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The acoustical characterization of clay pots in Ottoman architecture through experimental and numerical analysis

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ABSTRACT:

In medieval age, clay pots are utilized as multi-functional building elements serving not only for structural and ventilative purposes but also for the improvement of the acoustic qualities of the space. Although the medieval usage of acoustic pots is vaguely connected with the acoustic vessels of Vitruvius, their employment is also interpreted as cavity resonators as in the case of Süleymaniye Mosque. The 16th century edifice designed by Sinan the Architect Laureate is a significant example among its European counterparts with 224 clay pots embedded into its central dome. The present work aims to discuss the contribution of clay pots in acoustics of historical edifices focusing on Süleymaniye Mosque. In this study, a clay pot sample employed in the mosque is reproduced and impedance tube measurements are held. The results are then compared with finite element model simulations carried out to examine the effective frequency range of the clay pots. Finally, the data acquired from numerical simulations and the experimental measurements are applied in ray tracing simulations. The final results reinforce the contribution of clay pots on the improvement of sound energy decay rate measured after the final restorations within the mosque with repaired pots. © *2023 Acoustical Society of America*. https://doi.org/10.1121/10.0020731

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I. INTRODUCTION

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 1st 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 vessels called "echea" found in the ancient Greek theaters (Vitruvius, 1914). In his treatise, Vitruvius argues that the pots are utilized for the amplification of sound. Following the antiquity, the pots found in the medieval structures throughout Europe and Anatolia continued to be the objects of interest in terms of their true purpose (Valière *et al.*, 2013). The main arguments are centered on their employment as sound amplifiers, as Vitruvius once described, as well as cavity resonators. In Anatolia, employment of *sebu* (clay pot) as multi-purposed building elements was a widely used practice and at times, they are observed in the well-known works of Sinan the Architect Laureate of Ottoman Empire including Şehzade and Süleymaniye Mosques (Atay and Sü Gül, 2020). The clay pots found in the works of Sinan are often interpreted to be employed as Helmholtz resonators without sufficient scientific investigation. Therefore, the present study aims to assess the sound absorption performance of the 224 clay pots found in the grand dome of Süleymaniye Mosque, so as to understand whether they served as cavity resonators in the edifice.

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. Based on the available literature on their implementation in medieval structures, Arns and Crawford (1995) infer that the medieval motives behind their usage could be related to the adaptation of the sounding-vessel concept of Vitruvius and a symbolic implementation that is "representative of the belief in the role of musical tones in elevating the soul." On the other hand, although Valière and Palazzo-Bertholon (2017) acknowledge Vitruvius's influence on medieval practice, they indicate the lack of concrete evidence as to whether the medieval pots are modelled based on Vitruvius's description. Later in the 19th century, with the development of theoretical framework of Helmholtz resonance, pots' employment as cavity resonators, which control low frequency sound energy within the space, became one of the main arguments behind their usage. Nevertheless, the origins of such practice, the intentions of the builders for utilizing such devices, and pots' true effect on the acoustics of the space remain as the main questions.

Medieval structures containing clay pots throughout Europe and the pots' influence on the acoustics are examined through experimental and numerical investigations. A comprehensive study held in France (Valière *et al.*, 2013) investigated the number, size, placement, and the effective frequency range of clay pots found in medieval liturgical

