the ray tracing simulations. Previous acoustics field tests and the restoration works held in the edifice are consulted for the interpratation of the results when necessary.

In the final chapter, the thesis is concluded by the major findings and significant remarks regarding the sound absorption performance of the sebus in Süleymaniye Mosque.

Chapter 2

State of the Art

2.1 Acoustical Terminology

The basic terminology that is referred throughout the thesis are defined as follows:

Sound Absorption Coefficient (α):

When a sound wave hits on a surface, the contained energy in the sound wave is partially reflected, transmitted and absorbed within the material [5]. In the third case, the sound energy is converted to heat. The sound absorption performance of a material is defined with its particular "absorption coefficient" which describes the ratio of the absorbed energy by the material over the incident sound energy [6]. Theoretically, the perfect absorption of sound by a material is represented with 1.0 whilst no absorption is represented with 0.0. In other words, the unitless parameter represents the percantage of energy that is absorbed by the material surface.

Reverberation Time:

Reverberation time (RT) is described as the required time for sound energy level to drop by 60 dB once the source has been stopped [7]. The parameter

is accepted as one of the most significant depictors for the sound energy decay assessment of an enclosure [8]. In practice, the time required for sound to decay 20 dB is measured and multiplied by 3 or time required for a decay of 30 dB is measured and doubled to calculate the reverberation time. In these cases, parameters of T20 and T30 respectively, are utilized [9]. An enclosure with a high reverberation time is considered to be a lively environment. The finishing materials employed in the structure, the geometry of the enclosure as well as the volume of the space effect the reverberation time. In 1900s, Sabine proposed his famous formula of the reverberation time (T) for diffuse sound field that is derived by the total sound absorption (A) and the volume of the room (V) in m^3 (Equation 2.1). The total sound absorption of the room is acquired by the surface area (S) in m^2 and the sound absorption coefficents of the designated surfaces (α).

$$\begin{aligned} T &= \tfrac{0.161V}{A} \\ A &= \textstyle\sum S\alpha \\ \textstyle\sum S\alpha &= S_1\alpha_1 + S_2\alpha_2 + ... \end{aligned} \tag{2.1}$$

Helmholtz Resonator (Cavity Resonator):

Helmholtz resonators are volume absorbers that selectively absorb sound around their resonant frequency [5]. They are composed of a rigid-walled cavity volume (V) that is coupled to its surrounding space with a neck having an area of S and length of L [7, 10]. When the resonator receives a sound, the body of air inside the enclosure is compressed periodically by the air contained in the neck area [10]. Therefore, the body of air inside the enclosure acts as a spring, and the latter as a mass, the system performs as a special type of air-spring oscillator (Figure 2.1).

The literature covering the theoretical modeling of Helmholtz resonators are developed in the 19th century. The theoretical estimation of the resonance frequency of such devices is initially developed based on the physical characteristics of the resonators [11]. The accuracy of the well-known Helmholtz formula is

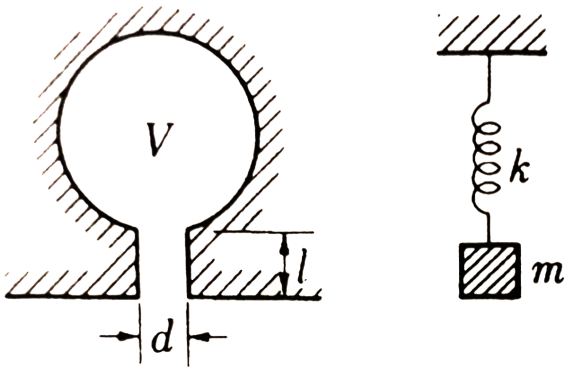


Figure 2.1: Schematically illustrated Helmholtz resonator [8]

improved by Rayleigh [12] by the inclusion of the correction factor. Ingard [13] considered the effect of different aperture geometries on the resonance frequency. Some other successive works considered the impact of the resonator geometry [14] as well as the aperture shape on the resonance frequency [15, 16]. Well-known formula of Helmholtz provides the natural frequency of the resonators based on the given physical parameters of the devices:

$$f_n = \frac{c_0}{2\pi}\sqrt{\frac{\pi(d/2)^2}{V}} \tag{2.2}$$

In the cases of an enclosed cavity contains an opening but do not have an apparent neck, the system still acts as a Helmholtz resonator [5]. The thickness of the cavity wall and the additional "end effect" factor together constitutes the length of the "neck". The resonance frequency of such oscilator is analytically defined as follows:

$$f_n = \frac{c_0}{2\pi}\sqrt{\frac{\pi(d/2)^2}{V(l_0 + 1.7(d/2))}} \tag{2.3}$$

2.2 Clay Pots as Building Elements

Clay pots are known to provide versatile means of building methods that is not only restricted to acoustical purposes. Their employment as load-lessening infill materials, water pipes and ventilation elements are known to be used for a long time in a wide geography. Their structural use is observed not only in the well-known building practices of Roman Empire [17], but also in middle-age Anatolia.

In Anatolia, the practice of the employment of clay pottery as building elements manifests itself in the structures from different historic eras and roots far back in history [18]. It is known that Sinan, the Architect Laureate of Ottoman Empire, applied multi-functional use of the building elements in his designs. In other words, an element or a specific type of application often serves for multiple purposes. Employment of clay pottery is such an example. Such practice includes structural, ventilative, and finally acoustical purposes. The state-of-the-art of the clay pottery applications in Ottoman Architecture in different building components including both acoustical and non-acoustical utilizations are investigated to provide a database of these elements including their sizes, forms, numbers and the placements in the selected structures.

2.2.1 Cases of Structural Usage

Clay pots are often used for reducing the load of the superstructure. Thus, their employment as filling substitute for the heavier brick elements is also observed frequently. Selected structures from Ottoman Architecture with such employment are listed in Table 2.1. Different utilizations in each structure including the dimension, type and placement of the clay pots are then elaborated.

Table 2.1: Selected structures with clay pottery employed for load reduction in Ottoman Architecture

Structure	Date	Architect	Location	Placement
Mahmud Paşa Mosque	15th cent	Mimar Atik Sinan	İstanbul	Portico for late comers [19]
II. Beyazıd Mosque	15th cent	Mimar Hayreddin	Edirne	Portico for late comers [19]
Hasan Paşa Hanı	16th cent	-	Diyarbakır	Domes above the rooms [18]
Yeni Mosque	17th cent	Mustafa Ağa Davut Ağa Dalgıç Ahmet Paşa	İstanbul	Pendentives of the central dome and semi-domes & portico for late comers [20]
Küçükmecidiye Mosque	19th cent	Balyan Family	İstanbul	Dome [21]
Hazine-i Evrak Building	19th cent	Gaspare Trajone Fosatti	İstanbul	Flooring [22]
Amasya Şirvanlı Mosque	19th cent	-	Amasya	Dome of the portico for late comers [21]

Mahmud Paşa Mosque (1462)

According to Hüsrev Tayla, the clay pipes were found in the portico for late comers in Mahmud Paşa Mosque [19]. Behind the marble claddings, stacking of clay pipes are vertically placed within the volume between the pendentives of the two adjacent domes and the corresponding spandrel of the portico. As Tayla puts, after each row of pipes, there is another single brick layer with 8-10 cm thick khorasan plaster coat on top. This alternating system continues way up to the cornice height of the wall and creates a base for the roof above [19]. According to the survey records, one of the pipes placed inside the wall has a diameter of 205 mm with a thickness of 24 mm along with a height of 330 mm. The diameter gets smaller at the top 50mm portion of the pipe. Tanyeli refers to this type of pottery as “geçmeli künk” which is “interlocking clay pipe” [23].

Edirne II. Beyazıd Mosque (1488)

The employment of clay pottery as a filling element is also observed in Edirne II. Beyazıd Mosque. Similar to the Mahmud Paşa Mosque, the pots are employed in the portico for late comers. Based on Tayla’s observations [19], more than 50



Figure 2.2: Mahmud Paşa Mosque, placement of the clay pottery between the arches of the portico for late comers (On the left). Drawing: Hüsrev Tayla [19].

clay pots were found in the volume between the four pendentives at the sides of the arch connecting the column to the exterior wall. According to Tayla, the pots have a height changing from 30 to 40 cm and have handles. It is also noted that these potteries are not custom production but most probably purchased from the local market [19].

Küçük Mecidiye Mosque (1848)

The pottery application on Küçük Mecidiye Mosque in İstanbul reestablishes a different methodology for the structural employment of clay pots. It is a late baroque style building that is from a later period when compared to the previous examples. In this building the clay pipes were found in the dome of the structure. According to the restoration team [21], the clay pipes could be observed when the lead coating on the exterior surface was removed for maintenance purposes. The layer of clay pipes, comparatively lightweight to the conventional full brick infill construction, applied on top of an existing dome structure with a purpose of elevating the dome and changing its silhouette. It was found in the restoration works that the intermediate layer accommodating pipes covers the interior layer of brick dome structure and have no connection with the interior space. According to Yücel et al., three thousand two hundred pipes were found in the dome structure all located perpendicularly to the dome surface, or in other words, their longitudinal axes point the center of the dome [21]. No bonding material is used between the elements as the pipes are squeezed within the brick envelope. Nevertheless, it is stated that they are locked up to their positions with T-shaped

metal bars which are also irregularly placed. As Yücel et al. puts, the clay pipes have a diameter of 29 cm and 26 cm on top and the bottom respectively, with a total height of 38 cm. The thickness of the pot is 1.8 cm.



Figure 2.3: Clay pot application in the dome of Küçükmecidiye Mosque. [21]

Hazine-i Evrak Building (1848)

The employment of pots in the flooring system of Hazine-i Evrak Building in İstanbul exhibits a different method. In this example, clay pipes are placed horizontally below the flooring as a filling element [22].

Amasya Şirvanlı Mosque (1873)

A similar application to Küçük Mecidiye Mosque is also evident in the dome of the portico for late comers in Amasya Şirvanlı Mosque. According to Yücel et al.,in this example, the pipes are employed to form the dome structure itself rather than lifting up the dome as in Küçükmecidiye Mosque [21]. Yet, its selection as the main structural material can similarly be accounted for its lightness when it is compared with the traditional brick construction method. An earlier 16th century structure, Hasanpaşa Hanı, also exhibits a similar employment to Amasya Şirvanlı Mosque. The rooms on the upper floors of the inn are covered with domes that contain clay pottery [18]. There is no information in the written sources on the dimensions of clay pots. In Table 2.2, the above-mentioned structural employments are summarized with the total number and dimensions of the clay pottery found in the selected structures.



Figure 2.4: Clay pot application in the flooring of Hazine-i Evrak Building [22].

2.2.2 Cases of Ventilative Usage

Another employment of clay pottery is for ventilation purposes. In such usage, clay pots are used to draw the fume caused by candles out of the place by creating ventilation channels. One other type of application is for fast process of the hardening of khorasan plaster. In these applications, the necessitated air is provided by the clay pipes placed between the bricks in pendentive and dome structures. As Tanyeli puts, Piyale Paşa Mosque can be exemplified for such employment [23]. Clay pots are also frequently observed in Turkish bath structures. They are used in the chimneys called *"tüteklik"* which were utilized for the adjustment of the interior temperature of the space when necessary [19]. The list of selected structures containing clay pottery that is used to ventilate the interior space are listed in Table 2.3.

Şehzade Mosque (1548)

As mentioned earlier, Şehzade Mosque contains clay pipes not only on its dome structure, but also on its pendentives and side walls. According to Erçağ, an air gap reaching up to 100 cm depth behind the pendentive that is connected to the air-shaft inside the piers was found during the restoration works held in the structure in 1990 [26]. This plenum space is connected to the main prayer hall through four clay pipes placed in the pendentive. As Erçağ puts, their function

Table 2.2: The number and sizes of the clay pottery employed for load reduction purposes in Ottoman Architecture

Structure	**Type of Pottery**	**Height**	**Top Diameter**	**Base Diameter**	**Diameter (widest)**	**Aperture Diameter**	**Total Number**
Mahmud Paşa Mosque [19]	Clay pipe "künk"	33cm	14.5cm	20.7cm	20.7cm	11.8cm	-
II. Beyazıd Mosque [19]	Pots with handles	30-40 cm	-	-	-	-	more than 50
Hasan Paşa Hanı [18]	Amphora type	-	-	-	-	-	-
Yeni Mosque [20]	Neckless/ amphora type	20-90 cm	-	-	60cm	2.5-30cm	15
Küçükmecidiye Mosque [21]	Clay pipe "künk"	38cm	29cm	26cm	29cm	25.4cm	3200
Hazine-i Evrak Building [22]	Clay pipe "künk"	-	-	-	-	-	-
Amasya Şirvanlı Mosque [21]	Clay pipe "künk"	-	-	-	-	-	-

is considered to be for ventilative purposes. The soot stains on the ceilings and the walls of the rooms below the gallery spaces on the Western and Eastern sides of the mosque which occurred due to the candlelight use inside the praying area validates such suggestion [26]. Similar to the ones employed in the dome structure, the clay pots on the walls has a diameter of 20 cm with a depth of 40 cm. 35 of these clay pots were also found in the Eastern and Western side walls of the structure facing the interior space. It was seen in the restoration works that these pots are also connected to the ventilation channels within the wall [28].

Süleymaniye Complex (1568)

Clay pots are utilized as ventilative elements in Süleymaniye Complex both in the Tomb of Sultan Süleyman the Magnificent and the Süleymaniye Mosque. The tomb structure accommodates clay pipe elements having two open ends that connects the interior to the plenum space between the double dome structures. As Tanyeli states, such placement provides an air flow between the inner and outer layers of the dome [23]. In the tomb structure, four of these clay pipes are

Table 2.3: Selected structures with clay pottery employment for ventilation purposes in Ottoman Architecture

Structure	**Date**	**Architect**	**Location**	**Placement**
Piyale Paşa Mosque	16th cent	Sinan the Architect	İstanbul	Pendentives [23]
Tomb of Süleyman the Magnificent	16th cent	Sinan the Architect	İstanbul	Between the & double domes [23, 24]
Süleymaniye Mosque	16th cent	Sinan the Architect	İstanbul	Walls of the soot room [25]
Şehzade Mosque	16th cent	Sinan the Architect	İstanbul	Pendentives & Walls [26, 27]

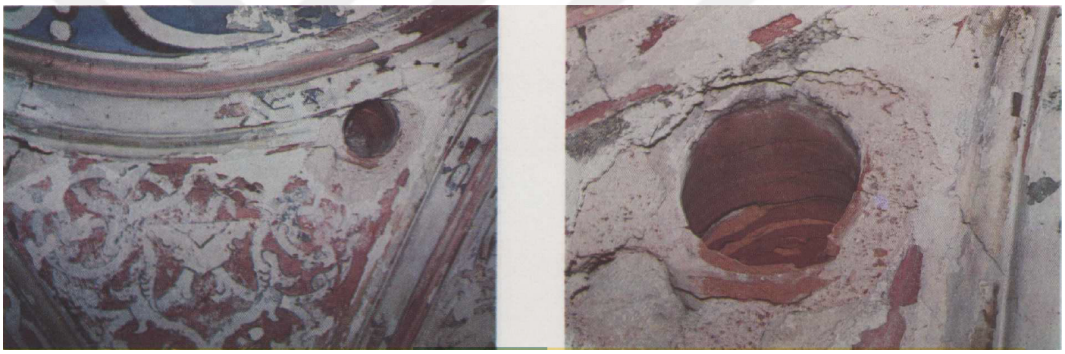


Figure 2.5: Şehzade Mosque, placement of the pots in the pendentive [26].

located around the keystone of the interior dome structure. They have a diameter of 13 cm and a height of 35cm with 5 cm protrusion above the surface [24]. Their interior-facing are also covered with perforated brass plates. In the mosque, the clay pots are employed in the "soot room" that connect the subspace to the main space of the Mosque. Similar to their employment in Şehzade Mosque, three *künks* placed in the wall enable the air to circulate within the structure. It is known that the soot collected on the walls of the soot room is later utilized for producing ink [25]. The number and sizes of the pots provided above are summarized in Table 2.4.

Table 2.4: The number and sizes of the clay pottery employed for ventilation in Ottoman Architecture

Structure	**Type of Pottery**	**Height**	**Top Diameter**	**Base Diameter**	**Diameter (widest)**	**Aperture Diameter**	**Total Number**
Piyale Paşa Mosque [23]	Clay pipe "künk"	-	-	-	-	-	-
Tomb of Süleyman the Magnificent [23, 24]	Clay pipe "künk"	35 cm	-	-	13 cm	13 cm	4
Süleymaniye Mosque [25]	Clay pipe "künk"	-	-	-	-	-	3
Şehzade Mosque [26, 27]	Clay pipe "künk"	-	-	-	-	20 cm	4 in a pendentive; 35 on the Western and Eastern walls

2.2.3 Acoustical Employment of Clay Pots in the History of Architecture

Different than their common employment as load lessening infill or ventilation elements that open up to an inner ventilation channel in the building, some pots found in many Ottoman Classical Era structures that are supposedly employed for acoustical purposes show distinctive features regarding their placement. In these buildings, clay pots with their inner enclosed volumes connected to the main space of the structures through their necks bear a resamblance to the cavity resonators which may help to control the reverberation times in their effective frequency range. In Anatolia, the supposedly acoustical utilization of the *sebu* pots are also mainly found in the concave interior surfaces of the structures. As is known, the large concave form of the dome structures has the potential to focus sound, create echo and eventually impair the diffused and even sound distribution within the space. As a result, the focused energy reduces the intelligibility of the sound. Embedment of the clay pottery within the dome structure with their

apertures facing the central point creates asymmetry and irregularity on the concave dome surface. Thus, these pots are known to contribute to the creation of a diffused sound field by scattering the sound back into the interior space and hereby enlargen the dome reflection zone [29]. As mentioned in Chapter 1.1., the acoustical utilization of clay pots are not only present in Anatolia, but also observed throughout Europe with a history reaching back to the Antiquity. In Figure 2.6, their applications in the liturgical architecture of Europe is presented.

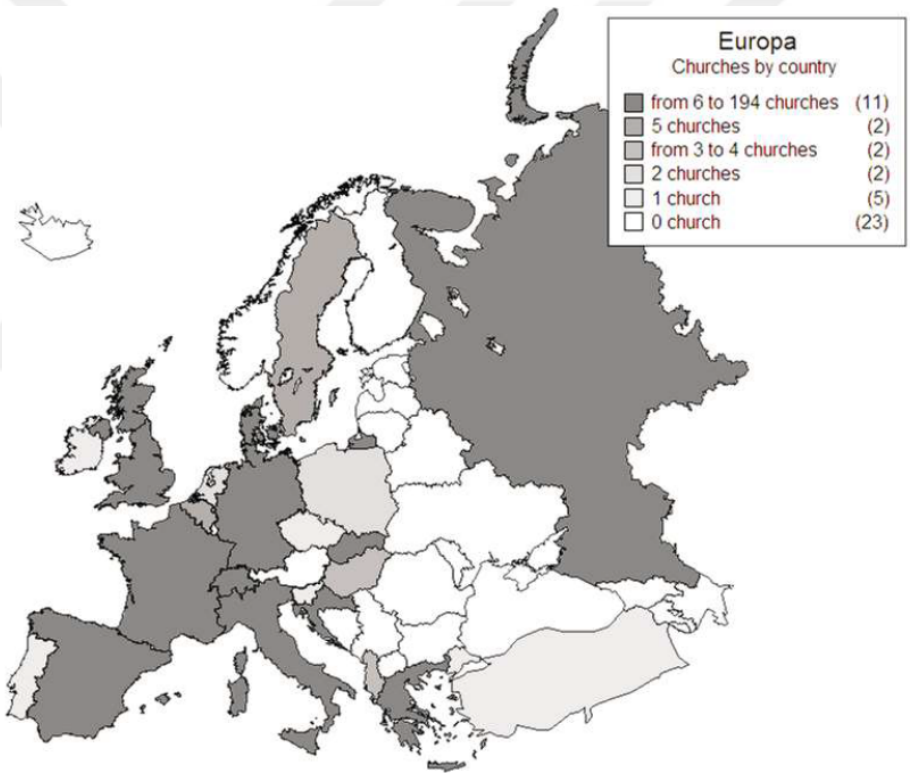


Figure 2.6: Distribution of churches that contain acoustical pots in Europe [30]

Examples of medieval structures that contain clay pots with supposedly acoustical intentions and related research studies covering the acoustical behaviour of these pots are presented in this chapter. Their employment in Anatolia and Europe are covered respectively. Structures with a possible acoustical employment of clay pots from Ottoman Architecture investigated in this study are given in Table 2.5.