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architecture mainly of France and surrounding countries. In this study, they investigate the connection of the pots to the sounding vessels of Vitruvius through available texts of the Antiquity and Medieval Age. The number, placement, and size of the acoustic pots found in Russia are reviewed by Kanev (2020). In this project, the effect of the pots placed in a 19th century structure, Rachmaninov Hall, is examined with *in situ* measurements with open and closed resonators. It is noted that no significant differences are identified in the room acoustics parameters. Works identifying the resonance frequency of such pots and their acoustic effects through experimental and numerical analysis are also present in Switzerland (Desernaulds *et al.*, 2001; Carvalho *et al.*, 2002), Greece (Zakinthinos and Skarlatos, 2017; Polychronopoulos *et al.*, 2013), and Serbia (Mijic and Sumarac-Pavlovic, 2004; Đorđević *et al.*, 2017). The laboratory measurements conducted by Carvalho *et al.* (2002) revealed that the amplification and absorption characteristics of the pots are very weak and their effect is only observed in the close vicinity of their aperture at the selective resonance frequencies. In another study, Zakinthinos and Skarlatos (2017) placed commercial bottles as identical resonators to an old Byzantine Church to conduct *in situ* measurements so as to study their effects on selected acoustic metrics. Their study shows that resonators perform as selective amplifiers in short distance and they also cause small attenuation in the resonance frequency and near a higher tone. Nevertheless, their effect is noted to be poor. In Serbia, laboratory experiments by Mijic and Sumarac-Pavlovic (2004) presented that the pots installed in Serbian churches are found to be ineffective due to their low resonance frequency in relation to the sonic ambience of the liturgical services held inside the structures. It is also noted that the contribution of the pots to the room acoustic parameters is not significant as the number of pots found in the structures is inadequate. Finally, it is indicated that their utilization in small churches does not provide much benefit for the acoustical control. The studies are in accord with the employment of clay pots transmitted in oral tradition without any acoustic knowledge. Nevertheless, the limited number of the pots found in European structures may hinder the examination of their 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 sound absorption performance of the clay pots.

The acoustical employment of pots in Anatolia is mainly observed in mosques. Although there are an abundant number of studies examining the soundscape of the Ottoman and contemporary era mosques (Karabiber, 2000; Sü and Yılmazer, 2008; Sü Gül and Çalışkan, 2013a,b; Sü Gül *et al.*, 2014, 2016, 2018; Sü Gül, 2019), none examine the contribution of the clay pottery to the sound field characteristics of the structures except one study (Kayılı, 1988). Kayılı suggests that the clay pots function as Helmholtz resonators controlling low frequency sound energy within the space. In this study, this hypothesis is aimed to be tested with impedance tube measurements, finite element modeling, and ray tracing simulations that reveal the sound absorption coefficient of the pots and their influence on the sound energy decay pattern of the Süleymaniye Mosque.

This paper is structured as follows: Sec. II describes the materials, architectural features, and the medieval soundscape of Süleymaniye Mosque. In Sec. III, the data collection techniques covering the theoretical calculations, impedance tube measurements, and numerical and ray tracing simulations are elaborated. In Sec. IV, the results are discussed, and finally, in Sec. V, the major conclusions are summarized.

II. SÜLEYMANİYE 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 is a popular subject of acoustical research with its vast acoustical volume of around 75 000 m^3 and multi-domed upper structure providing a multi-slope sound energy decay formation (Sü Gül *et al.*, 2016; 2018). The central dome with a diameter of 26.20 m and a height of 49.50 m sheltering the praying area rests on four colossal granite piers and is supported with two semi-domes placed along the North–South axis. The side aisles covered with five smaller domes on the East and West sides of the praying area complete the cascaded silhouette of the super structure. The circular rim of the central dome is connected to the square base through concave pendentive elements (Mungan, 2007; Kuban, 1987).

The acoustical design of Süleymaniye Mosque cannot be dissociated from the auditory aspects of the Muslim worship practices that mainly include the five-time prayers, sermons given by the preachers, and the recitation of the Qur-an. During the five-time prayers, the commands of the Imam are conveyed to the congregation by Müezzin from *müezzin mahfili* and sermons are preached from *minbar*, both of which require high intelligibility of sound. The endowment deeds that had been drafted by the command of Sultan Süleyman the Magnificent elucidate further knowledge regarding the 16th century soundscape of the edifice. According to the inventories, salaried worshippers employed in the complex were tasked with the recitation of selected suras and verses from the Qur-an chanted from the pulpit in between the canonical five-time prayers (Ergin, 2008).

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 (Barkan, 1972; Sü Gül, 2019). Not only the attentive use of materials but also the geometrical design of the mosque suggests acoustical design considerations. The fragmentation of large reflective surfaces with niches and decorative elements as well as the careful placement of sound scattering elements such as *kündekâri* (woodworks) and *muqarnases* made of gypsum help the even sound distribution within the space. The accounting registers of the construction of the mosque mentions the 255 clay pots ordered to be employed in the main dome. The registers that are compiled and translated by Barkan (1972) indicate that the pots are utilized for the acoustic reinforcement of the sound in the mosque. In the most recent restoration works dated 2011, the pots embedded into the brick structure of the main dome underwent a detailed investigation. In total, 224 pots are found to be scattered in seven horizontal rings all placed above the window rim level. Each ring contains 32 pots placed in a linear disposition with equal distances in between (Fig. 1). The highest elevation of the rings is at +45.90 m and it decreases down to the level of +39.74 m. The pots are placed radially in the central dome. Accordingly, the vertical axis of each pot is aligned with the central point of the main dome structure. They have a height of 50 cm and their widest diameter is measured to be 30 cm. Their apertures opening up to the main space are approximately 2.5–3 cm in diameter (Fig. 1). 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 the use of *sebu* for acoustical purposes. 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 from 4 to 6 cm on top of the brick structure (Olgun and Şengün, 2016). 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 (Olgun and Şengün, 2016). Such alterations are expected to have improved the acoustics of the structure to a certain extent. To understand the contribution of the clay pots to the acoustics of the space, experimental and numerical investigations elucidating the sound absorption performance of the clay pots employed in the central dome of the mosque are conducted.

III. METHODOLOGY

The methodology of the study includes the impedance tube measurements with a reproduction of the original-sized *sebu* (Atay and Sü Gül, 2021), analytical modeling of its Helmholtz resonance, and last numerical and ray tracing simulations. The sound absorption coefficients of the pots are acquired from impedance tube measurements and the results are verified with finite element model (FEM) simulations focusing on the Helmholtz resonance or fundamental frequencies and their harmonics. The resultant values are then inputted to the ray tracing simulations so as to understand the pots' precise contribution to the acoustics of the space based on the T_{30} parameter.

A. *Sebu* production and impedance tube measurements

Sebu sample utilized in the impedance tube measurements is produced as an original-sized replica with the dimensions provided by the restoration team [Fig. 2(a)]. The normal incidence sound absorption coefficients of the original-sized clay pots are first measured with an impedance tube setup. The results are obtained in accordance with the transfer function method based on the ISO 10534–2:1998 standard (ISO 10534–2, 1998). 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 (50–1000 Hz) are covered with the large tube that has a 100 mm interior diameter, and the higher frequencies (1000–5000 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, because the pot is larger than a regular sample and unable to fit inside the holder, coupling of the pot

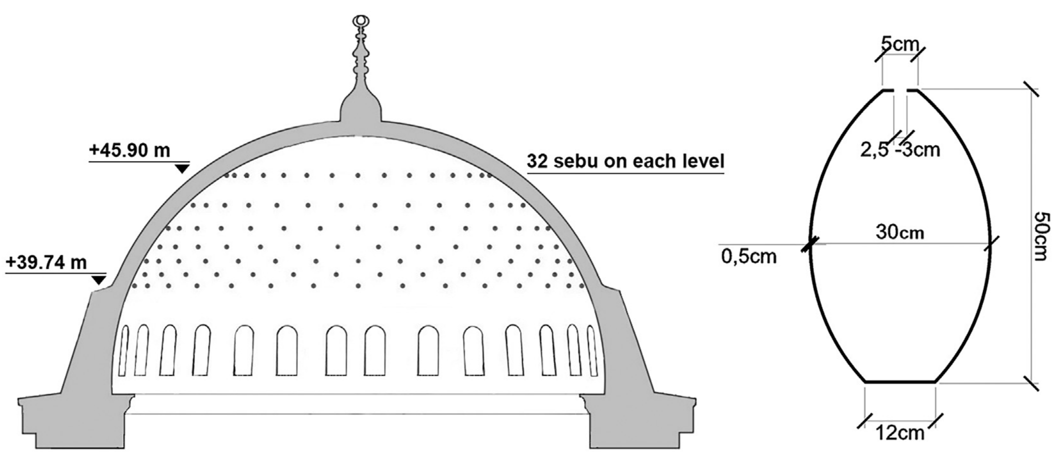

FIG. 1. (Left) Disposition of the clay pots in the central dome of Süleymaniye Mosque. (Right) Size of the original clay pot found in the dome structure. Adapted with permission from the documents provided by restorer Nilgün Olgun.