Table 2.5: Selected structures with possible acoustical employment of clay pots in Ottoman Architecture

Structure	Date	Architect	Location	Placement
Şehzade Mosque	16th cent	Sinan the Architect	İstanbul	Central Dome [27, 28]
Süleymaniye Mosque	16th cent	Sinan the Architect	İstanbul	Central Dome [31, 32]
Selimiye Mosque	16th cent	Sinan the Architect	Edirne	Central Dome [33]
Yeni Mosque	17th cent	Davud Ağa Dalgıç Ahmed Ağa Mustafa Ağa	İstanbul	Pendentives of the central dome and the semi-domes [20]
Sultan Ahmet Mosque	17th cent	Sedefkar Mehmed Ağa	İstanbul	Central dome [34, 35]

Şehzade Mosque (1548)

The first monumental mosque designed by Sinan the Architect Laureate, Şehzadepaşa Mosque, is known to contain such clay pottery in its dome structure. Şehzade Mosque has a square baldachin scheme plan with its central dome, supported by half-domes on four sides, rest on four great piers on a 40x40 square plan. In the restoration works held in 1990, 144 pots on 8 rings each containing 18 resonators were found embedded inside the main dome which has a diameter of 19m and a height of 37m from the ground level [26]. Nevertheless, some other source also mentions the employment of 168 interlocking clay pipe units "künk" in the dome structure that are distributed into 7 horizontal rings with each ring accommodating 24 pottery [27]. The layout of the pottery distribution is shown in the provided drawings (Figure 2.7). The pots are embedded inside the main dome with their openings facing the interior space with their longitudinal axes follow the center point of the dome. The pots have a 20 cm diameter with a 40 cm height. It is also stated by Erçağ that these pots were also found within the main wall of the structure located above the door level and the pendentives during the restoration works held in 1990 [28]. The ones on the wall are connected to the main space with thin metal plates placed in their openings.

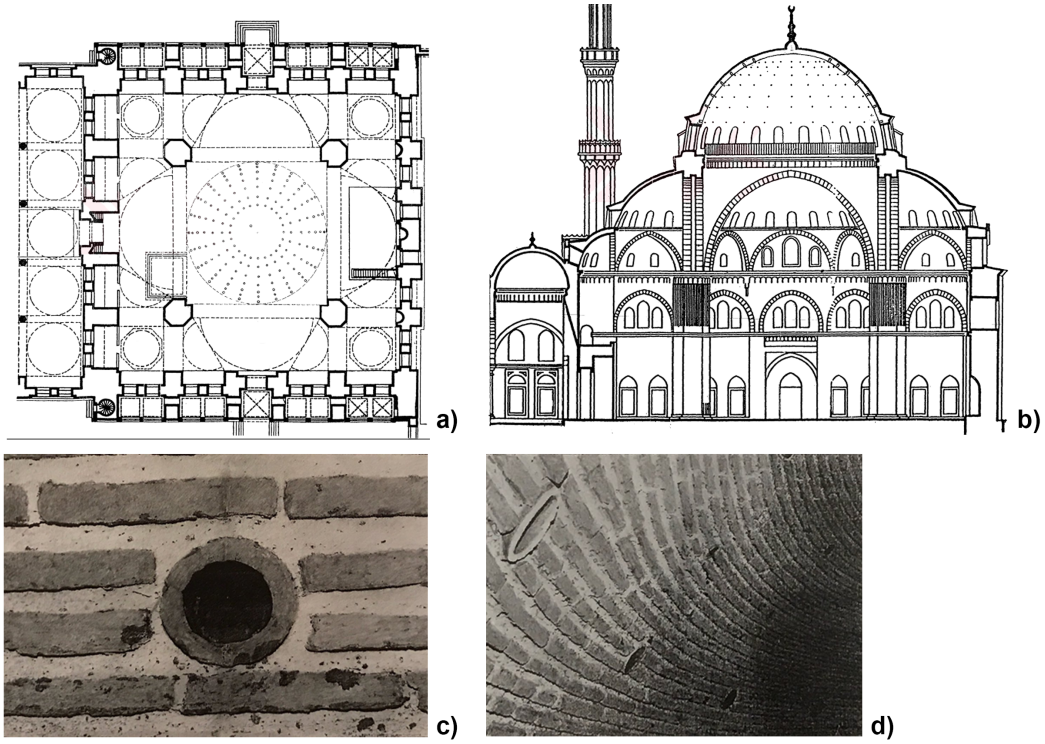


Figure 2.7: Employment of clay pots at the central dome of Şehzade Mosque a) Distribution of pots in plan view b) Distribution of pots in section view. c & d) Openings of the clay pots in the central dome [27].

Kadırga Sokollu Mehmed Paşa Mosque (1571)

Kadırga Sokullu Mehmed Paşa Mosque, another work of Sinan the Architect, has an estimated interior volume of 5.700 m3 [36]. The relatively small mosque when compared to the aforementioned imperial Ottoman Mosques, has a hexagonal baldachin scheme with a central dome resting on 6 piers supported with four semi domes on the corners. In a previous study, the upper structure of the edifice was laser scanned from the ground level of the mosque so as to document the size and number of holes observed on the surface of the dome that has a diameter of 23.20 m [37]. Nevertheless, the data regarding the interior of the holes was found to be limited due to the incidence angle of the laser beams and thus, it is not known whether the holes contain any clay pottery behind. The measurement revealed 163 holes in total on the main dome and semi-domes. 36 of the holes were spotted close to the drum level of the main dome with a diameter of 1.8cm

whilst 127 holes were detected on the smaller semi-domes surrounding the central dome with a diameter of 1.9 cm in the following quantities; 42 on the North West, 45 on North-East and 40 on South-East. It is also stated that the holes on the smaller semi-domes are found to be placed over three parallel lines starting in a certain rhythm yet becomes irregular towards the middle of the array. On the other hand, the ones in the central dome are found to be lined up in a more regular disposition. Tuncer [37] suggested that these holes cannot be related to any acoustic purpose within the space. Nevertheless, such holes exhibit strong similarities with the ones in Süleymaniye Mosque in terms of size and placement. Such resemblance strengthens the possibility of a potential employment of clay pottery for acoustic tuning of the space.

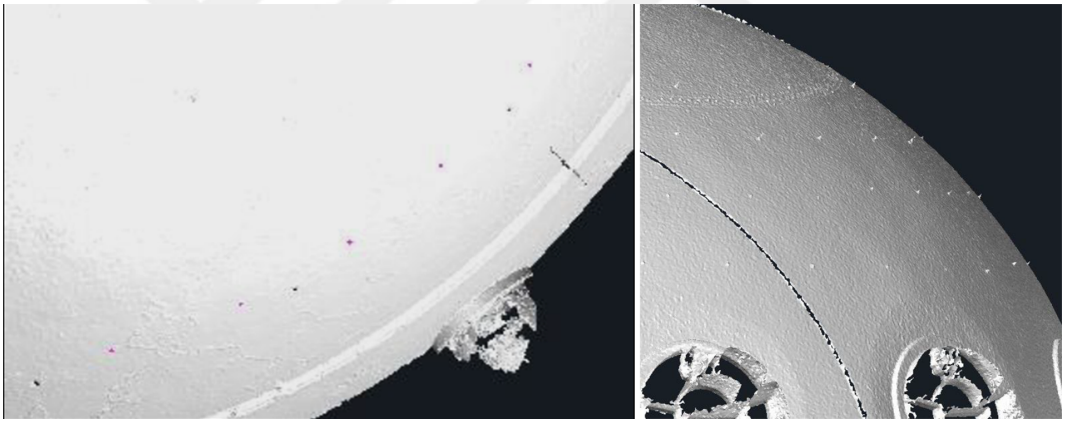


Figure 2.8: Laser scan view of the Kadırga Sokullu Mehmed Paşa Mosque [37].

Selimiye Mosque (1575)

Selimiye Mosque, an edifice known as the mastership work of Sinan, has an estimated interior volume of 79.300 m3 [36]. It has a central dome with 31.50 meters in diameter which rests on eight load bearing piers with an octagonal baldachin scheme. Altough there is no tangible evidence whether the structure contain any clay pottery on its central dome, Kayılı states that during the course of the restoration works at the time, authorities of the restoration work claimed that "they found a large number of earthenware jars (resonators) in the dome, but all of them had their openings covered with bricks which had been plastered over. After cleaning the interiors of the resonators, the bricks were replaced and plastered over once more." [33]

Sultan Ahmet Mosque (Blue Mosque) (1617)

Another well-known edifice in which clay pots are known to be employed is Sultan Ahmed Mosque, also known as the Blue Mosque. The mosque designed by Architect Sedefkâr Mehmet Ağa was constructed in the 17th century. In the restoration works held in 1986, a number of clay potteries were found in the dome structure in a way similar to the Süleymaniye and Şehzade examples. In a previous study [35] the placement of 75 potteries on the main dome on three rings: 7 pots in the inner ring, 28 in the middle ring, and 40 in the outer ring were mentioned. The same study states that the clay pots have 50 cm height and apertures with diameters ranging from 3 to 6 cm. According to a recent source, the type of the pottery employed in the structure is found to be clay pipe "künk" with a diameter that gets narrower towards its base rather than an amphora form as observed in Süleymaniye Mosque [34].

Yeni Mosque (1663)

The recent restoration works that are currently being carried out in Yeni Mosque also revealed the employment of clay pottery in the structure. According to the restoration team, 15 clay pots have been found on the upper structure on two levels so far [20]. 9 pots were found approximately 18m above the ground level embedded inside the pendentives supporting the semi domes and 6 pots were found 25m above the ground level in the pendentives supporting the central dome. The apertures of the pots face the interior space. The maximum depth of the pots reach 90 cm whilst the smallest aperture diameter is 2,5 cm. Nevertheless, as some of the pots are broken, the recorded dimensions vary. In addition to the pendentives, they were also observed on the rim level of the main dome as well as in the pendentive of the portico for late comers. The shape of the pottery found in the edifice, neckless amphora, resembles the form of cavity resonators similar to the pots found in Süleymaniye Mosque. Thus, it is possible that the pottery found in Yeni Mosque may serve for acoustic purposes in addition to their employment as filling elements that would lessen the load of the upper structure when compared to the traditional brick use. Hence, despite the fact that it dates to a later period than Sinan, Yeni Mosque also gives clues for the aforementioned

multi-purpose utilization. Although the number of pots found in the edifice so far makes them less likely to have a significant effect on acoustics when compared to the Süleymaniye and Şehzade Mosque, according to the restorer Sevgi Gemici, there may be another group of pottery embedded in the dome structure that is yet to be found under the plaster coatings [20].



Figure 2.9: Clay pots found in the restoration works in Yeni Mosque [20].

In the Table 2.6 below, the number and dimensions of acoustic pots found in Anatolia are summarized.

Table 2.6: The number and sizes of the clay pottery possibly employed as cavity resonators in Ottoman Architecture

Structure	**Type of Pottery**	**Height**	**Top Diameter**	**Base Diameter**	**Diameter (widest)**	**Aperture Diameter**	**Total Number**
Şehzade Mosque [27, 28]	Clay pipe "künk"	40 cm	-	-	-	20 cm	144 [28] 168 [27]
Süleymaniye Mosque [31, 32]	Neckless/ amphora type	50 cm	5 cm	12 cm	30 cm	2.5-3 cm	224
Selimiye Mosque [33]	-	-	-	-	-	-	-
Yeni Mosque [20]	Neckless/ amphora type	20-90 cm	-	-	60 cm	2.5-30 cm	15
Sultan Ahmet Mosque [34, 35]	Clay pipe "künk"	50 cm	-	-	-	3-6 cm	75

The acoustic clay pots found in Anatolia are mostly documented, but they have not been subjected to any scientific investigation regarding their acoustical behaviour. Nevertheless, in Europe, medieval structures containing clay pots and the pots' influence on the acoustics are examined through experimental and numerical investigations. Studies investigating the acoustic pots are present in France [3, 30, 38–41], Serbia [42–46], Russia [47, 48], Greece [49–52], Switzerland [53, 54] and Portugal [55, 56].

A comprehensive study held in France [38] investigates the number, size, placement, and the effective frequency range of clay pots found in medieval liturgical architecture mainly of France and surrounding countries and cover their connection with sounding vessels of Vitruvius through available texts of the Antiquity and Medieval Age. In this study, the intention behind the acoustic pots is investigated around three terms; "vox, voice-related interpretations", "locus, place-related interpretations" and "transitus, symbolic interpretations" [3]. The resonance frequencies of the pots found in the 35 selected churches are estimated through their frequency responses. A direct proportion between church volume and number of the pots is found whilst the mean resonance frequency of the pots have an inverse proportion with the church volume [30].

In Serbia, Mijic & Sumarac-Pavlovic investigated 24 churches that contain supposedly acoustic pots. The pots have heights changing from 25 to 45 cm. It is also stated that the pots are mainly found embedded in the walls of the churches except one example in which resonators are hung freely in the attic space [43]. It is also stated that the greatest number of pots found in a church is 24. Based on the difference between the sound levels measured outside and inside of the clay pot, the resonance curve of the pot is obtained. The resonance frequencies of the pots are found to be in between 124 - 132 Hz. It is concluded that the measured resonance frequencies and the number of pots found in the structures are too low to have a significant impact on the acoustics [42–44]. It is also stated that the pots are mainly found in the pendentives, rebated arches, drums below the dome and spherical surfaces all of which represent similarities with their placements in Anatolia [44].

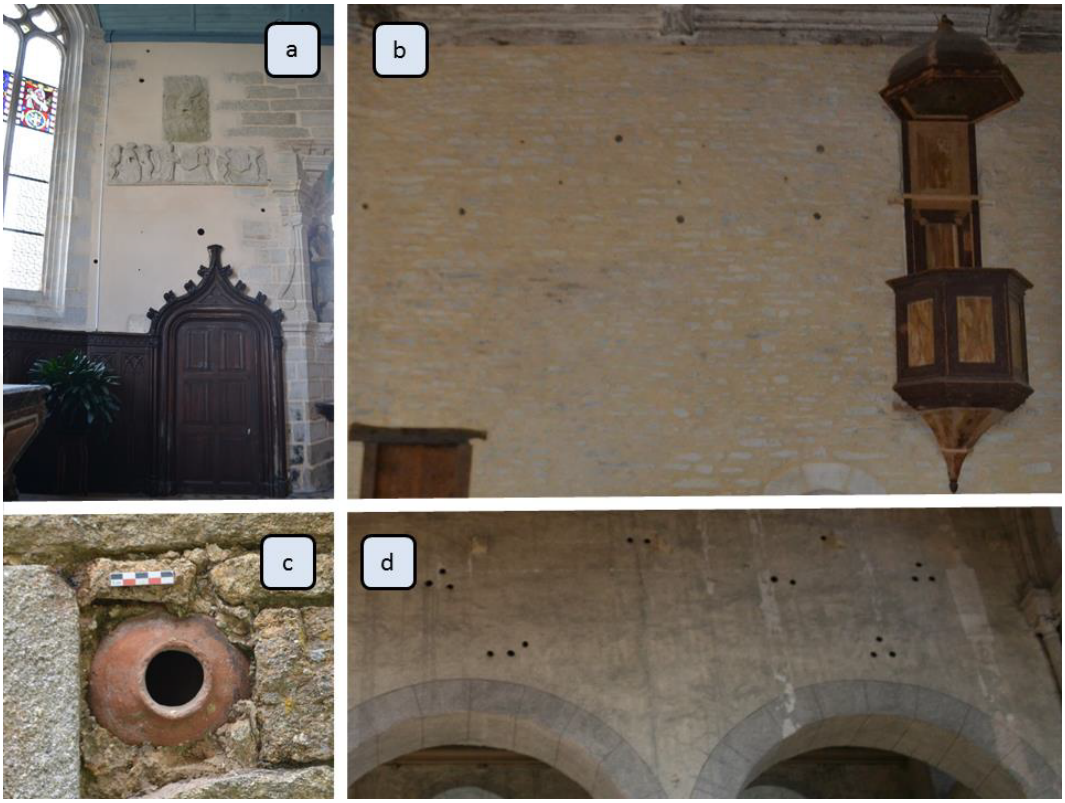


Figure 2.10: Examples of clay pots found in the medieval churches of France. a)Church of Saint-Pierre-et-Saint-Paul of Melgven, b)Ancient collegiate church of Kersaint, c)The ancient abbey church of Notre-Dame des Anges, d) Abbey church of Saint-Chef-en-Dauphiné [3].

In Greece, the acoustical field tests are held in a Byzantine church in which 480 commercial glass bottles as resonators are placed on the church floor. [49]. The study exhibited that the resonators acted as selective amplifiers in the short distance and slightly increased the absorption in the church and provided little improvement in clarity and definition. Nevertheless, their overall effect is noted to be weak. Works of Godman [57] and Polychronopoulos et al.[51] examine the clay pots as sound amplifiers based on Vitruvius' interpretation. Karampatzakis et al. recreates the phenomena based on Vitruvius's descriptions and compare the open-air measurements with FEM simulations of the amplification performance of the pot [50]. The effects of the pots on the acoustics of a Greek Theater are studied by Polychronopoulos et al. [51] through ray tracing and FEM simulations. As a result, it is concluded that the pots have significant effect on Center Time and

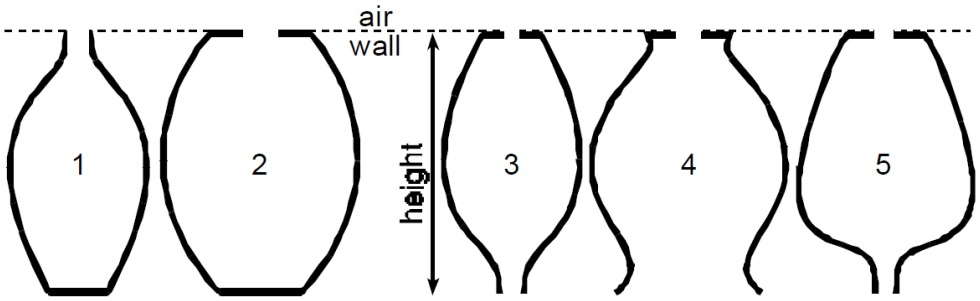


Figure 2.11: Examples of clay pots found in Serbian Churches [42].

LEF indices but they do not significantly amplify the sound. The studies mainly agree that the employment of clay pots follows an empirical tradition without any solid scientific knowledge. The number of pots per unit volume found in the medieval liturgical architecture among Europe is also found to be inadequate to improve the acoustics of large interiors and their acoustic effect is found to be rather poor.

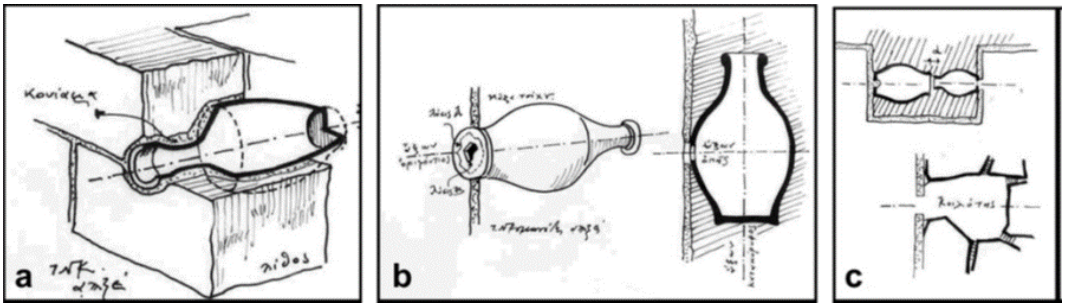


Figure 2.12: Examples of clay pots found in Greek Churches [49].

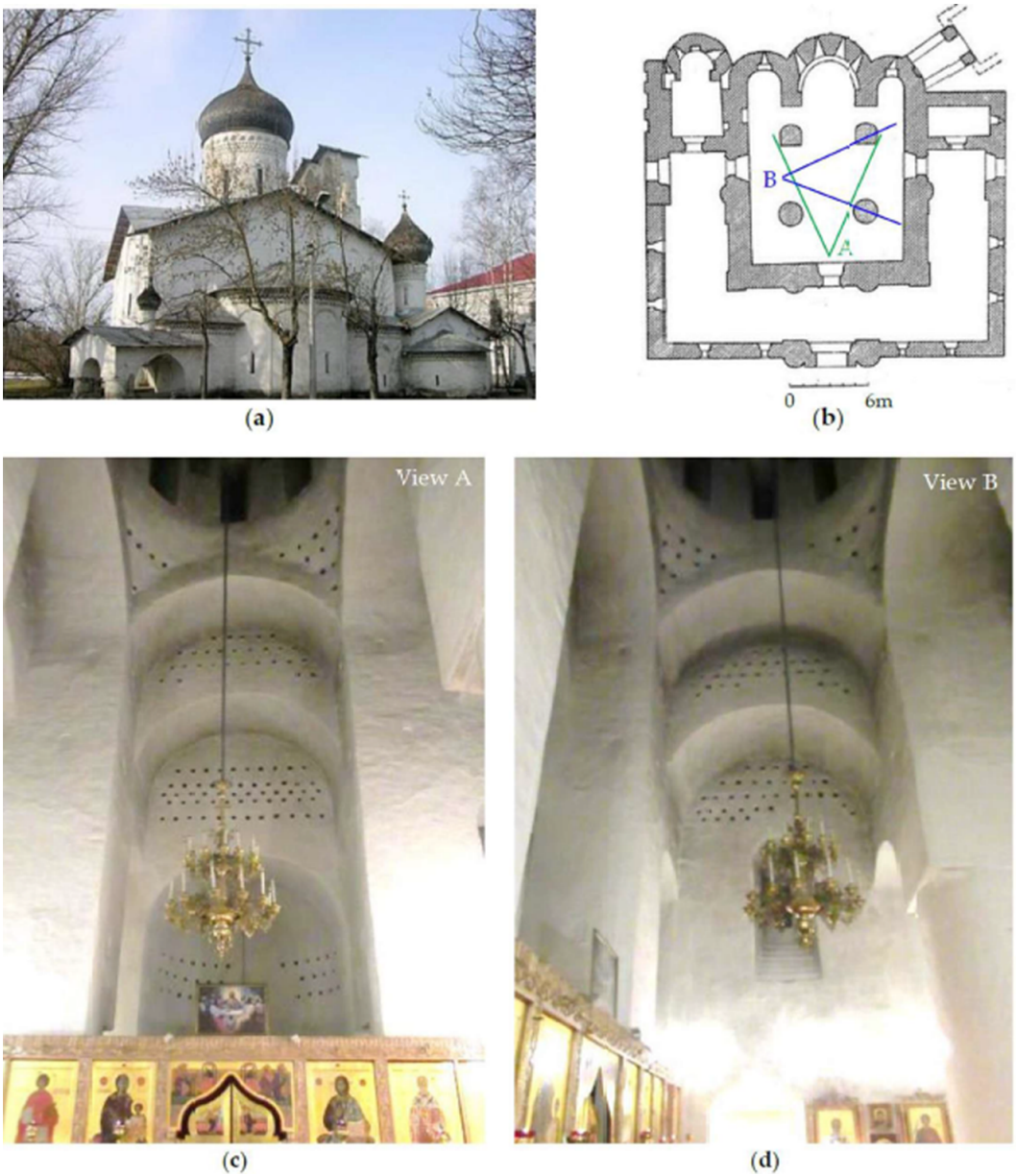


Figure 2.13: Examples of clay pots found in Church Nikoly so Usokhi Saka [47].