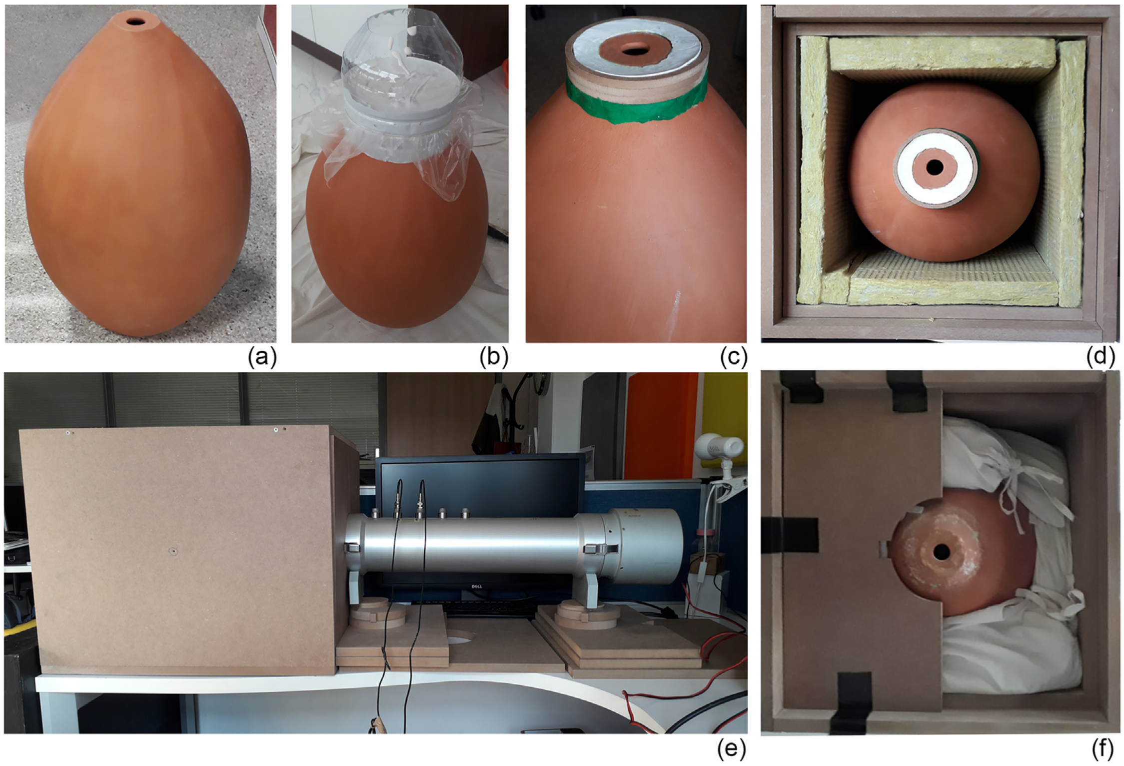

FIG. 2. (Color online) (a) Reproduction of the original clay pottery employed in the Süleymaniye Mosque by the authors. (b) Production of the plaster mold for the fitting piece. (c) Final fitting piece composed of MDF circles and the plaster. (d) Mineral wool as the infill material. (e) Impedance tube measurement experiment setup with large tube. (f) Sand as the infill material.

to the measurement chamber required the design of a custom fitting piece composed of MDF (medium density fiberboard) and a plaster model that enables a loss-free interlocking. The main plaster element of the fitting piece is produced based on a mock-up plaster mold of the aperture of the pot [Figs. 2(b) and 2(c)]. 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.

Three configurations with gradually improved backing support of the *sebu* are designed to perform the measurements with high accuracy in conditions 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 $40 \times 40 \times 51$ cm. The box is 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 [Figs. 2(d) and 2(f)]. The experiments are performed with a total of six setups composed of three backing configurations coupled with two impedance tubes of different sizes (Fig. 3). 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.

B. 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 as the precise measurement of its volume and modeling the accurate internal shape conditions of the neck is difficult. In a recent study, Valière and Prax investigate the internal corrections of Helmholtz resonators with the neck and improved the Helmholtz formula by developing a new semi-empirical model (Valière and Prax, 2021). Nevertheless, such expression cannot be utilized in the case of Süleymaniye as the clay pots employed in Süleymaniye Mosque are neckless resonators. Therefore, the well-known Helmholtz formula is utilized in this study. The volume used in this equation is obtained from the three-dimensional (3D) solid model generated based on the given dimensions supplied by the restoration team. The Helmholtz equation, formula for obtaining the resonance frequency of the Helmholtz resonators, is given below (Long, 2006). Based on this equation, the fundamental frequency of the clay pots employed in Süleymaniye Mosque is calculated as 52 Hz:

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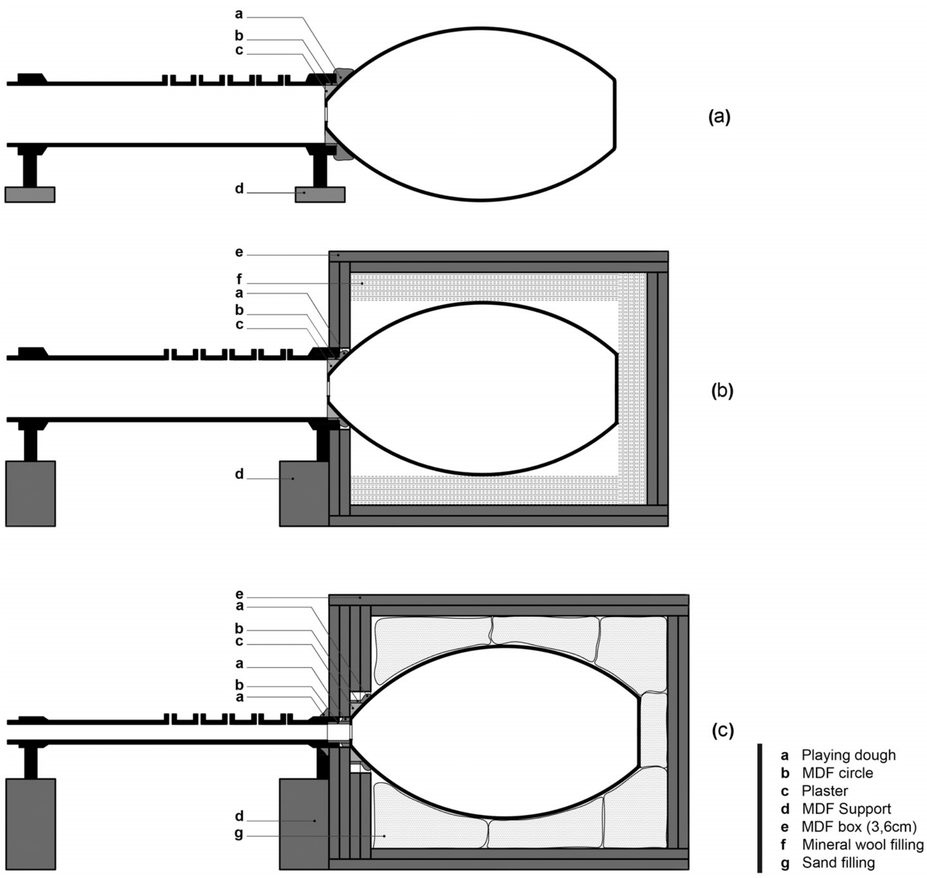

FIG. 3. Three different backing configurations coupled with small and larger impedance tubes.

$$f_n = \frac{c_0}{2\pi}\sqrt{\frac{\pi a^2}{V(l_0 + 1.7a)}}. \tag{1}$$

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

C. Finite element modeling for *sebu* absorption

Finite element simulations are done to verify the results obtained from the experimental measurements and the analytical model as presented in Secs. III A and III B. The FEM simulations are conducted with COMSOL Multiphysics. The 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 incident and absorbed energy. As presented in Fig. 4, the model of the first phase includes the internal air volume of the *sebu* and its neck, connected to an external cylindrical volume, from which the planar propagating sound waves are emitted from the inlet of its free surface. A non-reflecting condition is defined at the outlet of the tube domain.

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 radius (r) of the cylindrical domain through which the acoustic field is applied has an effect on the absorption coefficient obtained from simulations. Thus, this effect is investigated using a series of analysis in which the radius is varied from 0.02 to 0.30 m as presented in Table I. Additionally, such dimensional variations of the cylindrical domain made it possible to examine the effect of *sebu* spacing, or the characteristic length, on the absorption performance.