Chapter 3

Süleymaniye Mosque

Süleymaniye Mosque, constructed between the years 1550 and 1557, is one of the most imposing monuments of the Ottoman Architecture designed by Sinan the Architect Laureate, during the reign of Süleyman the Magnificent at the Classical Era of Ottoman Empire. The mosque exists as the centerpiece of a socioreligious complex (*külliye*) consists of madrasas, a hospital, a hostel, hammam and accompanying shops. The *külliye* overlooks the Golden Horn, Bosphorus and Topkapı Palace from its well-situated location at the third hill of Istanbul in the imperial site [58].

3.1 Architectural Features

The mosque has a square baldachin scheme in which the central dome is supported by four elephant feet. According to Doğan Kuban, the domed baldachin scheme and the surrounding buttressing elements play an essential role in dictating not only the exterior configuration but also the interior space of Sinan's Mosques [59]. The central dome with a diameter of 26.20 m is supported with two semi-domes placed along the North-South axis rests on four colossal granite piers and shelters the praying area. The load of the central dome is transferred to the

ground through arches and pendentive elements [60]. The geometrical transition from circular rim to the square-based plan as well as the transitions from side domes to the arches are achieved with the utilization of pendentive and muqarnas forms [61]. The side aisles covered with 5 smaller domes on the East and West sides of the praying area completes the cascaded silhouette of the super structure. The smaller domes placed on the corners of the square based plan have a diameter of 9.00 m whilst the central dome placed on the side aisles have 7.20 m diameter. The ground floor of the mosque is a rectangle with the dimensions of 63 and 69 m. The height of the key stone of the central dome is 47.75 m [60]. The structure has an interior volume of 75000 m^3.

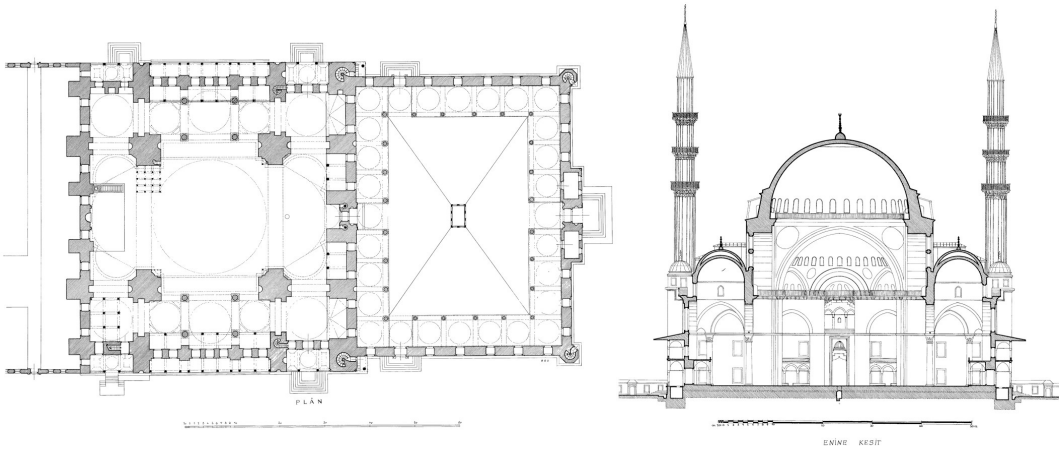


Figure 3.1: Plan and section view of Süleymaniye Mosque [62]

The material selection of the mosque including stone, brick, ceramic tiles, plaster, paint, glass and wood exhibits mainly sound reflective characteristics. On the other hand, the absorption of middle-high frequency sound energy content is mainly provided with the carpet with straw backing [63]. On its original state, the historic plasters applied on the domes are known to contain 134 scale of linen as indicated in the accounting registers of the construction [64]. Such additive is known to improve the tensile strength of the plaster and enhance its sound absorption performance at low and mid frequencies which may aid the control of reverberation times in the edifice in its original state [63]. The geometrical design of the mosque causes the occurrence of standing waves owing to the square based plan scheme. Nonetheless, the fragmentation of large reflective surfaces

with niches and decorative elements as well as the careful placement of sound scattering elements such as mahfil, woodworks (kündekari) and muqarnases made of gypsum help the even sound distribution within the space. According to the accounting registers of the construction compiled and translated by Barkan, it is recorded that 255 clay potteries were ordered to be employed in the main dome [64]. As Barkan indicates, the clay pots were ordered with the purpose of acoustic reinforcement of the sound within the space. In the recent restoration work held between 2007 and 2011, a detailed inspection of the clay pots embedded inside the brick dome structure was conducted. 224 pots were found scattered in 7 rings in linear disposition around the dome, each ring containing 32 pots with equal distance all of which placed above the window rim level 3.2. According to the restorers, the elevations of the rings start from +39.74 meters above the dome drum and reach up to +45.90 meters. The pots are placed in the dome radially as the vertical axis of each pot is directed towards the central point of the concave dome form. The pots are 50 cm in depth with their widest diameter being 30 cm. Clay pots open up to the main interior space with apertures approximately 2.5 - 3cm in diameter (Figure 2). Despite the fact that the employment of clay pots in the superstructure of many medieval buildings indicate the load reduction purposes, the apertures opening up to the interior volume of the mosque supports their acoustical intention. During the examinations of the pots, it is recorded that some of them were found broken or flawed due to the structural cracking of the dome.

During the recent restorations held between 2007 and 2011, the 19th century plaster on the main dome is replaced with the coarse aggregated “Horasan” plaster with a changing thickness varying between 4 - 6 cm on top of the brick structure [31]. It is also noted that all the cement-based plasters applied on the mosque during the 1955-1960 restorations are removed and replaced with Horasan plaster. Through these alterations, the improvement of the acoustics of the structure is expected to a certain extent. The acoustical investigations held in the structure so far is elaborated in the following section.

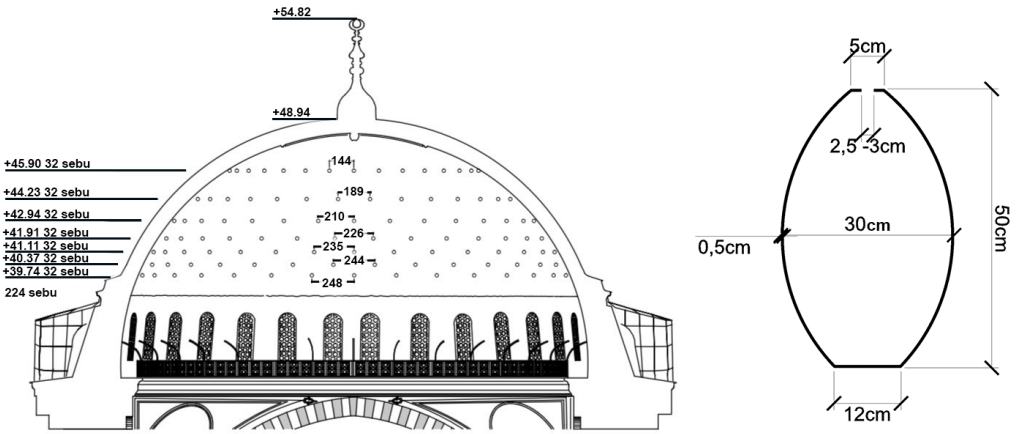


Figure 3.2: (On the left) Disposition of the clay pots in the central dome of Süleymaniye Mosque. (On the right) Size of the original clay pot found in the dome structure.[32]

3.2 Investigation on the Acoustics of Süleymaniye Mosque

Süleymaniye Mosque is subjected to numerous researches regarding its interior sound fields due to its symbolic position representing the historical and cultural heritage of Ottoman Empire. Such acoustical surveys also provide an opportunity to assess the acoustical effects of the restoration works held in the edifice. In this section, the previous acoustical field tests are presented in chronological order. The mosque is a popular subject of acoustical research with its vast acoustical volume of around 75000 m3. With the recent findings regarding its multi-domed upper structure providing circumstances for multi-slope sound energy decay formation, [65, 66] the mosque has once again become the center of a scientific interest.

One of the first restoration works held in the edifice was in the 19th century. [67] One of the most significant result of this restoration work was covering the openings of *sebus* with plaster which turned them inactive. After the initial works that are attributed to the Fosatti Brothers [68], a secondary restoration work that covers mainly the courtyard section of the Mosque is conducted and it is followed by the repairments held between 1955-1960. During these past repairments, it

is noted that the structure was damaged with the usage of cement-based plaster [68]. The most recent and the most comprehensive restoration work was held in 2007 and included the detailed survey, restitution and restoration projects [31]. In the most recent works, the cement-based plasters which do not show the same acoustical features as the original Horasan plasters along with other unoriginal alterations were removed.

The first acoustical investigation of the structure is made by Mutbul Kayılı in 1988, following the 1960 restoration works [35]. The selected frequency range for these measurements are from 100 Hz to 8000 Hz in 1/3 octave band [29]. Kayılı also was the first to speak of the clay pots found in the dome of Süleymaniye and he referred to these pots as cavity resonators [69]. Nevertheless, a detailed inspection regarding their sound absorption performance was not included in the study. The following measurements are held by ODTU in 1996 as a part of a more comprehensive project covering a selection of Classical Era Ottoman Mosques [70]. An international research project called CAHRISMA "Conservation of the Acoustical Heritage by the Revival and Identification of Sinan's Mosques Acoustics" was conducted in 2000 with the collobaration of Yıldız Technical University, Ferrara University (UNIFE), Technical University of Denmark (DTU), École Polytechnique Fédérale de Lausanne (EPFL), University of Geneva (UNIGE), and University of Malta. In this study, the acoustical characteristics of Sinan's Mosques including Süleymaniye are compared with the selected Byzantine churches through field measurements and acoustical simulations [71]. Finally, the most recent acoustical study of the edifice is held in 2013 after the 2007 repairments which cover both in-situ measurements and the acoustical simulations examining the double-slope decay observed in the structure. This study is referred for the present state of the acoustical field of the Süleymaniye Mosque [66].

Chapter 4

Methods

4.1 Sebu Production and Impedance Tube Measurements

The original-sized *sebu* sample used in the impedance tube measurements is produced in Turkey based on the dimensions provided by the restoration team (Figure 3.2). The normal incidence sound absorption coefficients of the original-sized clay pots are first measured within a Kundt tube set-up. The results are obtained in accordance with the Transfer Function Method based on the ISO 10534-2: 1998 standard [72]. The experiment is conducted with two S.C.S Kundt Tubes for low and high frequency ranges as well as two equivalent microphones. Low frequencies (100 Hz to 1000 Hz) are covered with the large tube that has a 100 mm interior diameter, and the higher frequencies (1000 Hz to 5000 Hz) are covered with a smaller tube with a 28 mm diameter. The microphones and the tube are calibrated before the measurements. In a standard impedance tube measurement procedure, the sample ideally needs to be placed in the sample holder and sealed into the measurement chamber. Nevertheless, due to the fact that the pot is larger than a regular sample to fit inside the holder, coupling the pot to the measurement chamber required the design of a custom fitting piece composed of

MDF circles and a plaster model which enables a loss-free interlocking [73]. The main plaster element of the fitting piece is produced based on a mock-up plaster mold of the aperture of the pot (Figure 4.1). The MDF circles enabled the plaster fitting to interlock with the tube seamlessly. Pieces of playing dough are applied on the connection parts between the fitting, tube, and the clay pot so as to seal the potential gaps in the junction areas.

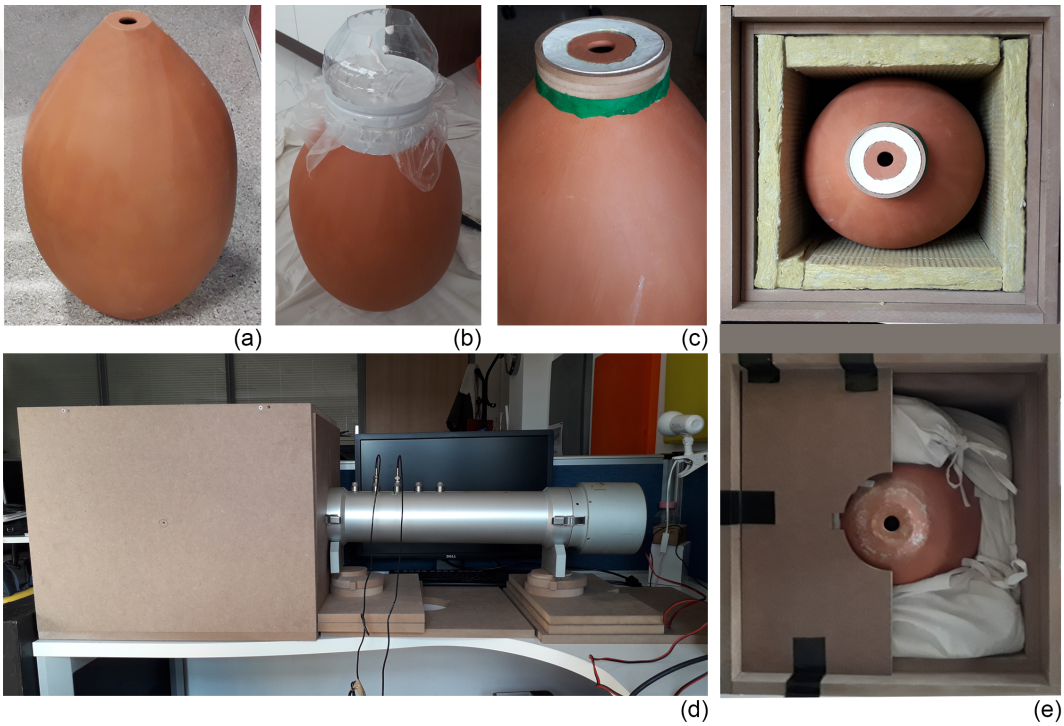


Figure 4.1: (a) Reproduction of the original clay pottery employed in the Süleymaniye Mosque by the author. (b) Production of the plaster mold for the fitting piece. (c) Final fitting piece composed of MDF circles and the plaster. (d) Impedance tube measurement experiment set-up with large tube. (e) Mineral wool and sand as the infill materials

Three configurations with gradually improving backing support of the *sebu* are designed so as to perform the measurements with high accuracy similar to their placements in the dome. In the first experimental setup, the clay pot is coupled with the impedance tube without any backing support. In the following two setups, the pot is placed inside a 3.6 cm thick MDF box with the interior dimensions of 40 cm x 40 cm x 51 cm. The box is seperately filled with 5 cm thick mineral wool and sand bags for isolation purposes as the clay pottery embedded

in the dome is originally fitted tight in between the steady and solid structure constructed of bricks. The experiments are performed with a total of six setups composed of three backing configurations coupled with two impedance tubes of different sizes (Figure 4.2). The connection details between the MDF boxes and the different sized tubes do not show any alteration based on the changing infill materials. Measurements for each setup were repeated 10 times for checking the reliability/repeatability of the measurements. In the next step, the results are compared to numerical simulations.

4.2 Analytical Modeling of Helmholtz Resonance of Sebu

It is known that the estimation of the resonance frequency of a Helmholtz resonator based on the parameters required in the Helmholtz formula is complicated due to the fact that the precise measurement of its volume as well as the accurate internal shape conditions of the neck is difficult [74]. The volume used in this equation is attained from the computer model produced based on the given dimensions by the restoration team. The Helmholtz Equation, the common formula for obtaining the resonance frequency of the neckless Helmholtz resonators, is given below [5]. Based on this equation, the fundamental frequency of the clay pots employed in Süleymaniye Mosque is calculated as 52 Hz.

$$f_n = \frac{c_0}{2\pi}\sqrt{\frac{\pi a^2}{V(l_0 + 1.7a)}} \tag{4.1}$$

Nevertheless, the analytical and experimental results are needed to be supported and verified with finite-element simulations for higher accuracy.

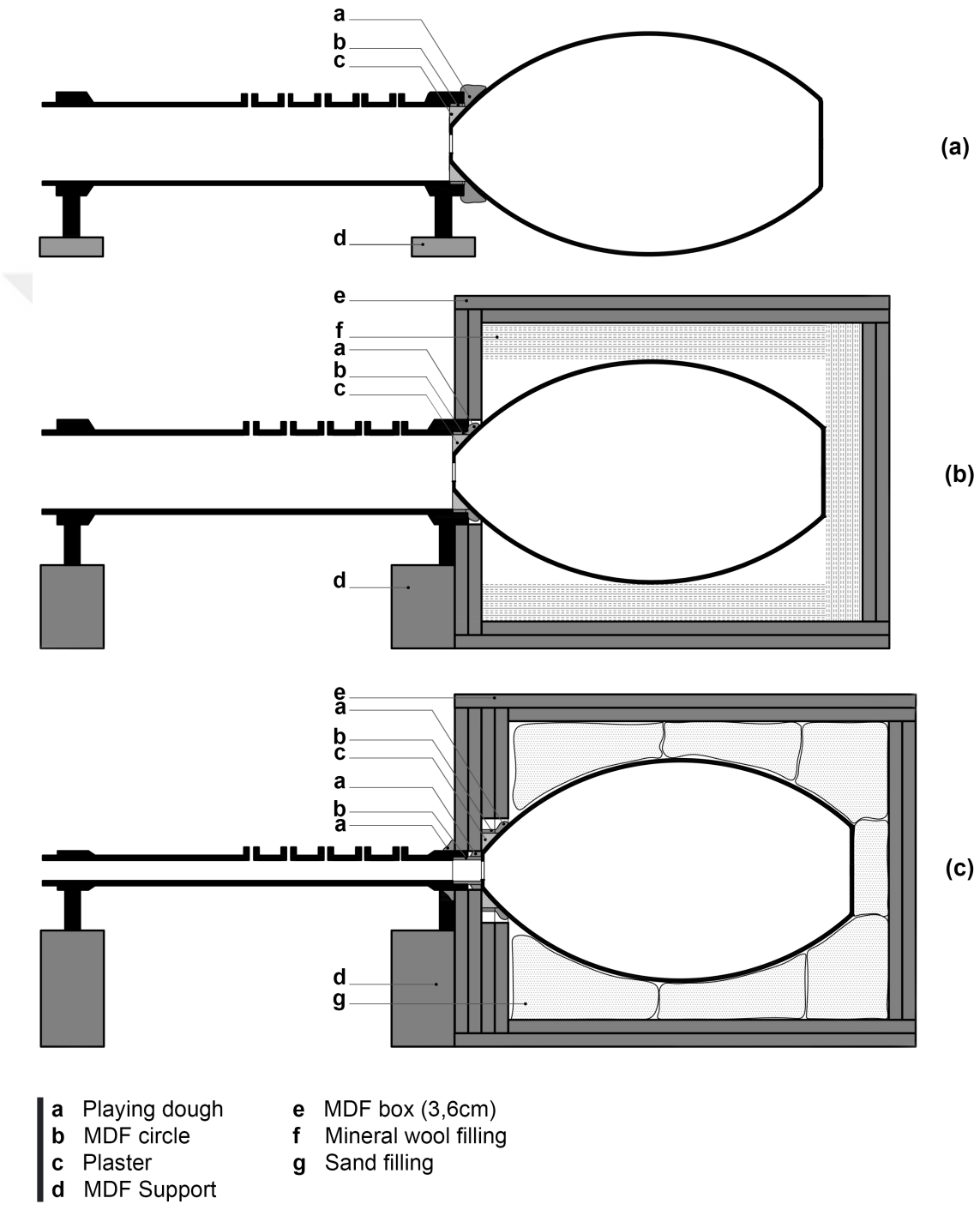


Figure 4.2: Three different backing configurations coupled with small and larger impedance tubes: a)Large impedance tube - no enclosure. b)Large impedance tube - mineral wool filling. c)Small impedance tube - sand filling

4.3 Finite Element Modeling for Sebu Absorption

Finite element simulations are conducted to verify the results obtained from the experimental measurements and the analytical model. The finite element simulations are performed in two phases:

i) Simulations of a single clay pot,

ii) Simulations of the central dome with multiple clay pots embedded into the surface.