In both phases of the numerical simulations, the absorption coefficients are derived from the ratio of the absorbed energy to the incident sound energy [Eq. (2)]. The absorbed energy can readily be found by the difference between the incident energy and the reflected energy. The parameters used for the Phase 1 simulations are given on Table I,

$$\alpha = \frac{E_{incident} - E_{reflected}}{E_{incident}}. \tag{2}$$

In Phase 2 of the FEM analyses, the total absorption of the dome surface, including the embedded clay pots, is studied. 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. In Phase 2 of numerical analyses, the geometry of the dome and interactions between *sebus* are expected to affect the absorption performance. The domains modelled in the second phase involve the body of air inside the pots attached to the body of air inside the central dome. Similar to Phase 1, the domains

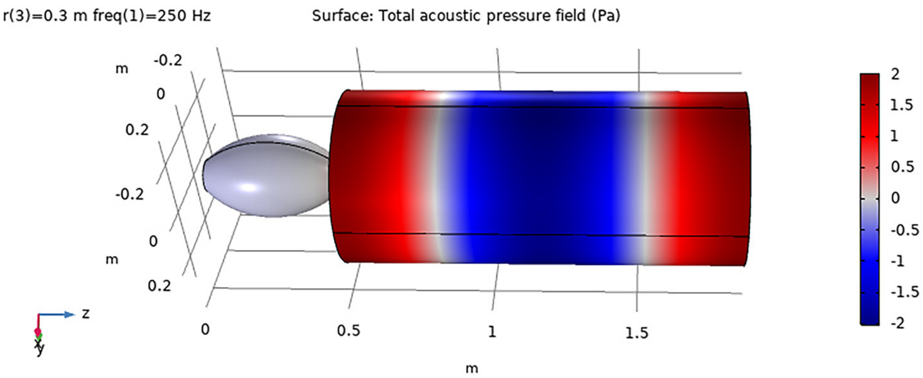

FIG. 4. (Color online) Acoustic pressure field map example from Phase 1 FEM simulations (250 Hz, 0.3 m radius of the cylindrical domain).

are bordered by sound hard boundaries. Because 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 to verify that the models are able to represent the whole structure. The slices are cut with two different angles (11.25° and 45°) from the dome structure with varying thicknesses of the air domain (Fig. 5). 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 frequency sweep step used in the Phase 2 analysis is narrowed down to 0.2 Hz in the vicinity of higher elastic modes of the cavity obtained from the Phase 1 of numerical simulations due to aforementioned reduction of computational cost. This narrow increment is selected as the Helmholtz resonance exhibit extremely narrow bandwidth. In both of the numerical simulations, including Phase 1 and Phase 2, the losses due to the viscous and thermal dissipation in the acoustic boundary layer fluid are defined to the neck volume of the clay pot model.

D. 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 of the interior volume of Süleymaniye Mosque. The restoration applications held in the dome structure may have helped many of the pottery regain their formal integrity and therefore functionalities. Hence, 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.

During its life-span, the structure went through several significant restoration works, followed by *in situ* acoustic measurements–some of which were held in 1996 by Middle East Technical University (Topaktaş, 2003), in 2000 under CAHRISMA project (CAHRISMA, 2000), and finally, in 2013 again by Middle East Technical University (Sü Gül *et al.*, 2014). In this study, 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 tests held in the edifice in 2013 after the restoration works completed in 2011 (Sü Gül *et al.*, 2014). The sound absorption values assigned to the surfaces are mostly referenced from an earlier study in accordance with the field test tuned acoustical models (Sü Gül, 2019). 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 effect on the interior sound field of the mosque by comparing reverberation times acquired from the simulations (Fig. 6).

The model employed in the ray tracing simulations does not include the clay pot volumes attached to the dome geometry. Rather, the difference between the two models is based on the changing absorption coefficients assigned to the dome surface with clay pots embedded in the dome. The absorption coefficients acquired from experimental measurements and the numerical simulations are applied to the

TABLE I. The changing dimensions of the tube domain coupled with the pot at the 1st Phase of the numeric modeling.