In both phases of the numerical simulations, the absorption coefficients are derived from the ratio of the absorbed energy to the incident sound energy. The absorbed energy can readily be found by the difference between the incident energy and the reflected energy (Equation 4.2). As presented in Figure 4.3, the model of the first phase includes the internal air volume of the *sebu* and its neck, connected to an external cylindrical volume of which the planar propagating sound waves are emitted from the inlet of its free surface. The planar sound waves are incident normally on the neck of the pot domain. A non-reflecting condition is defined at the outlet of the tube domain.

$$\alpha = \frac{E_{incident} - E_{reflected}}{E_{incident}} \tag{4.2}$$

The length of the cylindrical domain is set depending on the frequency range of the analysis ensuring at least one full wavelength is present during the study. As expected, the diameter of the cylindrical domain through which the acoustic field is applied has an effect of the absorption coefficient obtained from simulations; thus, this effect is investigated using a series of analysis in which the diameter is varied from 0.04 m to 0.6 m as presented in Table 4.1.

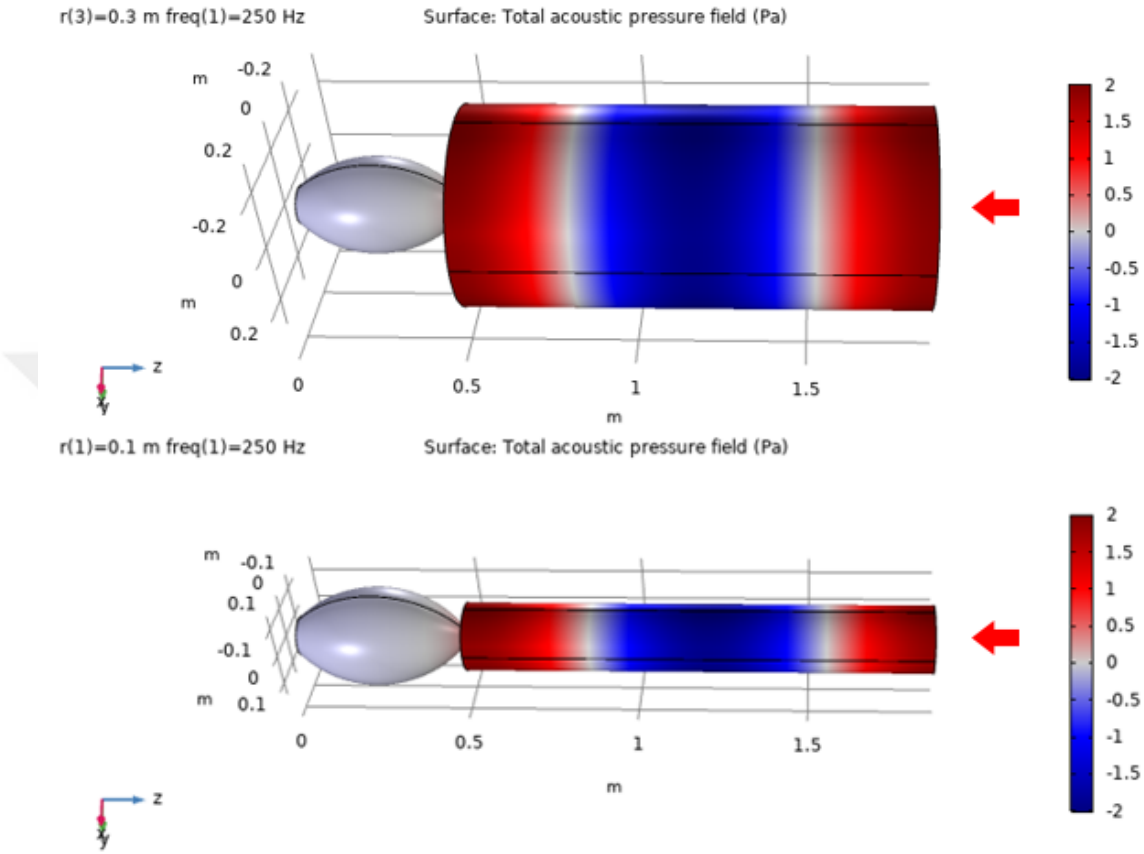


Figure 4.3: Computer model employed in Phase 1 FEM simulations. Red arrow shows the inlet of the plane propagating incident sound wave.

In Phase 2 of the FEM analyses, the total absorption of the dome surface including the embedded clay pots are studied as the geometry of the dome and interactions between *sebus* are expected to affect the absorption performance. In this model, it is aimed to obtain the sound absorption coefficient of the whole dome surface on which the clay potteries are placed instead of a single sample as in Phase 1 of numerical analyses. The domains modeled in the second phase involve the body of air inside the pots attached to the body of air inside the central dome. Similar to the Phase 1, the domains are bordered by sound hard boundaries. Due to the fact that the dome structure has an axisymmetric form, the model is created based on the periodically defined portions of the overall dome that can be axisymmetrically mirrored from the side surfaces so as to decrease the required computational power. Three different "dome slices" were tested to ensure convergence and models were able to represent the whole structure.

Table 4.1: The changing dimensions of the tube domain coupled with the pot at the 1st Phase of the numeric modeling.

		Low frequencies		**High frequencies**					
		Step1	Step2	Step1	Step2	Step3	Step4	Step5	Step6
f_min[Hz]		50	250	1000	2000	3000	3500	4000	4500
f_max [Hz]	Low Frequencies: f_min*5	250	1250	-	-	-	-	-	-
	High Frequencies: f_min + 1000 & f_min + 500	-	-	2000	3000	3500	4000	4500	5000
λ_min (343/f_max) [m]		1.37	0.27	0.17	0.11	0.10	0.08	0.08	0.07
Maximum meshing size	λ_min/5	0.27	0.05	0.03	0.02	0.02	0.016	0.016	0.014
Radius of the tube [m]		0.1, 0.2, 0.3		0.02, 0.03, 0.05, 0.1					
Tube length (h)	H : λ_max (343/f_min) [m]	6.86	1.372	0.343	0.17	0.11	0.1	0.08	0.08

The slices were cut with two different angles (11.25 and 45 degrees) from the dome structure with varying thicknesses of the air domain are set (Figure 4.4). The accuracy of the model is tested by the utilization of these three different slices. The surfaces designated as inlet from which the plane propagating waves are emitted are defined as the non-reflecting boundary condition. The range of frequency examined in the Phase 2 analysis is narrowed down to a finer band with increments of 0.2 Hz in the vicinity of designated frequencies, namely 488Hz and 819 Hz, of the clay pot attained from the Phase 1 of numerical simulations due to aforementioned reduction of computational cost. This narrow increment is selected as the Helmholtz resonance exhibit a narrow bandwidth.

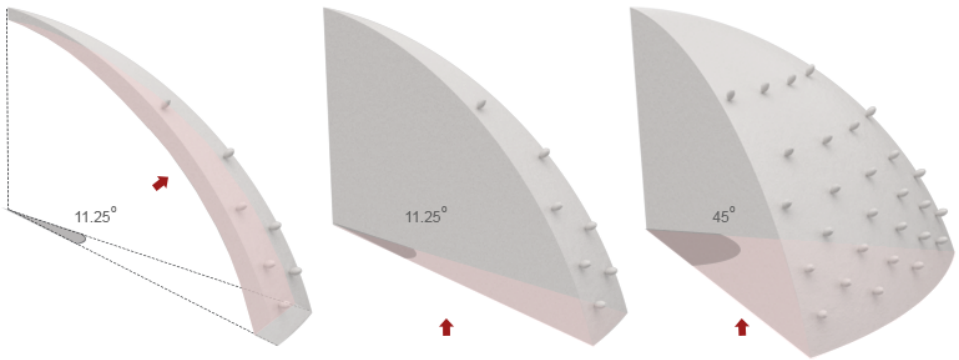


Figure 4.4: Phase 2 Numeric Models: 11.25 degree shell slice, 11.25 slice and 45 degree slice. Red arrows show the inlet of the plane propagating incident sound wave.

4.4 Ray Tracing Simulations

The main objective of the ray tracing simulations is to exhibit the effect of the clay pots on the sound energy decay pattern within the interior volume of Süleymaniye Mosque. The restoration applications held in the dome structure might have helped many of the pottery regain their formal integrity and functionalities. Therefore, the acoustical state of the mosque with functioning clay pots and a hypothetical model in which no clay pottery employed in its dome structure is compared by acoustical simulations. The initial model with the fully functioning clay pots is first produced based on the previous field tests held in the edifice in 2013 after the restoration works [29]. The sound absorption coefficients of the finishing materials employed in the simplified acoustic model with fully functioning clay pots are tuned in accordance with the most recent field test results.

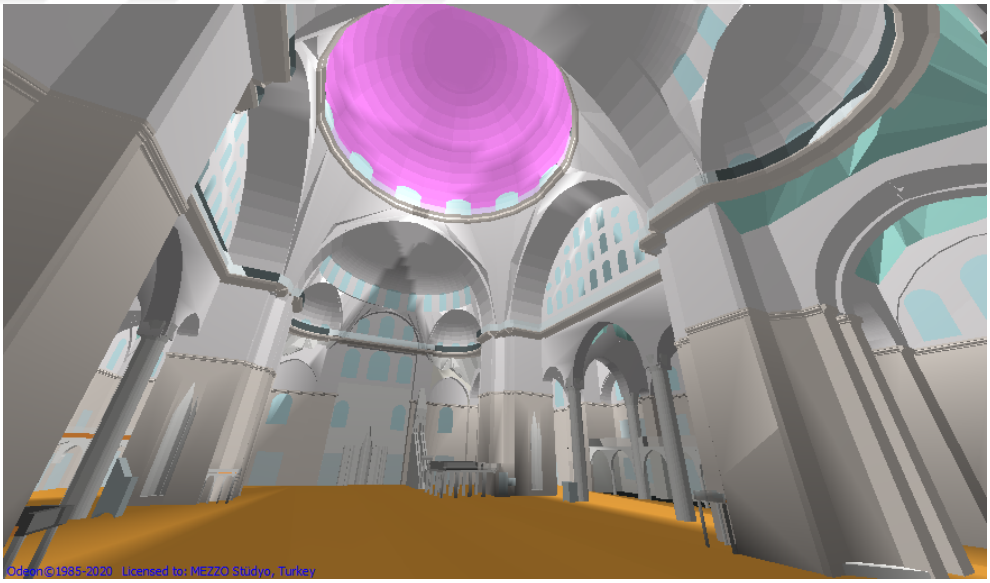


Figure 4.5: 3D OpenGl view of Süleymaniye Mosque in the case of clay pots employed in the dome surface

A virtual reconstruction of the latter model without the clay pots is also made to better understand whether the 224 clay pots embedded in the dome had any contributions or effect on the interior sound field of the mosque by comparing reverberation times at the effective frequency range of the pot. The ray tracing

simulations are carried out with ODEON Room Acoustics Software 16.08. The model employed in the ray tracing simulations does not include the clay pot volumes attached to the dome geometry. But rather, the difference between the two models is based on the changing absorption coefficients assigned to the dome surface. The absorption coefficients acquired from Phase 2 numerical simulations are applied to the dome surface as they represent the sound absorption coefficient of the overall dome surface with clay pots embedded into the dome. As for the hypothetical scenario without the clay pots in the dome form, the sound absorption coefficient of the plaster [63] is employed for the whole dome surface for the frequencies of interest.

The material list and their sound absorption coefficients at 1/1 octave bands applied to the surfaces in the ray-tracing simulations are listed in Table 4.2.

Table 4.2: The sound absorption coefficients of the materials employed in ray-tracing simulations

Materials [63]	**Sound Absorption Coefficients over 1/1 Octave Bands**					
	125 Hz	**250 Hz**	**500 Hz**	**100 Hz**	**2000 Hz**	**4000 Hz**
Stone surfaces	0.05	0.05	0.06	0.09	0.11	0.11
Carpet	0.02	0.12	0.10	0.38	0.55	0.58
Plastered surfaces (dome without clay pots)	0.13	0.09	0.06	0.02	0.03	0.04
Dome with clay pots	0.13	0.09	0.87[1]	0.02	0.03	0.04
Glass surfaces	0.18	0.06	0.04	0.03	0.02	0.02
Marble surfaces	0.01	0.01	0.01	0.01	0.02	0.02
Wood surfaces	0.10	0.07	0.05	0.04	0.04	0.04
Gypsum decorations	0.29	0.10	0.05	0.04	0.07	0.09
Copper decorations	0.12	0.08	0.02	0.01	0.01	0.01

[1]Absorption coefficient at 488 Hz attained from Phase 2 numerical simulations

Chapter 5

Results and Discussion

5.1 Impedance Tube Measurements

In the first phase of the study, sound absorption coefficient measurements of the clay pottery employed in the dome of Süleymaniye Mosque are conducted with the impedance tubes. Three different configurations of gradually improving backing supports are coupled with the tube. As explained in the previous section, these configurations are as follows: clay pot without any backing support, and clay pots placed in a MDF box filled with mineral wool and sand-filled bags. These configurations are respectively named as "a", "b" and "c". The results obtained from these three setups in 1/3 octave bands are shown in Figure 5.1.

It is observed that the results obtained from the different backing supports exhibited an overall coherency. A notable sound absorption performance at 500 Hz frequency is observed in all setups. An increase in the sound absorption level is observed at mid-high frequency ranges especially after the 800 Hz and above frequency levels. Nevertheless, such high values are most likely to be associated with the surface texture of the clay pot at millimetric scale. A notable discrepancy among the different backing setups, however, is that clay pot in the configuration "a" exhibited relatively lower absorption performance in mid-range

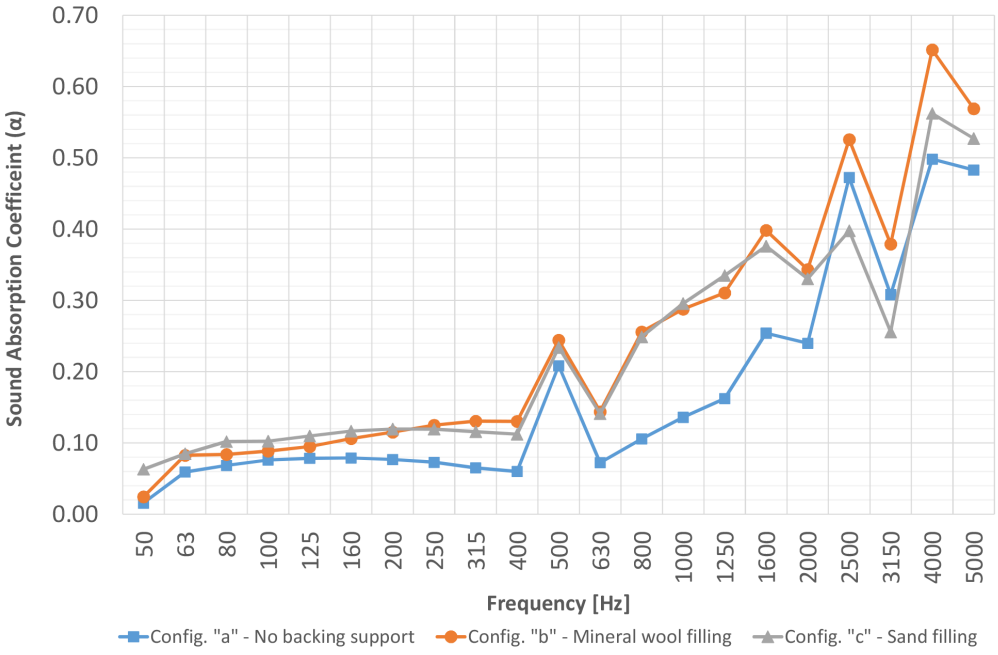


Figure 5.1: Sound absorption coefficients measured with the impedance tube at 1/3 octave bands

frequency when compared to clay pots placed in the configurations “b” and “c”. It is seen that the infill materials placed inside the MDF boxes in configurations “b” and “c” prevent the reflection of the planar sound wave back into the tube from the aperture to a certain extent. The latter configurations are resulted in higher accuracy in the measurements compared to the configuration “a” which lacks such isolation. Clay pots backed with the MDF boxes also exhibit similar sound absorption coefficients in the mid-frequency ranges which proves the sound isolation performance of the two backing materials to be similar.

5.2 Finite Element Modeling for Sebu Absorption

The fundamental frequency of the pot calculated with the analytical model in Chapter 4.2 is not observed in the initial impedance tube measurements of the

study probably due to the fact that 52 Hz corresponds to the lower cut-off frequency limit of the impedance tube. The resonance at 52 Hz, however, is verified in the numerical simulation results.

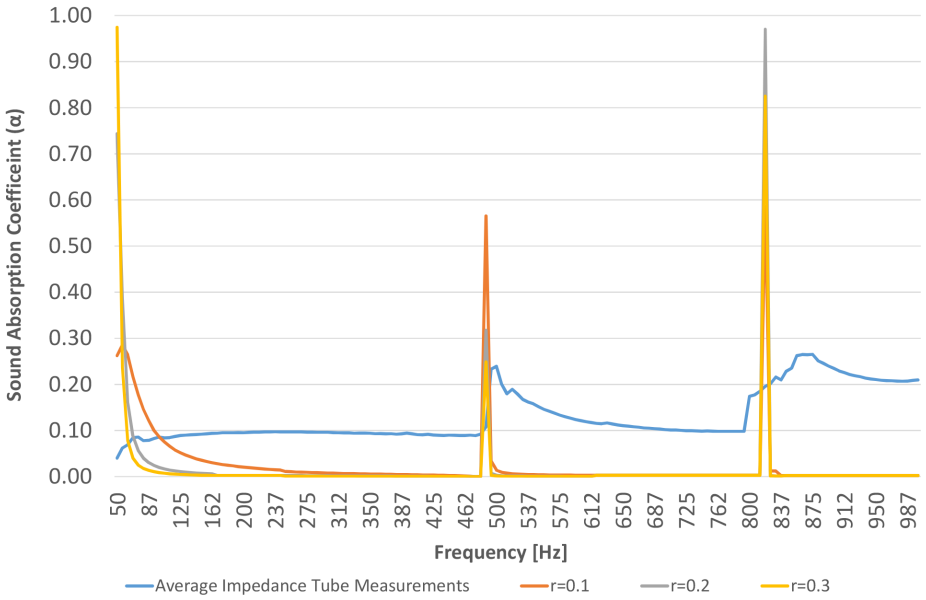


Figure 5.2: Sound Absorption Coefficients Simulated in Phase 1 Numerical Analysis and Comparison between the Impedance Tube Measurement Results 50-1000 Hz

Figure 5.2 presents the sound absorption coefficients of a single clay pot acquired from the Phase 1 of numerical simulations. It is seen that three notable peaks are occured at 51-53 Hz, 488 Hz and the 816 Hz. The first peak indicating the fundamental frequency of the pot is followed by the peak at 488 Hz which confirms the initial results obtained from the impedance tube measurements.

The increasing number of peaks observed in the higher frequencies possibly indicate the higher elastic modes of the cavity. Nevertheless, in the historic/original state of the dome, attenuation of high frequency sounds are likely to be attained by the historic plaster with linen content applied on the interior surface of the dome as the plaster used at the time is known to have high sound absorption performance at high frequencies [75]. Thus, the high absorption coefficients of the clay pot in higher octave bands may remain insignificant compared to the sound absorption capacity of the plaster.

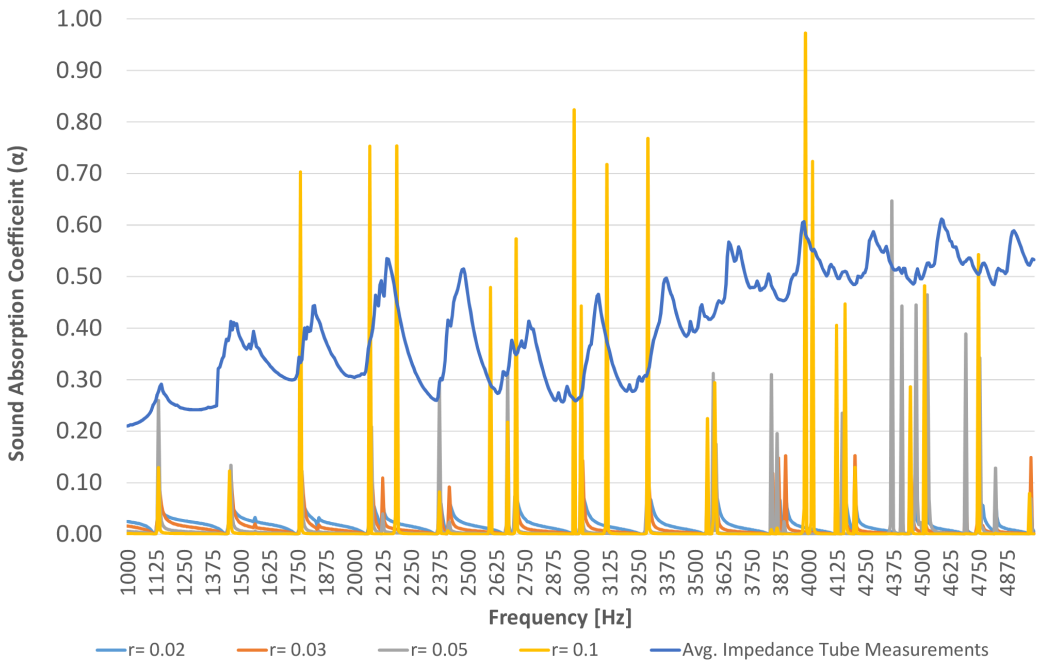


Figure 5.3: Sound absorption coefficients simulated in phase 2 numerical analysis and comparison between the impedance tube measurement results 1000-5000 Hz

The results of the Phase 2 numerical simulations, which examine the total sound absorption of the dome surface, exhibit consistency with the results of Phase 1 which simulates the sound absorption performance of a single clay pot. Due to high computational cost, the frequency band is localized on the aforementioned frequencies obtained in the previous simulations. Results of the examination at the 819 Hz is only acquired from the shell model due to the higher computing power required for the other models.

Table 5.1: Sound Absorption Coefficient Acquired from the Phase 2 Numerical Analysis

11.25 Degree Model		**11.25 Degree Shell Model**		**45 Degree Model**	
Peak Frequency	α	Peak Frequency	α	Peak Frequency	α
488	0.87	489	0.87	488	0.97
-	-	816.8	0.86	-	-

An overall comparison of the numerical analysis and experimental measurements are given in Figure 5.4. As seen both in the results of the impedance tube

measurements and following numerical analysis, the peaks occur at low-mid frequency ranges are 50 Hz, 488 Hz and 819 Hz. The 500 Hz octave band is therefore selected for the investigation of the effect of the clay pots on the sound energy decay pattern of Süleymaniye Mosque in ray tracing simulations.

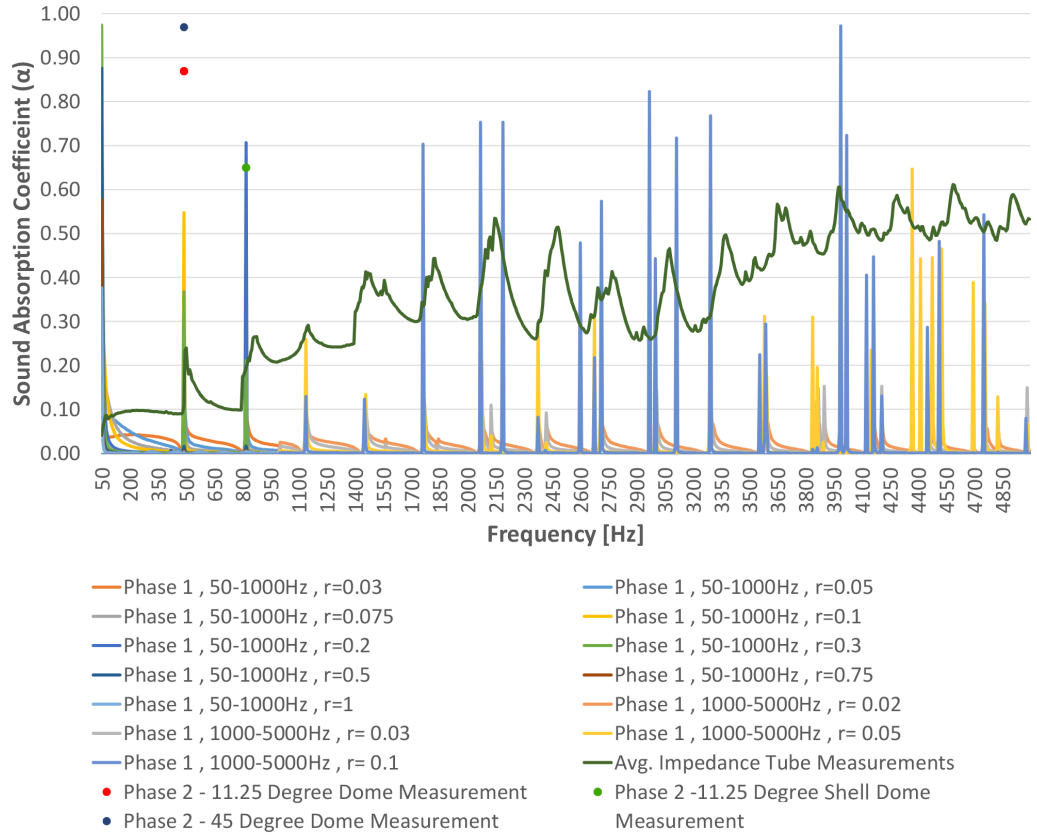


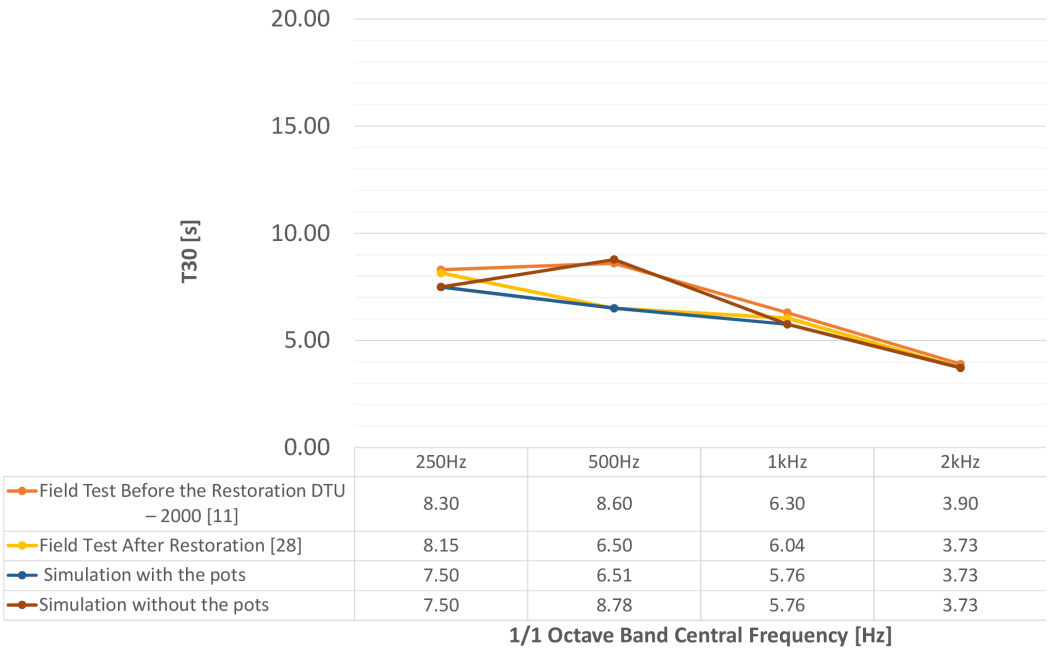
Figure 5.4: Sound Absorption Coefficients Acquired from the Numerical Analyses and an Overall Comparison between the Impedance Tube Measurement Results 50-5000 Hz

5.3 Ray Tracing Simulations

The numerical simulations are followed by the ray tracing simulations in which T30 values with and without the effect of pots considered in the dome of Süleymaniye Mosque are examined. Sound absorption value at the peak frequency of 488 Hz attained from 11.25 degree shell model from the Phase 2 of

numerical simulations (Table 5.1) is employed as the sound absorption coefficient at 500 Hz octave band for ray tracing simulations in which the acoustic model with the clay pots is aimed to be virtually reconstructed.

The results of the T30 simulations are given in Figure 5.5. It is observed that the increased sound absorption area provided with the clay pots in the dome surface bring two seconds drop of T30 at 500 Hz octave band. The T30 analysis conducted with ray tracing simulations require alpha values at 1/1 octave bands for the assigned materials. Nevertheless, it should be reminded that the sound absorption performance of the clay pots is obtained in a finer band, meaning that they only have a localized effect/absorption in the vicinity of their fundamental frequency and the effective frequencies, namely 488 Hz.



	250Hz	500Hz	1kHz	2kHz
Field Test Before the Restoration DTU – 2000 [11]	8.30	8.60	6.30	3.90
Field Test After Restoration [28]	8.15	6.50	6.04	3.73
Simulation with the pots	7.50	6.51	5.76	3.73
Simulation without the pots	7.50	8.78	5.76	3.73

Figure 5.5: Comparative T30 simulation results of with and without the employment of clay pots in the edifice.

5.4 Discussion

Preparatory to commenting on the influence of the pots on the current acoustics of the space, a brief examination of the acoustic timeline of the edifice in relation with the restoration works held in 2007-2011 is found necessary. In Table 5.2, T30 values recorded in different field measurements exhibiting the acoustical states of Süleymaniye Mosque before and after the restoration works are provided.

Table 5.2: Reverberation Times at 1/1 Octave Bands from Previously Published Field Measurements Held in Süleymaniye Mosque

	1/1 Octave Band Frequency			
Field Measurements	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**
METU - 1996 [70]	8.79 s	8.44 s	6.15 s	4.35 s
CAHRISMA / UNIFE - 2000 [76]	8.40 s	8.60 s	6.20 s	3.80 s
CAHRISMA / DTU - 2000 [76]	8.30 s	8.60 s	6.30 s	3.90 s
Restoration works				
METU - 2013 [29]	8.15 s	6.50 s	6.04 s	3.73 s

The results reveal the positive effect of the recent restoration works especially in the 500Hz octave band. In an earlier study [63], the 2 seconds drop in the relevant octave band is linked with the replacement of cement-based plasters with the historically compatible Horasan plaster. In the light of the present knowledge, the 2 seconds drop now can be accounted with the nominal influence of the functioning clay pots in addition to the renovated plaster. Hence, it is shown that the clay pots employed in the central dome of Süleymaniye Mosque may actually help control the excessive low-mid frequency sound content during the religious service but only in a localized frequency range.

The calculated Helmholtz resonance of the *sebu* found in Süleymaniye Mosque is 52 Hz. The FEM simulations also verify this result. Additionally, the experimental measurements and numerical simulations also reveal the effective frequency ranges that *sebus* exhibit high sound absorption performance. These frequencies are at the vicinity of 488 Hz and 819 Hz. The peaks found at the frequencies higher than 1000 Hz observed at the simulation results are not taken into consideration as the excessive sound energy at the mid-high frequency ranges

are mainly controlled with the carpet and the historical plasters. Therefore, the effect of *sebus* in this frequency range is insignificant. Also, the audial dimension of the Muslim worship practices include sermons and preaching as well as chanting. Due to its relevance for such activities, the sound absorption coefficients derived at 500 Hz are selected for investigation of their effect on sound energy decay pattern.

In the experimental measurements, the sound absorption coefficent of the clay pot at 500 Hz is found slightly above 0.2. The Phase 1 of the numerical simulations in which the absorption performance of a single clay pot is investigated; on the other hand, exhibit sound absorption coefficents between 0.3-0.6. Finally, the cumulative effect of the clay pots on the dome of Süleymaniye Mosque reveal sound absorption coefficients that reach up to 0.8-0.9 (see Appendix). An important result of the examinations is that the effective frequency range of the clay pots are found to be similar in all analysis methods.

In the Phase 1 of numerical simulations in which the sound absorption performance of a single clay pot is examined, the length and the diameter of the cylindirical domain is varied to ensure that at least one full wavelength is present during the study (Table 4.1). In these setups the sound absorption coefficient of the pot at the related frequency ranges vary, but the effective frequency ranges of clay pots remain the same. Therefore, it is verified that the peaks occured in FEM simulations do not result from the standing wave occurences in the cylindirical domain, but from the elastical modes of the air body inside the clay pot.

Hereby, it is seen that the *sebus* employed in the central dome of Süleymaniye Mosque indeed show sound absorption performance in the low-mid frequency ranges and has the potantial to improve the intelligibility in the space. Despite the fact that the sound absorption is only effective at a narrow bandwith, the results exhibit that the pots indeed serve for acoustical purposes and the long-standing myth behind the acoustic pots of Süleymaniye Mosque is verified. Nevertheless, with the current resources and present empirical data on the matter, the original intention of Sinan the Architect Leaureate behind placing these pots remains unknown.

In addition to their sound absorption performance, their placement in the concave surface of the dome may suggest further intentions. The concave form of the dome structure is known to create sound foci and hereby impair the even sound distribution in the environment which lead to low intelligibility. Asymmetry and irregularity created with the substantial number of pots in the large concave surfaces of the dome may aid the scattering of sound and thus help creating a diffuse sound field by enlarging the dome reflection zone [77]. In the light of the findings summarized above, the employment of effectively tuned clay pots may be a potent solution for the control of the excessive reverberation at low to mid frequencies.

Chapter 6

Conclusion

The acoustical employment of clay pots is placed at the center of a scholarly debate for a long time. The main arguments for their acoustical utilization in the space revolve around their employment as sound amplifiers, their symbolic placements in the walls of liturgical structures, and finally their employment as sound absorbers. In Anatolia, the clay pots found embedded into the dome structures that supposedly serve for acoustical purposes with their apertures facing the interior space are mainly interpreted to be functioning as Helmholtz resonators without sufficient scientific investigation. Therefore, in this study the sound absorption performance of the clay pots found in the central dome of Süleymaniye Mosque is examined and their contribution to the sound energy decay pattern of the mosque is studied through experimental and numerical analysis methods.

Süleymaniye Mosque is long acknowledged as one of the grand landmarks of Ottoman Empire and a power symbol of Sultan Süleyman the Magnificent. The edifice has also become a center of interest for the acoustical solutions it embodies in its geometrical form and material selection. In this study, 224 clay pots found embedded in the dome structure of the edifice are investigated with the object of understanding their contribution to the acoustics of the space. Initially, the influence of the mosque geometry and the material selection on the acoustics is analyzed. Then, the study is followed by the analytical, experimental, and

numerical investigations on finding the effective frequency range as well as the sound absorption performance of the pots. The research questions of the thesis given in Chapter 1 are answered as follows:

• Firstly, it is seen that the employment of clay pots as building elements is a common application since the Antiquity. Their employment as infrastructure elements, load lessening-infill materials, ventilation channels and finally acoustical components are observed in Europe, Near East and Anatolia especially in medieval structures.

• In Süleymaniye Mosque, the 224 clay pots are found scattered in 7 rings with a linear disposition around the central dome. Each ring contain 32 pots with equal distances in between. Their placement in the concave surface of the dome is also significant as they may also contribute to the even sound distribution in the edifice as they minimize the sound-focusing effects of the dome by creating asymetry and irregularity on the surface. The pots' placement in concave surfaces such as domes, pendentives and arches is also present in some of their European contemporaries [44].

• The 224 clay pots found embedded in the central dome of the edifice is often accounted as cavity resonators. As a result of the impedance tube measurements and FEM simulations, it is observed that the pots indeed perform as sound absorbers in particular frequencies. The high sound absorption coefficients at their effective frequency ranges acquired from the analyses exhibit that they may aid the control of sound energy decay in the space. Nevertheless, they are only effective in a narrow bandwith.

• The Helmholtz resonance of the clay pots employed in Süleymaniye Mosque are calculated to be 52 Hz. Their effective absorption at the vicinity of 488 Hz and 819 Hz are also identified.

• The impedance tube measurements exhibited that the pots have an absorption coefficient of 0.24 at the 500 Hz octave band. The following FEM simulations held to verify these results are conducted at two phases. In the first phase, sound

absorption performance of a single clay pot is examined. In the Phase 1 of FEM simulations the sound absorption coefficient of the *sebu* is found to be 0.57. In the Phase 2 of FEM simulations, the total sound absorption of the dome surface is simulated. In this phase, the dome surface is found to have an absorption coefficient of 0.87.

- The ray tracing simulations exhibit that at 500 Hz octave band the pots reduce the reverberation time about 2 seconds. Nevertheless, such reduction is only valid for the narrow bandwith that the pots are effective, namely at the vicinity of 488 Hz.

As a result, it is shown that the pots found in the central dome of Süleymaniye Mosque act as Helmholtz resonators at particular frequencies. It is shown that many historical structures of Anatolia are known to accomodate similar acoustic pots and these structures are not only limited to the designs of Sinan the Architect Leaureate. Therefore, a future work may be the acoustical characterization of the pots utilized in a similar fashion in Anatolia.

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Appendix A

Data

Table A.1: Impedance tube measurement results in 1/3 octave band.

Frequency [Hz]	**Sound Absorption Coefficient (α)**			
	Config. "a" No backing support	**Config. "b" Mineral wool filling**	**Config. "c" Sand filling**	**Avarage value**
50	0.02	0.02	0.06	0.03
63	0.06	0.08	0.08	0.08
80	0.07	0.08	0.10	0.08
100	0.08	0.09	0.10	0.09
125	0.08	0.09	0.11	0.09
160	0.08	0.11	0.12	0.10
200	0.08	0.12	0.12	0.10
250	0.07	0.13	0.12	0.11
315	0.07	0.13	0.12	0.10
400	0.06	0.13	0.11	0.10
500	0.21	0.24	0.23	0.23
630	0.07	0.14	0.14	0.12
800	0.11	0.26	0.25	0.20
1000	0.14	0.29	0.30	0.24
1250	0.16	0.31	0.34	0.27
1600	0.25	0.40	0.38	0.34
2000	0.24	0.34	0.33	0.30
2500	0.47	0.53	0.40	0.47
3150	0.31	0.38	0.26	0.31
4000	0.50	0.65	0.56	0.57
5000	0.48	0.57	0.53	0.53

Table A.2: Numerical Simulations Phase 1 Results
50-1000 Hz

Frequency [Hz]	**Sound Absorption Coefficient (α)**		
	r= 0.1	**r= 0.2**	**r= 0.3**
50	0.26	0.74	0.97
56	0.29	0.39	0.24
62	0.26	0.16	0.08
69	0.22	0.09	0.04
75	0.18	0.06	0.03
81	0.15	0.04	0.02
87	0.12	0.03	0.01
94	0.10	0.02	0.01
100	0.09	0.02	0.01
106	0.08	0.02	0.01
112	0.07	0.01	0.01
119	0.06	0.01	0.01
125	0.05	0.01	0.00
131	0.05	0.01	0.00
137	0.04	0.01	0.00
144	0.04	0.01	0.00
150	0.04	0.01	0.00
156	0.03	0.01	0.00
162	0.03	0.01	0.00
169	0.03	0.00	0.00
175	0.03	0.00	0.00
181	0.02	0.00	0.00
187	0.02	0.00	0.00
194	0.02	0.00	0.00
200	0.02	0.00	0.00
206	0.02	0.00	0.00
212	0.02	0.00	0.00

Table A.2 continued from previous page

219	0.02	0.00	0.00
225	0.02	0.00	0.00
231	0.02	0.00	0.00
237	0.02	0.00	0.00
244	0.01	0.00	0.00
250	0.01	0.00	0.00
256	0.01	0.00	0.00
262	0.01	0.00	0.00
269	0.01	0.00	0.00
275	0.01	0.00	0.00
281	0.01	0.00	0.00
287	0.01	0.00	0.00
294	0.01	0.00	0.00
300	0.01	0.00	0.00
306	0.01	0.00	0.00
312	0.01	0.00	0.00
319	0.01	0.00	0.00
325	0.01	0.00	0.00
331	0.01	0.00	0.00
337	0.01	0.00	0.00
344	0.01	0.00	0.00
350	0.01	0.00	0.00
356	0.01	0.00	0.00
362	0.01	0.00	0.00
369	0.01	0.00	0.00
375	0.01	0.00	0.00
381	0.00	0.00	0.00
387	0.00	0.00	0.00
394	0.00	0.00	0.00
400	0.00	0.00	0.00
406	0.00	0.00	0.00

Table A.2 continued from previous page

412	0.00	0.00	0.00
419	0.00	0.00	0.00
425	0.00	0.00	0.00
431	0.00	0.00	0.00
437	0.00	0.00	0.00
444	0.00	0.00	0.00
450	0.00	0.00	0.00
456	0.00	0.00	0.00
462	0.00	0.00	0.00
469	0.00	0.00	0.00
475	0.00	0.00	0.00
481	0.00	0.00	0.00
487	0.57	0.32	0.25
494	0.03	0.01	0.00
500	0.01	0.00	0.00
506	0.01	0.00	0.00
512	0.01	0.00	0.00
519	0.01	0.00	0.00
525	0.01	0.00	0.00
531	0.01	0.00	0.00
537	0.00	0.00	0.00
544	0.00	0.00	0.00
550	0.00	0.00	0.00
556	0.00	0.00	0.00
562	0.00	0.00	0.00
569	0.00	0.00	0.00
575	0.00	0.00	0.00
581	0.00	0.00	0.00
587	0.00	0.00	0.00
594	0.00	0.00	0.00
600	0.00	0.00	0.00

Table A.2 continued from previous page

606	0.00	0.00	0.00
612	0.00	0.00	0.00
619	0.00	0.00	0.00
625	0.00	0.00	0.00
631	0.00	0.00	0.00
637	0.00	0.00	0.00
644	0.00	0.00	0.00
650	0.00	0.00	0.00
656	0.00	0.00	0.00
662	0.00	0.00	0.00
669	0.00	0.00	0.00
675	0.00	0.00	0.00
681	0.00	0.00	0.00
687	0.00	0.00	0.00
694	0.00	0.00	0.00
700	0.00	0.00	0.00
706	0.00	0.00	0.00
712	0.00	0.00	0.00
719	0.00	0.00	0.00
725	0.00	0.00	0.00
731	0.00	0.00	0.00
737	0.00	0.00	0.00
744	0.00	0.00	0.00
750	0.00	0.00	0.00
756	0.00	0.00	0.00
762	0.00	0.00	0.00
769	0.00	0.00	0.00
775	0.00	0.00	0.00
781	0.00	0.00	0.00
787	0.00	0.00	0.00
794	0.00	0.00	0.00

Table A.2 continued from previous page

800	0.00	0.00	0.00
806	0.00	0.00	0.00
812	0.00	0.00	0.00
819	0.59	0.97	0.83
825	0.01	0.00	0.00
831	0.01	0.00	0.00
837	0.00	0.00	0.00
844	0.00	0.00	0.00
850	0.00	0.00	0.00
856	0.00	0.00	0.00
862	0.00	0.00	0.00
869	0.00	0.00	0.00
875	0.00	0.00	0.00
881	0.00	0.00	0.00
887	0.00	0.00	0.00
894	0.00	0.00	0.00
900	0.00	0.00	0.00
906	0.00	0.00	0.00
912	0.00	0.00	0.00
919	0.00	0.00	0.00
925	0.00	0.00	0.00
931	0.00	0.00	0.00
937	0.00	0.00	0.00
944	0.00	0.00	0.00
950	0.00	0.00	0.00
956	0.00	0.00	0.00
962	0.00	0.00	0.00
969	0.00	0.00	0.00
975	0.00	0.00	0.00
981	0.00	0.00	0.00
987	0.00	0.00	0.00

Table A.2 continued from previous page

994	0.00	0.00	0.00
1000	0.00	0.00	0.00

Table A.3: Numerical Simulations Phase 1 Results
1000-5000 Hz

Frequency [Hz]	**Sound Absorption Coefficient (α)**			
	r= 0.02	**r= 0.03**	**r= 0.05**	**r= 0.1**
1000	0.02	0.02	0.01	0.00
1006	0.02	0.02	0.01	0.00
1012	0.02	0.02	0.01	0.00
1018	0.02	0.01	0.01	0.00
1024	0.02	0.01	0.00	0.00
1030	0.02	0.01	0.00	0.00
1036	0.02	0.01	0.00	0.00
1042	0.02	0.01	0.00	0.00
1048	0.02	0.01	0.00	0.00
1054	0.02	0.01	0.00	0.00
1060	0.02	0.01	0.00	0.00
1066	0.02	0.01	0.00	0.00
1072	0.02	0.01	0.00	0.00
1078	0.02	0.01	0.00	0.00
1084	0.02	0.01	0.00	0.00
1090	0.01	0.01	0.00	0.00
1096	0.01	0.01	0.00	0.00
1102	0.01	0.00	0.00	0.00
1108	0.01	0.00	0.00	0.00
1114	0.00	0.00	0.00	0.00
1120	0.00	0.00	0.00	0.00
1126	0.01	0.00	0.00	0.00
1132	0.03	0.04	0.03	0.01

Table A.3 continued from previous page

1138	0.04	0.10	0.26	0.47
1144	0.05	0.08	0.05	0.01
1150	0.04	0.06	0.03	0.00
1162	0.04	0.04	0.01	0.00
1168	0.04	0.03	0.01	0.00
1174	0.04	0.03	0.01	0.00
1180	0.03	0.03	0.01	0.00
1186	0.03	0.02	0.01	0.00
1192	0.03	0.02	0.01	0.00
1198	0.03	0.02	0.01	0.00
1204	0.03	0.02	0.01	0.00
1210	0.03	0.02	0.01	0.00
1216	0.03	0.02	0.01	0.00
1222	0.03	0.02	0.01	0.00
1228	0.03	0.02	0.01	0.00
1234	0.03	0.02	0.01	0.00
1240	0.03	0.02	0.01	0.00
1246	0.03	0.02	0.01	0.00
1252	0.03	0.02	0.01	0.00
1258	0.03	0.02	0.01	0.00
1264	0.03	0.01	0.00	0.00
1270	0.02	0.01	0.00	0.00
1276	0.02	0.01	0.00	0.00
1282	0.02	0.01	0.00	0.00
1288	0.02	0.01	0.00	0.00
1294	0.02	0.01	0.00	0.00
1300	0.02	0.01	0.00	0.00
1306	0.02	0.01	0.00	0.00
1312	0.02	0.01	0.00	0.00
1318	0.02	0.01	0.00	0.00
1324	0.02	0.01	0.00	0.00

Table A.3 continued from previous page

1330	0.02	0.01	0.00	0.00
1336	0.02	0.01	0.00	0.00
1342	0.02	0.01	0.00	0.00
1348	0.02	0.01	0.00	0.00
1354	0.02	0.01	0.00	0.00
1360	0.02	0.01	0.00	0.00
1366	0.02	0.01	0.00	0.00
1372	0.02	0.01	0.00	0.00
1378	0.02	0.01	0.00	0.00
1384	0.01	0.01	0.00	0.00
1390	0.01	0.01	0.00	0.00
1396	0.01	0.01	0.00	0.00
1402	0.01	0.00	0.00	0.00
1408	0.01	0.00	0.00	0.00
1414	0.01	0.00	0.00	0.00
1420	0.00	0.00	0.00	0.00
1426	0.00	0.00	0.00	0.00
1432	0.00	0.00	0.00	0.00
1438	0.00	0.00	0.00	0.00
1444	0.01	0.01	0.00	0.00
1450	0.04	0.06	0.07	0.67
1456	0.05	0.11	0.28	0.01
1462	0.05	0.08	0.03	0.01
1468	0.05	0.05	0.02	0.00
1474	0.04	0.04	0.01	0.00
1480	0.04	0.03	0.01	0.00
1486	0.04	0.03	0.01	0.00
1492	0.04	0.02	0.01	0.00
1498	0.03	0.02	0.01	0.00
1504	0.03	0.02	0.01	0.00
1510	0.03	0.02	0.01	0.00

Table A.3 continued from previous page

1516	0.03	0.02	0.01	0.00
1522	0.03	0.02	0.01	0.00
1528	0.03	0.02	0.01	0.00
1534	0.03	0.02	0.00	0.00
1540	0.03	0.01	0.00	0.00
1546	0.03	0.01	0.00	0.00
1552	0.02	0.01	0.00	0.00
1558	0.02	0.01	0.00	0.00
1564	0.03	0.01	0.00	0.00
1570	0.02	0.01	0.00	0.00
1576	0.02	0.01	0.00	0.00
1582	0.02	0.01	0.00	0.00
1588	0.02	0.01	0.00	0.00
1594	0.02	0.01	0.00	0.00
1600	0.02	0.01	0.00	0.00
1606	0.02	0.01	0.00	0.00
1612	0.02	0.01	0.00	0.00
1618	0.02	0.01	0.00	0.00
1624	0.02	0.01	0.00	0.00
1630	0.02	0.01	0.00	0.00
1636	0.02	0.01	0.00	0.00
1642	0.02	0.01	0.00	0.00
1648	0.02	0.01	0.00	0.00
1654	0.02	0.01	0.00	0.00
1660	0.02	0.01	0.00	0.00
1666	0.02	0.01	0.00	0.00
1672	0.02	0.01	0.00	0.00
1678	0.01	0.01	0.00	0.00
1684	0.01	0.01	0.00	0.00
1690	0.01	0.01	0.00	0.00
1696	0.01	0.01	0.00	0.00

Table A.3 continued from previous page

1702	0.01	0.00	0.00	0.00
1708	0.01	0.00	0.00	0.00
1714	0.01	0.00	0.00	0.00
1720	0.01	0.00	0.00	0.00
1726	0.01	0.00	0.00	0.00
1732	0.00	0.00	0.00	0.00
1738	0.00	0.00	0.00	0.00
1744	0.00	0.00	0.00	0.00
1750	0.00	0.00	0.00	0.00
1756	0.01	0.01	0.00	0.00
1762	0.03	0.04	0.04	0.70
1768	0.06	0.12	0.30	0.01
1774	0.06	0.09	0.03	0.00
1780	0.05	0.05	0.02	0.00
1786	0.05	0.04	0.01	0.00
1792	0.04	0.03	0.01	0.00
1798	0.04	0.02	0.01	0.00
1804	0.04	0.02	0.01	0.00
1810	0.03	0.02	0.01	0.00
1816	0.03	0.02	0.00	0.00
1822	0.03	0.01	0.00	0.00
1828	0.03	0.01	0.00	0.00
1834	0.02	0.01	0.00	0.00
1840	0.05	0.06	0.02	0.00
1846	0.03	0.02	0.00	0.00
1852	0.03	0.01	0.00	0.00
1858	0.03	0.01	0.00	0.00
1864	0.02	0.01	0.00	0.00
1870	0.02	0.01	0.00	0.00
1876	0.02	0.01	0.00	0.00
1882	0.02	0.01	0.00	0.00

Table A.3 continued from previous page

1888	0.02	0.01	0.00	0.00
1894	0.02	0.01	0.00	0.00
1900	0.02	0.01	0.00	0.00
1906	0.02	0.01	0.00	0.00
1912	0.02	0.01	0.00	0.00
1918	0.02	0.01	0.00	0.00
1924	0.02	0.01	0.00	0.00
1930	0.02	0.01	0.00	0.00
1936	0.02	0.01	0.00	0.00
1942	0.02	0.01	0.00	0.00
1948	0.02	0.01	0.00	0.00
1954	0.02	0.01	0.00	0.00
1960	0.02	0.01	0.00	0.00
1966	0.01	0.01	0.00	0.00
1972	0.01	0.01	0.00	0.00
1978	0.01	0.01	0.00	0.00
1984	0.01	0.01	0.00	0.00
1990	0.01	0.01	0.00	0.00
1996	0.01	0.00	0.00	0.00
2002	0.01	0.00	0.00	0.00
2008	0.01	0.00	0.00	0.00
2014	0.01	0.00	0.00	0.00
2020	0.01	0.00	0.00	0.00
2026	0.01	0.00	0.00	0.00
2032	0.01	0.00	0.00	0.00
2038	0.00	0.00	0.00	0.00
2044	0.00	0.00	0.00	0.00
2050	0.00	0.00	0.00	0.00
2056	0.00	0.00	0.00	0.00
2062	0.00	0.00	0.00	0.00
2068	0.02	0.02	0.01	0.75

Table A.3 continued from previous page

2074	0.06	0.13	0.31	0.00
2080	0.06	0.10	0.03	0.00
2086	0.05	0.05	0.01	0.00
2092	0.05	0.03	0.01	0.00
2098	0.04	0.02	0.01	0.00
2104	0.03	0.02	0.00	0.00
2110	0.02	0.01	0.00	0.00
2116	0.01	0.01	0.00	0.00
2122	0.01	0.00	0.00	0.01
2128	0.05	0.04	0.01	0.00
2134	0.04	0.02	0.01	0.00
2140	0.03	0.02	0.00	0.00
2146	0.03	0.01	0.00	0.00
2152	0.03	0.01	0.00	0.00
2158	0.03	0.01	0.00	0.00
2164	0.03	0.01	0.00	0.00
2170	0.02	0.01	0.00	0.00
2176	0.02	0.01	0.00	0.00
2182	0.02	0.01	0.00	0.75
2188	0.02	0.01	0.00	0.04
2194	0.02	0.01	0.00	0.01
2200	0.02	0.01	0.00	0.00
2206	0.02	0.01	0.00	0.00
2212	0.02	0.01	0.00	0.00
2218	0.02	0.01	0.00	0.00
2224	0.02	0.01	0.00	0.00
2230	0.02	0.01	0.00	0.00
2236	0.02	0.01	0.00	0.00
2242	0.02	0.01	0.00	0.00
2248	0.02	0.01	0.00	0.00
2254	0.01	0.01	0.00	0.00

Table A.3 continued from previous page

2260	0.01	0.01	0.00	0.00
2266	0.01	0.01	0.00	0.00
2272	0.01	0.01	0.00	0.00
2278	0.01	0.01	0.00	0.00
2284	0.01	0.01	0.00	0.00
2290	0.01	0.00	0.00	0.00
2296	0.01	0.00	0.00	0.00
2302	0.01	0.00	0.00	0.00
2308	0.01	0.00	0.00	0.00
2314	0.01	0.00	0.00	0.00
2320	0.01	0.00	0.00	0.00
2326	0.01	0.00	0.00	0.00
2332	0.01	0.00	0.00	0.00
2338	0.00	0.00	0.00	0.00
2344	0.00	0.00	0.00	0.00
2350	0.00	0.00	0.00	0.00
2356	0.00	0.00	0.00	0.00
2362	0.00	0.00	0.00	0.00
2368	0.01	0.00	0.00	0.00
2374	0.04	0.07	0.22	0.74
2380	0.06	0.07	0.02	0.00
2386	0.04	0.02	0.01	0.00
2392	0.03	0.01	0.00	0.00
2398	0.01	0.01	0.00	0.00
2404	0.00	0.00	0.00	0.00
2410	0.01	0.00	0.00	0.00
2416	0.06	0.13	0.10	0.01
2422	0.06	0.05	0.01	0.00
2428	0.05	0.03	0.01	0.00
2434	0.04	0.02	0.01	0.00
2440	0.04	0.02	0.00	0.00

Table A.3 continued from previous page

2446	0.03	0.02	0.00	0.00
2452	0.03	0.01	0.00	0.00
2458	0.03	0.01	0.00	0.00
2464	0.03	0.01	0.00	0.00
2470	0.02	0.01	0.00	0.00
2476	0.02	0.01	0.00	0.00
2482	0.02	0.01	0.00	0.00
2488	0.02	0.01	0.00	0.00
2494	0.02	0.01	0.00	0.00
2500	0.02	0.01	0.00	0.00
2506	0.02	0.01	0.00	0.00
2512	0.02	0.01	0.00	0.00
2518	0.02	0.01	0.00	0.00
2524	0.02	0.01	0.00	0.00
2530	0.02	0.01	0.00	0.00
2536	0.02	0.01	0.00	0.00
2542	0.02	0.01	0.00	0.00
2548	0.01	0.01	0.00	0.00
2554	0.01	0.01	0.00	0.00
2560	0.01	0.01	0.00	0.00
2566	0.01	0.01	0.00	0.00
2572	0.01	0.01	0.00	0.00
2578	0.01	0.00	0.00	0.00
2584	0.01	0.00	0.00	0.00
2590	0.01	0.00	0.00	0.00
2596	0.01	0.00	0.00	0.48
2602	0.01	0.00	0.00	0.01
2608	0.01	0.00	0.00	0.00
2614	0.01	0.00	0.00	0.00
2620	0.01	0.00	0.00	0.00
2626	0.01	0.00	0.00	0.00

Table A.3 continued from previous page

2632	0.01	0.00	0.00	0.00
2638	0.00	0.00	0.00	0.00
2644	0.00	0.00	0.00	0.00
2650	0.00	0.00	0.00	0.00
2656	0.00	0.00	0.00	0.00
2662	0.00	0.00	0.00	0.00
2668	0.01	0.01	0.31	0.00
2674	0.07	0.14	0.01	0.22
2680	0.02	0.01	0.00	0.00
2686	0.01	0.00	0.00	0.00
2692	0.00	0.00	0.00	0.00
2698	0.00	0.00	0.00	0.00
2704	0.02	0.02	0.02	0.00
2710	0.05	0.14	0.33	0.57
2716	0.07	0.08	0.02	0.03
2722	0.06	0.04	0.01	0.01
2728	0.05	0.03	0.01	0.00
2734	0.04	0.02	0.00	0.00
2740	0.04	0.02	0.00	0.00
2746	0.03	0.01	0.00	0.00
2752	0.03	0.01	0.00	0.00
2758	0.03	0.01	0.00	0.00
2764	0.03	0.01	0.00	0.00
2770	0.02	0.01	0.00	0.00
2776	0.02	0.01	0.00	0.00
2782	0.02	0.01	0.00	0.00
2788	0.02	0.01	0.00	0.00
2794	0.02	0.01	0.00	0.00
2800	0.02	0.01	0.00	0.00
2806	0.02	0.01	0.00	0.00
2812	0.02	0.01	0.00	0.00

Table A.3 continued from previous page

2818	0.02	0.01	0.00	0.00
2824	0.02	0.01	0.00	0.00
2830	0.02	0.01	0.00	0.00
2836	0.01	0.01	0.00	0.00
2842	0.01	0.01	0.00	0.00
2848	0.01	0.01	0.00	0.00
2854	0.01	0.01	0.00	0.00
2860	0.01	0.00	0.00	0.00
2866	0.01	0.00	0.00	0.00
2872	0.01	0.00	0.00	0.00
2878	0.01	0.00	0.00	0.00
2884	0.01	0.00	0.00	0.00
2890	0.01	0.00	0.00	0.00
2896	0.01	0.00	0.00	0.00
2902	0.01	0.00	0.00	0.00
2908	0.01	0.00	0.00	0.00
2914	0.01	0.00	0.00	0.00
2920	0.01	0.00	0.00	0.00
2926	0.01	0.00	0.00	0.00
2932	0.01	0.00	0.00	0.00
2938	0.00	0.00	0.00	0.00
2944	0.00	0.00	0.00	0.00
2950	0.00	0.00	0.00	0.00
2956	0.00	0.00	0.00	0.00
2962	0.00	0.00	0.00	0.00
2968	0.05	0.07	0.34	0.82
2974	0.00	0.00	0.00	0.00
2980	0.00	0.00	0.00	0.00
2986	0.00	0.00	0.00	0.00
2992	0.01	0.01	0.01	0.00
2998	0.03	0.087	0.34	0.44

Table A.3 continued from previous page

3004	0.06	0.14	0.04	0.00
3010	0.07	0.08	0.01	0.00
3016	0.06	0.04	0.01	0.00
3022	0.05	0.03	0.01	0.00
3028	0.04	0.02	0.00	0.00
3034	0.03	0.01	0.00	0.00
3040	0.03	0.01	0.00	0.00
3046	0.03	0.01	0.00	0.00
3052	0.03	0.01	0.00	0.00
3058	0.03	0.01	0.00	0.00
3064	0.02	0.01	0.00	0.00
3070	0.02	0.01	0.00	0.00
3076	0.02	0.01	0.00	0.00
3082	0.02	0.01	0.00	0.00
3088	0.02	0.01	0.00	0.00
3094	0.02	0.01	0.00	0.00
3100	0.02	0.01	0.00	0.00
3106	0.02	0.01	0.00	0.01
3112	0.02	0.01	0.00	0.72
3118	0.02	0.01	0.00	0.01
3124	0.01	0.01	0.00	0.00
3130	0.01	0.01	0.00	0.00
3136	0.01	0.01	0.00	0.00
3142	0.01	0.00	0.00	0.00
3148	0.01	0.00	0.00	0.00
3154	0.01	0.00	0.00	0.00
3160	0.01	0.00	0.00	0.00
3166	0.01	0.00	0.00	0.00
3172	0.01	0.00	0.00	0.00
3178	0.01	0.00	0.00	0.00
3184	0.01	0.00	0.00	0.00

Table A.3 continued from previous page

3190	0.01	0.00	0.00	0.00
3196	0.01	0.00	0.00	0.00
3202	0.01	0.00	0.00	0.00
3208	0.01	0.00	0.00	0.00
3214	0.01	0.00	0.00	0.00
3220	0.01	0.00	0.00	0.00
3226	0.01	0.00	0.00	0.00
3232	0.00	0.00	0.00	0.00
3238	0.00	0.00	0.00	0.00
3244	0.00	0.00	0.00	0.00
3250	0.00	0.00	0.00	0.00
3256	0.00	0.00	0.00	0.00
3262	0.00	0.00	0.00	0.00
3268	0.00	0.00	0.00	0.00
3274	0.00	0.00	0.00	0.00
3280	0.00	0.00	0.00	0.00
3286	0.02	0.02	0.03	0.00
3292	0.04	0.15	0.30	0.77
3298	0.07	0.12	0.01	0.02
3304	0.07	0.05	0.01	0.00
3310	0.06	0.03	0.00	0.00
3316	0.05	0.02	0.00	0.00
3322	0.04	0.02	0.00	0.00
3328	0.03	0.01	0.00	0.00
3334	0.03	0.01	0.00	0.00
3340	0.03	0.01	0.00	0.00
3346	0.03	0.01	0.00	0.00
3352	0.02	0.01	0.00	0.00
3358	0.02	0.01	0.00	0.00
3364	0.02	0.01	0.00	0.00
3370	0.02	0.01	0.00	0.00

Table A.3 continued from previous page

3376	0.02	0.01	0.00	0.00
3382	0.02	0.01	0.00	0.00
3388	0.02	0.01	0.00	0.00
3394	0.02	0.01	0.00	0.00
3400	0.01	0.01	0.00	0.00
3406	0.01	0.01	0.00	0.00
3412	0.01	0.01	0.00	0.00
3418	0.01	0.00	0.00	0.00
3424	0.01	0.00	0.00	0.00
3430	0.01	0.00	0.00	0.00
3436	0.01	0.00	0.00	0.00
3442	0.01	0.00	0.00	0.00
3448	0.01	0.00	0.00	0.00
3454	0.01	0.00	0.00	0.00
3460	0.01	0.00	0.00	0.00
3466	0.01	0.00	0.00	0.00
3472	0.01	0.00	0.00	0.00
3478	0.01	0.00	0.00	0.00
3484	0.01	0.00	0.00	0.00
3490	0.01	0.00	0.00	0.00
3496	0.01	0.00	0.00	0.00
3502	0.01	0.00	0.00	0.00
3508	0.01	0.00	0.00	0.00
3514	0.00	0.00	0.00	0.00
3520	0.00	0.00	0.00	0.00
3526	0.00	0.00	0.00	0.00
3532	0.00	0.00	0.00	0.00
3538	0.00	0.00	0.00	0.00
3544	0.00	0.00	0.00	0.00
3550	0.00	0.00	0.14	0.00
3556	0.07	0.11	0.00	0.22

Table A.3 continued from previous page

3562	0.00	0.00	0.00	0.00
3568	0.00	0.00	0.00	0.00
3574	0.00	0.00	0.00	0.00
3580	0.02	0.03	0.31	0.01
3586	0.07	0.15	0.01	0.29
3592	0.00	0.13	0.17	0.07
3598	0.07	0.05	0.01	0.00
3604	0.06	0.03	0.00	0.00
3610	0.04	0.02	0.00	0.00
3616	0.04	0.01	0.00	0.00
3622	0.03	0.01	0.00	0.00
3628	0.03	0.01	0.00	0.00
3634	0.02	0.01	0.00	0.00
3640	0.02	0.01	0.00	0.00
3646	0.02	0.01	0.00	0.00
3652	0.02	0.01	0.00	0.00
3658	0.02	0.01	0.00	0.00
3664	0.02	0.01	0.00	0.00
3670	0.02	0.01	0.00	0.00
3676	0.02	0.01	0.00	0.00
3682	0.01	0.01	0.00	0.00
3688	0.01	0.01	0.00	0.00
3694	0.01	0.00	0.00	0.00
3700	0.01	0.00	0.00	0.00
3706	0.01	0.00	0.00	0.00
3712	0.01	0.00	0.00	0.00
3718	0.01	0.00	0.00	0.00
3724	0.01	0.00	0.00	0.00
3730	0.01	0.00	0.00	0.00
3736	0.01	0.00	0.00	0.00
3742	0.01	0.00	0.00	0.00

Table A.3 continued from previous page

3748	0.01	0.00	0.00	0.00
3754	0.01	0.00	0.00	0.00
3760	0.01	0.00	0.00	0.00
3766	0.01	0.00	0.00	0.00
3772	0.01	0.00	0.00	0.00
3778	0.01	0.00	0.00	0.00
3784	0.01	0.00	0.00	0.00
3790	0.01	0.00	0.00	0.00
3796	0.00	0.00	0.00	0.00
3802	0.00	0.00	0.00	0.00
3808	0.00	0.00	0.00	0.00
3814	0.00	0.00	0.00	0.00
3820	0.00	0.00	0.00	0.00
3826	0.00	0.00	0.00	0.00
3832	0.00	0.00	0.00	0.00
3838	0.01	0.01	0.31	0.03
3844	0.07	0.12	0.00	0.00
3850	0.01	0.00	0.00	0.00
3856	0.00	0.00	0.00	0.00
3862	0.00	0.00	0.20	0.01
3868	0.04	0.15	0.01	0.00
3874	0.07	0.04	0.00	0.00
3880	0.04	0.01	0.00	0.00
3886	0.01	0.00	0.00	0.00
3892	0.00	0.00	0.00	0.00
3898	0.08	0.15	0.00	0.00
3904	0.06	0.02	0.00	0.00
3910	0.04	0.01	0.00	0.00
3916	0.03	0.01	0.00	0.00
3922	0.03	0.01	0.00	0.00
3928	0.02	0.01	0.00	0.00

Table A.3 continued from previous page

3934	0.02	0.01	0.00	0.00
3940	0.02	0.01	0.00	0.00
3946	0.02	0.01	0.00	0.00
3952	0.02	0.01	0.00	0.00
3958	0.02	0.01	0.00	0.00
3964	0.02	0.01	0.00	0.00
3970	0.01	0.00	0.00	0.00
3976	0.01	0.00	0.00	0.01
3982	0.01	0.00	0.00	0.97
3988	0.01	0.00	0.00	0.04
3994	0.01	0.00	0.00	0.01
4000	0.01	0.00	0.00	0.00
4006	0.01	0.00	0.00	0.00
4012	0.01	0.00	0.00	0.62
4018	0.01	0.00	0.00	0.72
4024	0.01	0.00	0.00	0.01
4030	0.01	0.00	0.00	0.00
4036	0.01	0.00	0.00	0.00
4042	0.01	0.00	0.00	0.00
4048	0.01	0.00	0.00	0.00
4054	0.01	0.00	0.00	0.00
4060	0.01	0.00	0.00	0.00
4066	0.01	0.00	0.00	0.00
4072	0.01	0.00	0.00	0.00
4078	0.00	0.00	0.00	0.00
4084	0.00	0.00	0.00	0.00
4090	0.00	0.00	0.00	0.00
4096	0.00	0.00	0.00	0.00
4102	0.00	0.00	0.00	0.00
4108	0.00	0.00	0.00	0.00
4114	0.00	0.00	0.00	0.00

Table A.3 continued from previous page

4120	0.00	0.00	0.04	0.00
4126	0.07	0.15	0.00	0.41
4132	0.01	0.00	0.00	0.00
4138	0.00	0.00	0.00	0.00
4144	0.00	0.00	0.00	0.00
4150	0.01	0.00	0.23	0.00
4156	0.03	0.15	0.00	0.00
4162	0.08	0.07	0.00	0.45
4168	0.06	0.02	0.00	0.02
4174	0.04	0.01	0.00	0.00
4180	0.03	0.01	0.00	0.00
4186	0.02	0.01	0.00	0.00
4192	0.01	0.00	0.00	0.00
4198	0.00	0.00	0.00	0.00
4204	0.08	0.15	0.00	0.13
4210	0.06	0.02	0.00	0.01
4216	0.04	0.01	0.00	0.00
4222	0.03	0.01	0.00	0.00
4228	0.02	0.01	0.00	0.00
4234	0.02	0.01	0.00	0.00
4240	0.02	0.01	0.00	0.00
4246	0.02	0.01	0.00	0.00
4252	0.02	0.01	0.00	0.00
4258	0.01	0.00	0.00	0.00
4264	0.01	0.00	0.00	0.00
4270	0.01	0.00	0.00	0.00
4276	0.01	0.00	0.00	0.00
4282	0.01	0.00	0.00	0.00
4288	0.01	0.00	0.00	0.00
4294	0.01	0.00	0.00	0.00
4300	0.01	0.00	0.00	0.00

Table A.3 continued from previous page

4306	0.01	0.00	0.00	0.00
4312	0.01	0.00	0.00	0.00
4318	0.01	0.00	0.00	0.00
4324	0.01	0.00	0.00	0.00
4330	0.01	0.00	0.00	0.00
4336	0.01	0.00	0.00	0.00
4342	0.01	0.00	0.00	0.00
4348	0.01	0.00	0.00	0.00
4354	0.01	0.00	0.00	0.00
4360	0.01	0.00	0.01	0.00
4366	0.00	0.00	0.65	0.00
4372	0.00	0.00	0.03	0.00
4378	0.00	0.00	0.00	0.00
4384	0.00	0.00	0.00	0.00
4390	0.00	0.00	0.00	0.00
4396	0.00	0.00	0.00	0.00
4402	0.00	0.00	0.00	0.00
4408	0.07	0.09	0.00	0.02
4414	0.01	0.00	0.44	0.00
4420	0.00	0.00	0.00	0.00
4426	0.00	0.00	0.00	0.00
4432	0.00	0.00	0.00	0.00
4438	0.00	0.00	0.00	0.00
4444	0.01	0.01	0.00	0.00
4450	0.03	0.06	0.00	0.29
4456	0.07	0.15	0.00	0.01
4462	0.08	0.03	0.01	0.00
4468	0.05	0.02	0.03	0.00
4474	0.03	0.01	0.44	0.00
4480	0.03	0.01	0.09	0.00
4486	0.02	0.01	0.02	0.00

Table A.3 continued from previous page

4492	0.01	0.00	0.01	0.00
4498	0.01	0.00	0.01	0.00
4502	0.01	0.00	0.01	0.00
4508	0.00	0.00	0.00	0.00
4514	0.08	0.14	0.00	0.48
4520	0.05	0.01	0.03	0.00
4526	0.03	0.01	0.46	0.00
4532	0.02	0.01	0.05	0.00
4538	0.02	0.01	0.02	0.00
4544	0.02	0.01	0.01	0.00
4550	0.01	0.00	0.01	0.00
4556	0.01	0.00	0.01	0.00
4562	0.01	0.00	0.01	0.00
4568	0.01	0.00	0.00	0.00
4574	0.01	0.00	0.00	0.00
4580	0.01	0.00	0.00	0.00
4586	0.01	0.00	0.00	0.00
4592	0.01	0.00	0.00	0.00
4598	0.01	0.00	0.00	0.00
4604	0.01	0.00	0.00	0.00
4610	0.01	0.00	0.00	0.00
4616	0.01	0.00	0.00	0.00
4622	0.01	0.00	0.00	0.00
4628	0.01	0.00	0.00	0.00
4634	0.01	0.00	0.00	0.00
4640	0.01	0.00	0.00	0.00
4646	0.01	0.00	0.00	0.00
4652	0.01	0.00	0.00	0.00
4658	0.00	0.00	0.00	0.00
4664	0.00	0.00	0.00	0.00
4670	0.00	0.00	0.00	0.00

Table A.3 continued from previous page

4676	0.00	0.00	0.00	0.00
4682	0.00	0.00	0.00	0.00
4688	0.00	0.00	0.00	0.00
4694	0.08	0.15	0.39	0.00
4700	0.01	0.00	0.00	0.00
4706	0.00	0.00	0.00	0.00
4712	0.00	0.00	0.00	0.00
4718	0.00	0.00	0.00	0.00
4724	0.00	0.00	0.00	0.00
4730	0.00	0.00	0.00	0.00
4736	0.00	0.00	0.00	0.00
4742	0.01	0.01	0.00	0.00
4748	0.03	0.15	0.01	0.54
4754	0.08	0.06	0.34	0.00
4760	0.07	0.02	0.02	0.00
4766	0.03	0.01	0.01	0.00
4772	0.04	0.01	0.01	0.00
4778	0.03	0.01	0.00	0.00
4784	0.02	0.01	0.00	0.00
4790	0.02	0.01	0.00	0.00
4796	0.02	0.00	0.00	0.00
4802	0.01	0.00	0.00	0.00
4808	0.01	0.00	0.00	0.00
4814	0.01	0.00	0.00	0.00
4820	0.00	0.00	0.00	0.00
4826	0.08	0.13	0.13	0.00
4832	0.03	0.01	0.00	0.00
4838	0.02	0.01	0.00	0.00
4844	0.02	0.01	0.00	0.00
4850	0.01	0.00	0.00	0.00
4856	0.01	0.00	0.00	0.00

Table A.3 continued from previous page

4862	0.01	0.00	0.00	0.00
4868	0.01	0.00	0.00	0.00
4874	0.01	0.00	0.00	0.00
4880	0.01	0.00	0.00	0.00
4886	0.01	0.00	0.00	0.00
4892	0.01	0.00	0.00	0.00
4898	0.01	0.00	0.00	0.00
4904	0.01	0.00	0.00	0.00
4910	0.01	0.00	0.00	0.00
4916	0.01	0.00	0.00	0.00
4922	0.01	0.00	0.00	0.00
4928	0.01	0.00	0.00	0.00
4934	0.01	0.00	0.00	0.00
4940	0.01	0.00	0.00	0.00
4946	0.00	0.00	0.00	0.00
4952	0.00	0.00	0.00	0.00
4958	0.00	0.00	0.00	0.00
4964	0.00	0.00	0.00	0.00
4970	0.00	0.00	0.00	0.00
4976	0.00	0.15	0.07	0.08
4982	0.08	0.01	0.00	0.00
4988	0.01	0.00	0.00	0.00
4994	0.01	0.00	0.00	0.00
5000	0.00	0.00	0.00	0.00

Table A.4: Numerical Simulations Phase 2 Results Narrow Bandwith 487-492 Hz

Frequency [Hz]	**Sound Absorption Coefficient (α)**		
	11.25 Degree	**11.25 Degree Shell**	**45 Degree**
487	0.00	0.08	0.00
487.2	0.01	0.12	0.02
487.4	0.01	0.19	0.02
487.6	0.06	0.29	0.03
487.8	0.56	0.55	0.19
488	0.87	0.75	0.97
488.2	0.87	0.52	0.51
488.4	0.47	0.48	0.78
488.6	0.77	0.73	0.46
488.8	0.52	0.87	0.26
489	0.24	0.79	0.15
489.2	0.11	0.43	0.10
489.4	0.10	0.16	0.19
489.6	0.47	0.07	0.42
489.8	0.15	0.27	0.17
490	0.05	0.04	0.04
490.2	0.12	0.03	0.12
490.4	0.02	0.03	0.06
490.6	0.06	0.03	0.04
490.8	0.02	0.03	0.02
491	0.38	0.04	0.75
491.2	0.01	0.10	0.01
491.4	0.01	0.23	0.01
491.6	0.00	0.08	0.00
491.8	0.02	0.03	0.02
492	0.01	0.02	0.01

Table A.5: Numerical Simulations Phase 2 Results Narrow Bandwith 816-820 Hz

Frequency [Hz]	**Sound Absorption Coefficient (α)**
	11.25 Degree Shell
816	0.04
816.2	0.10
816.4	0.56
816.6	0.35
816.8	0.86
817	0.46
817.2	0.33
817.4	0.41
817.6	0.17
817.8	0.15
818	0.17
818.2	0.20
818.4	0.21
818.6	0.16
818.8	0.11
819	0.40
819.2	0.65
819.4	0.14
819.6	0.09
819.8	0.07
820	0.06

Appendix B

Pressure Field Maps

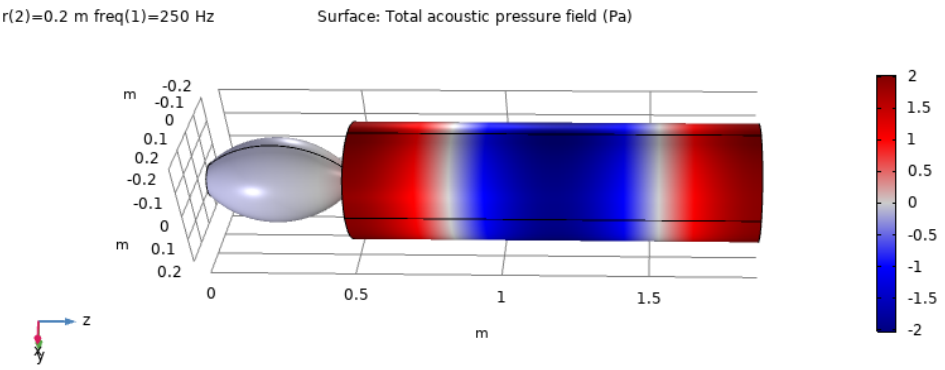


Figure B.1: Pressure field of the Phase 1 numerical simulations, r=0.2m, 250 Hz

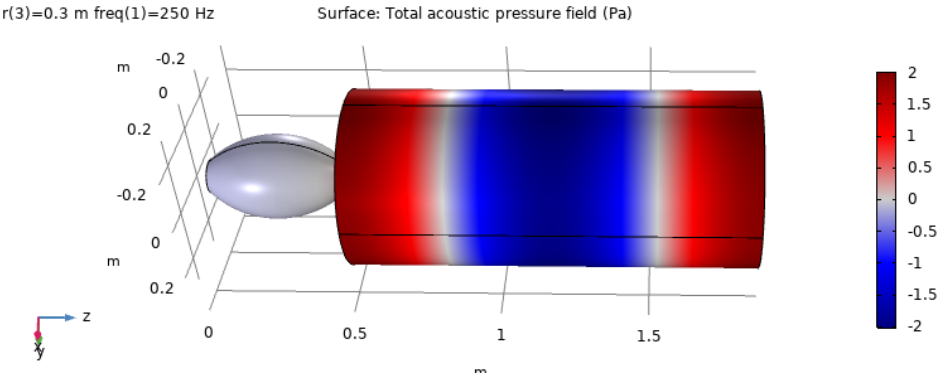


Figure B.2: Pressure field of the Phase 1 numerical simulations, r=0.3m, 250 Hz

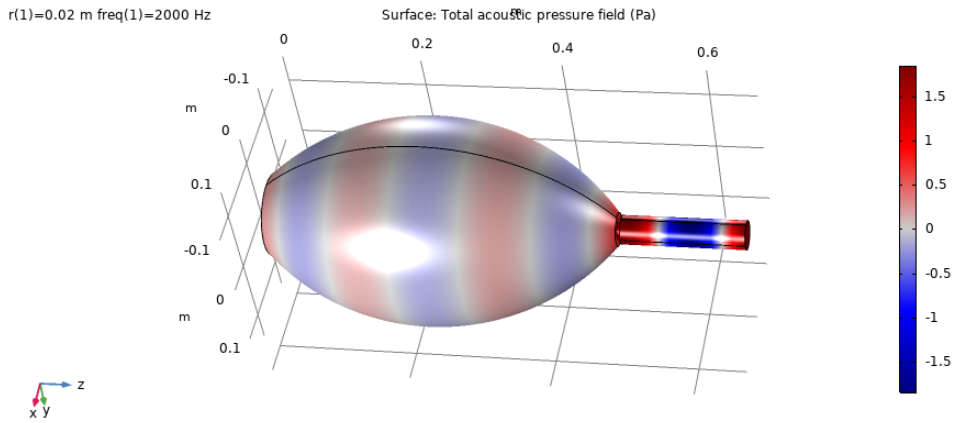


Figure B.3: Pressure field of the Phase 1 numerical simulations, r=0.02m, 2000 Hz

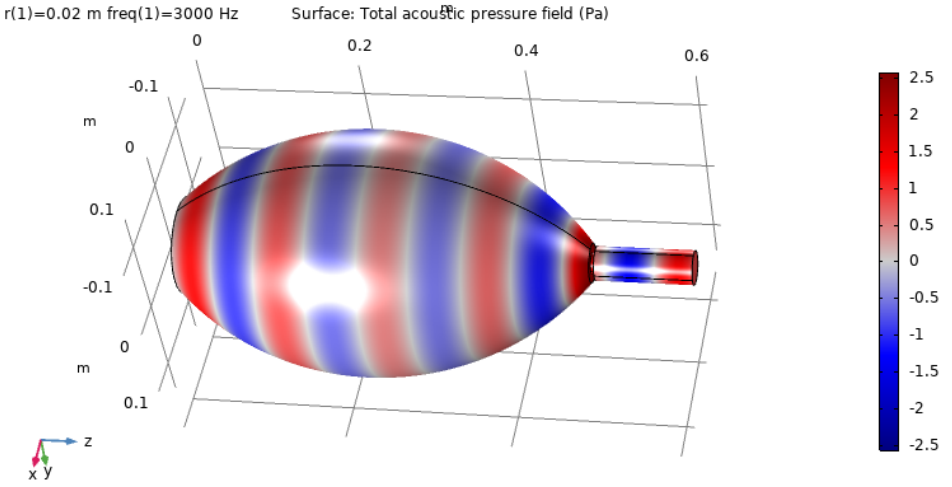


Figure B.4: Pressure field of the Phase 1 numerical simulations, r=0.02m, 3000 Hz

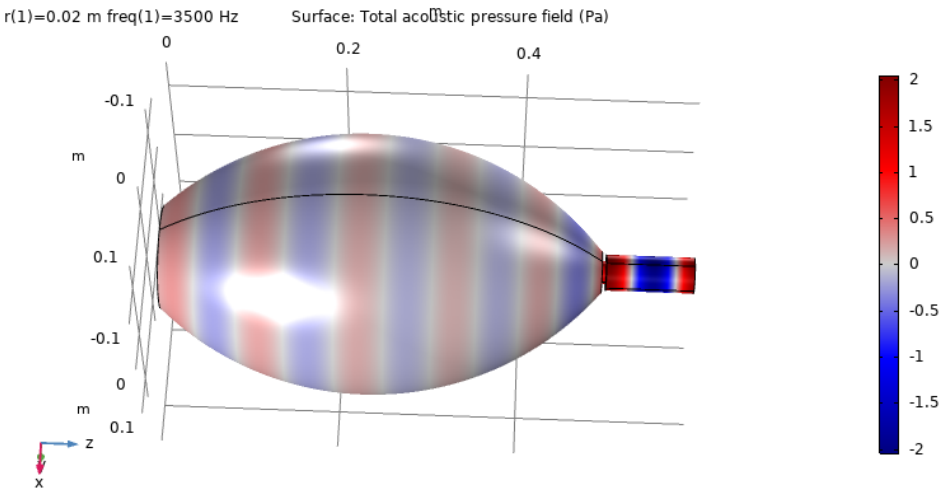


Figure B.5: Pressure field of the Phase 1 numerical simulations, r=0.02m, 3500 Hz

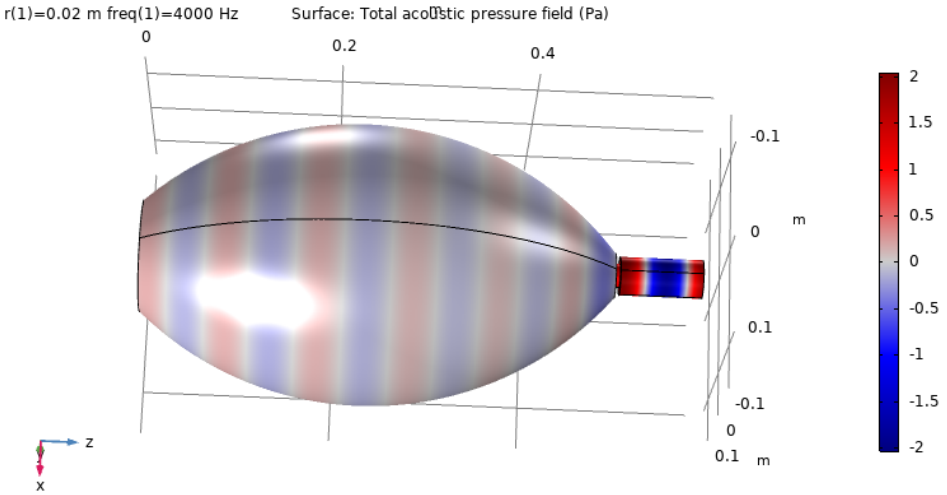


Figure B.6: Pressure field of the Phase 1 numerical simulations, r=0.02m, 4000 Hz

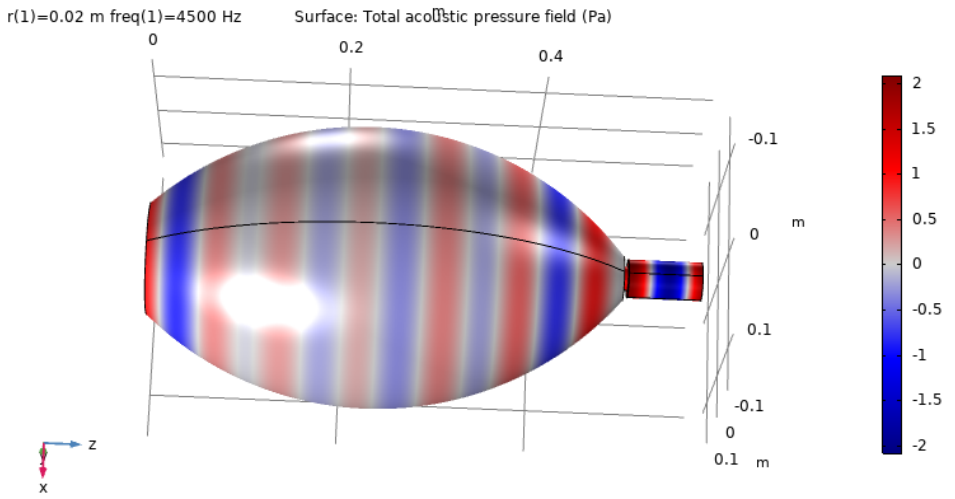


Figure B.7: Pressure field of the Phase 1 numerical simulations, r=0.02m, 4500 Hz

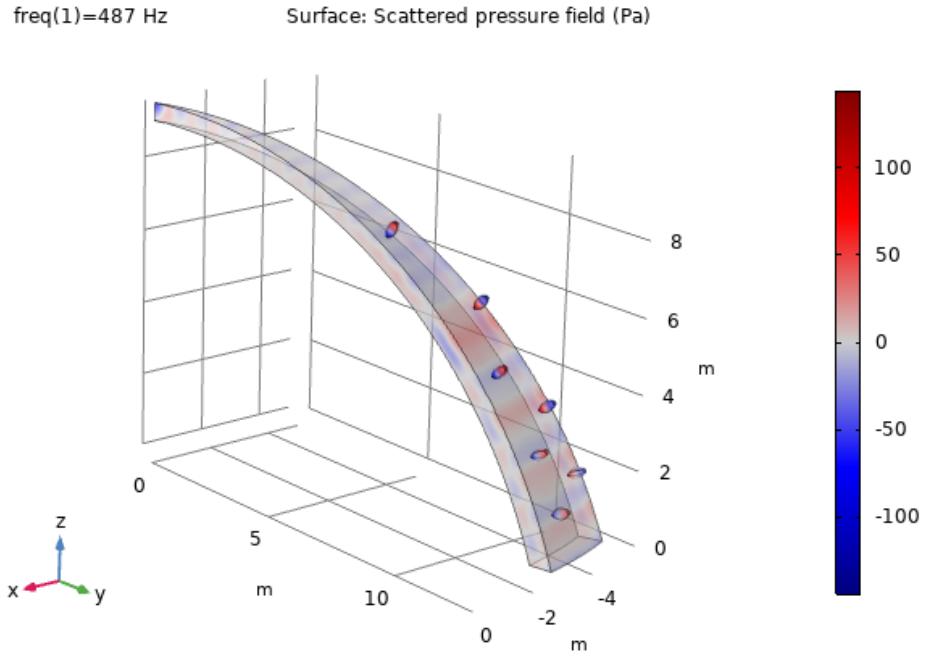


Figure B.8: Pressure field of the Phase 2 numerical simulations, 11.25 Degree Shell Model, 487 Hz

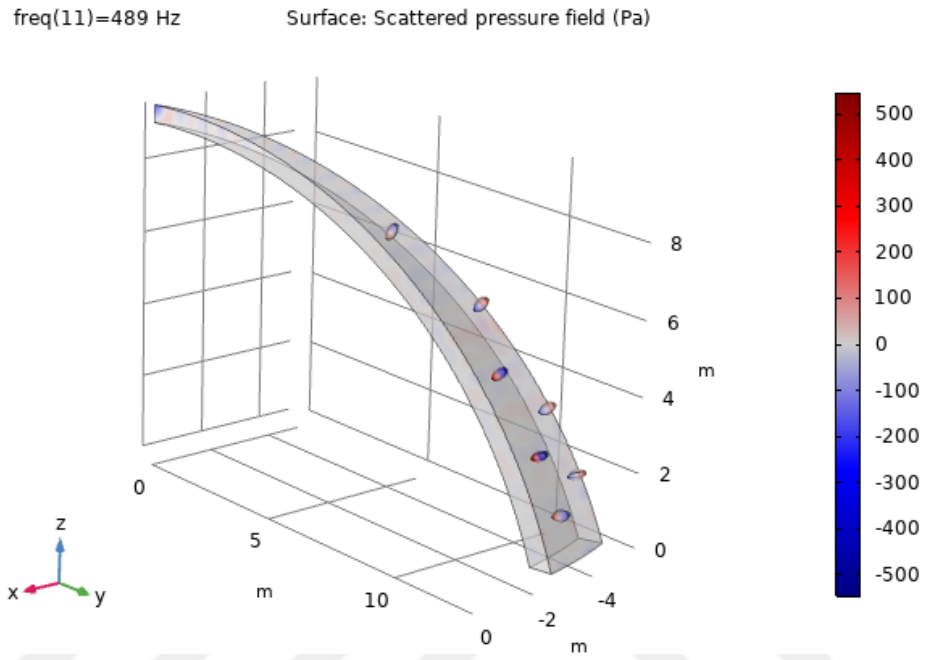


Figure B.9: Pressure field of the Phase 2 numerical simulations, 11.25 Degree Shell Model, 489 Hz

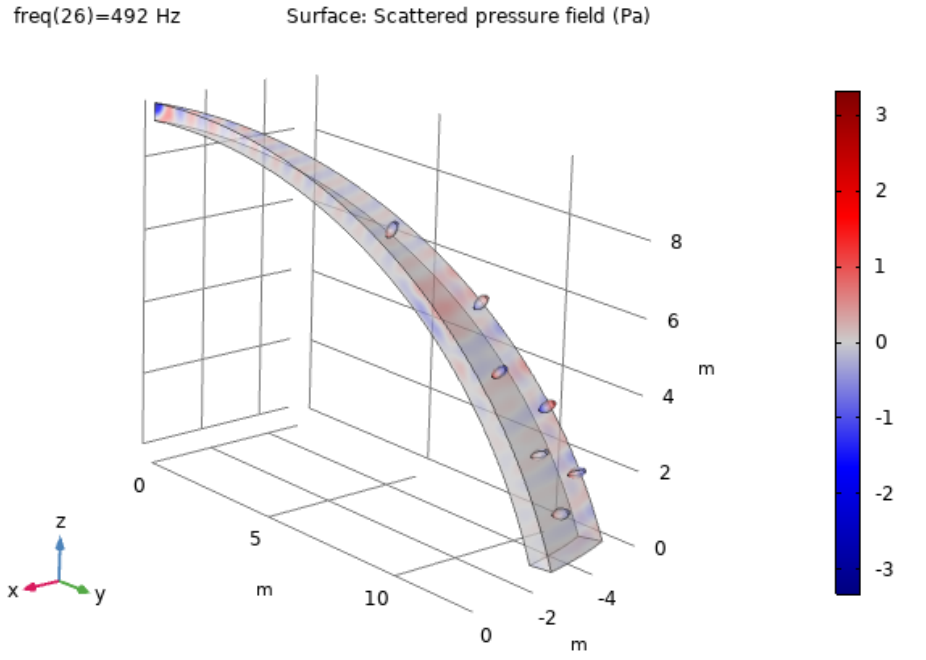


Figure B.10: Pressure field of the Phase 2 numerical simulations, 11.25 Degree Shell Model, 492 Hz

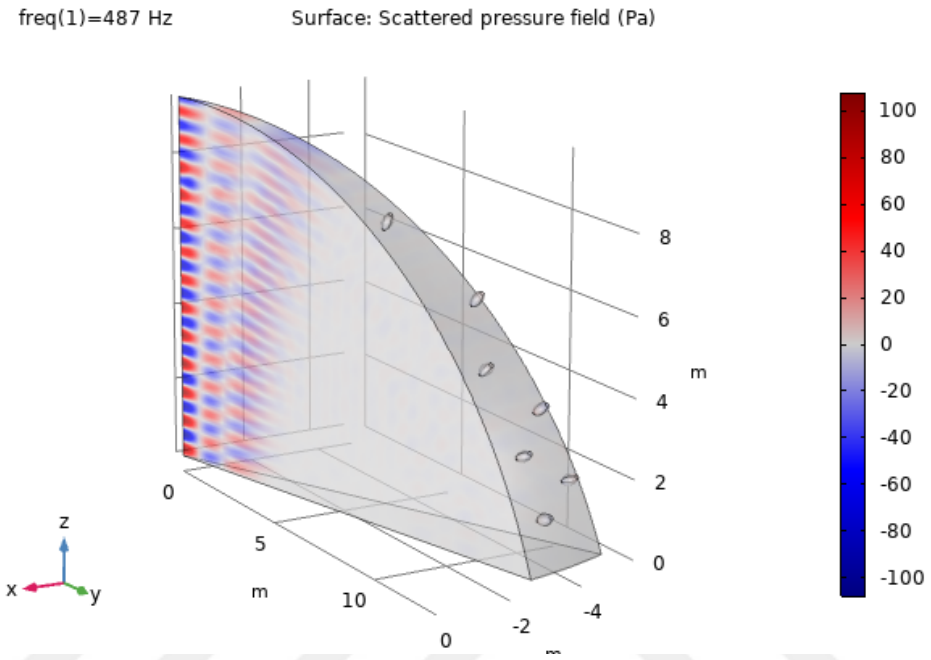


Figure B.11: Pressure field of the Phase 2 numerical simulations, 11.25 Degree Model, 487 Hz

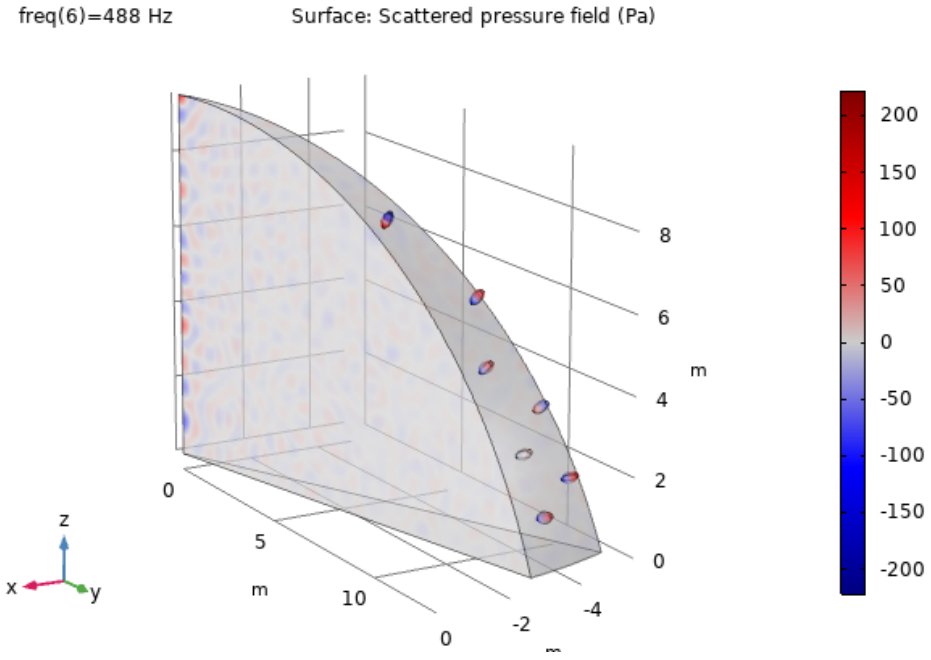


Figure B.12: Pressure field of the Phase 2 numerical simulations, 11.25 Degree Model, 488 Hz

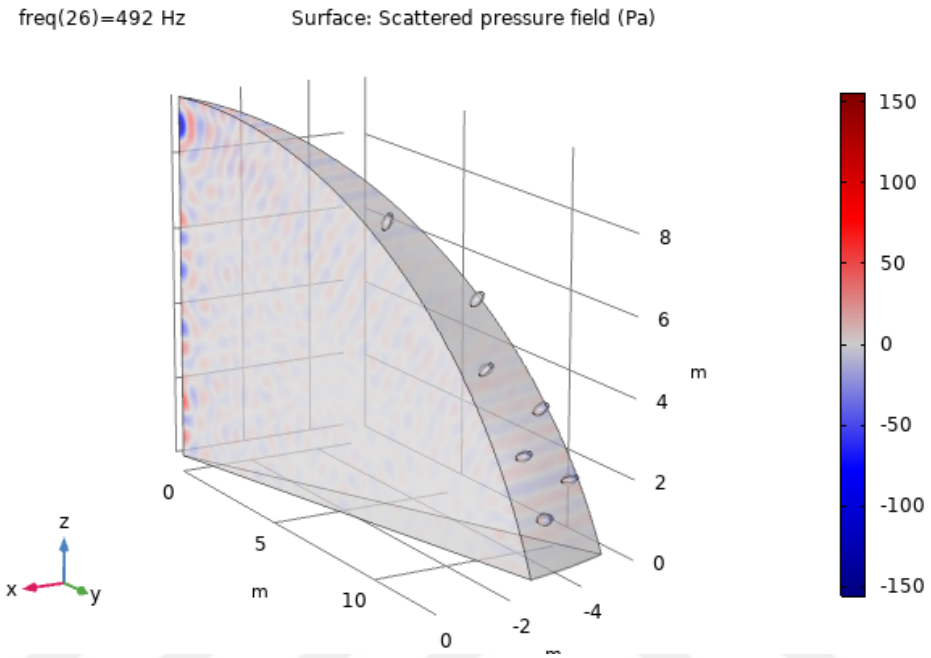


Figure B.13: Pressure field of the Phase 2 numerical simulations, 11.25 Degree Model, 492 Hz

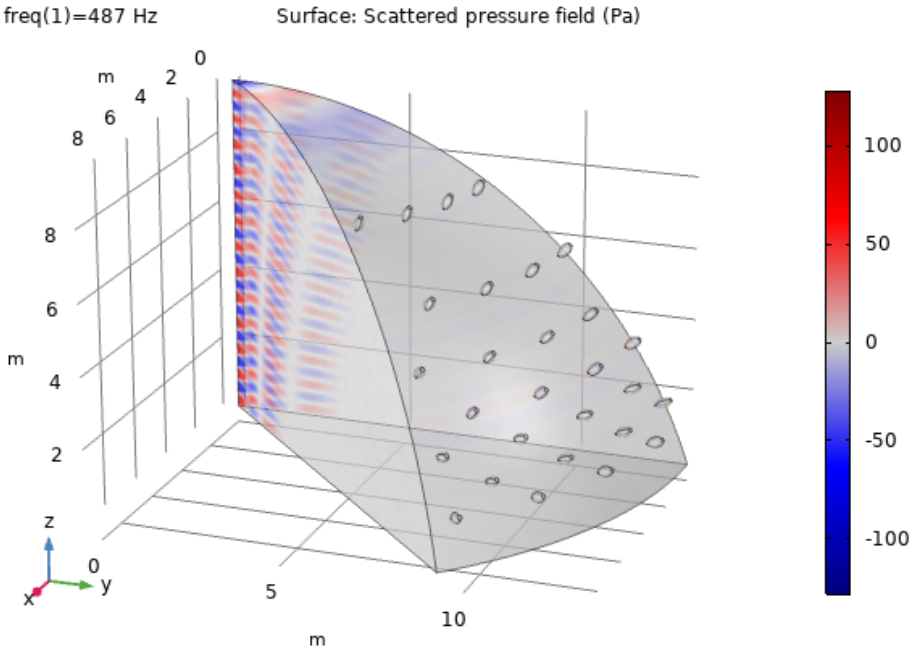


Figure B.14: Pressure field of the Phase 2 numerical simulations, 45 Degree Model, 487 Hz

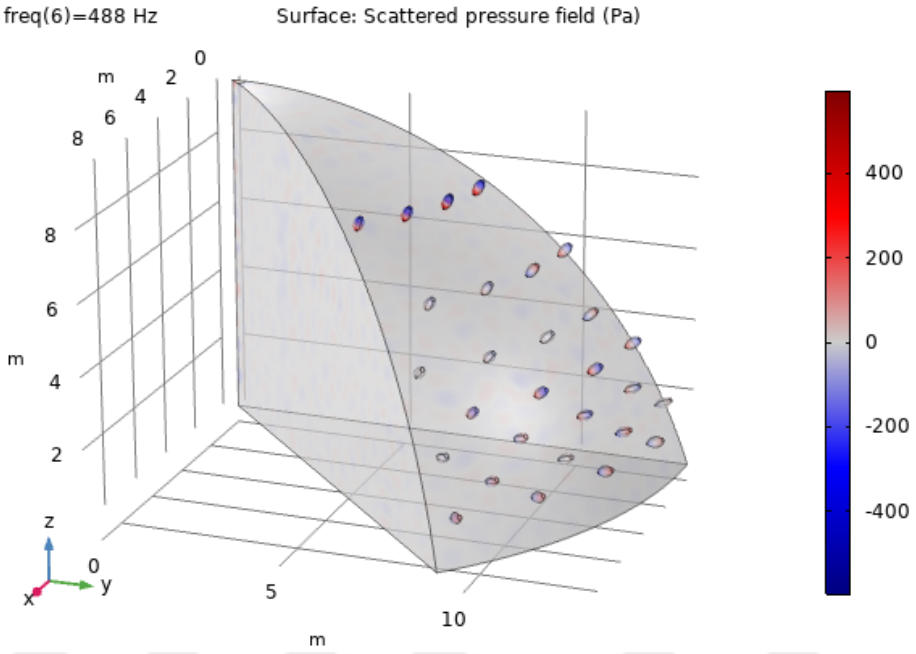


Figure B.15: Pressure field of the Phase 2 numerical simulations, 45 Degree Model, 488 Hz

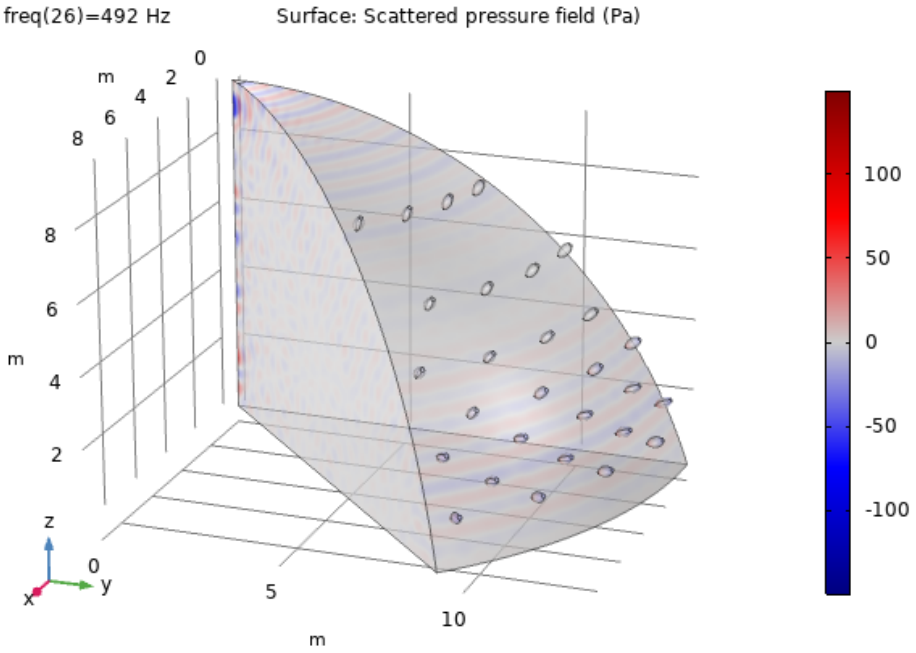


Figure B.16: Pressure field of the Phase 2 numerical simulations, 45 Degree Model, 492 Hz