		Low frequencies		High frequencies					
		Step 1	Step 2	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
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 and 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 (m)	(λ_min/ 5)	0.27	0.05	0.03	0.02	0.02	0.02	0.02	0.01
Radius of the tube (r) (m)		0.10, 0.20, 0.30		0.02, 0.03, 0.05, 0.10					
Tube length (h)	h = λ_max (343/f_min) (m)	6.86	1.37	0.34	0.17	0.11	0.10	0.08	0.08

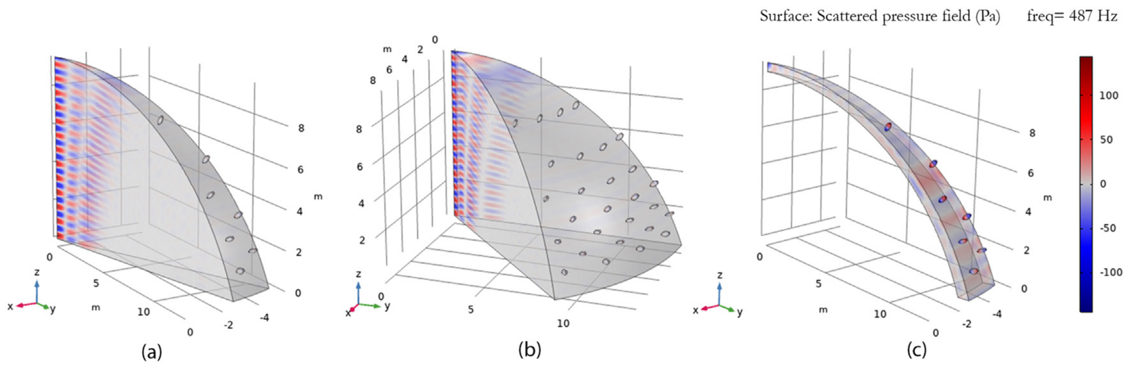

FIG. 5. (Color online) Acoustic pressure field map example from Phase 2 FEM simulations. (a) 11.25° dome model. (b) 45° dome model. (c) 11.25° dome shell model.

dome surface. As for the hypothetical scenario without the clay pots in the dome form, the sound absorption coefficient of the plaster (Sü Gül, 2019) is employed for the whole dome surface for the frequencies of interest (Table II).

IV. RESULTS AND DISCUSSION

A. Impedance tube measurements

In the first phase of the study, experimental measurement of the sound absorption coefficients of the clay pottery employed in the dome of Süleymaniye Mosque is held 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, clay pot placed in a MDF box filled with mineral wool. and sand-filled bags that are named as "a," "b," and "c," respectively. The results obtained from these three setups in 1/3 octave bands are shown in Fig. 7.

It is observed that the results obtained from the different backing supports exhibited an overall coherency. A notable sound absorption performance at 500 Hz is observed in all configurations. 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 configurations, however, is that clay pot in the configuration "a" exhibited relatively lower absorption performance in mid-range frequency when compared to clay pots placed in the configurations "b" and "c." The latter configurations 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.

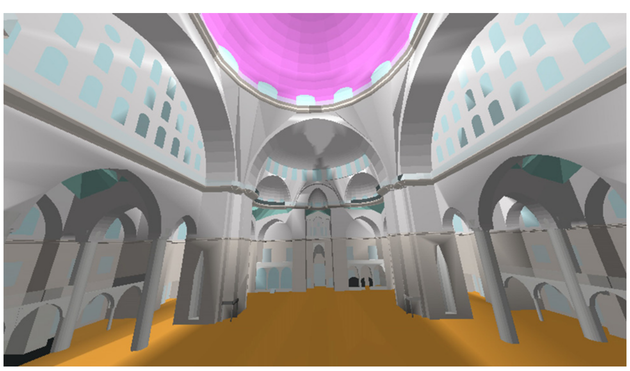

FIG. 6. (Color online) 3D OpenGl view of Süleymaniye Mosque in the case of clay pots employed in the dome surface. Odeon Room Acoustics Software 16.08 is utilized for the ray tracing simulations.

B. Finite element modeling for *sebu* absorption

The Helmholtz resonance of the pot calculated with the analytical model in Sec. III B is not observed in the initial impedance tube measurements of the study, probably since 52 Hz corresponds to the lower cutoff frequency limit of the impedance tube. The resonance at 52 Hz, however, is verified in the numerical simulation results.

Figure 8 presents the sound absorption coefficients of a single clay pot acquired from the Phase 1 of the numeric simulations. Changing radius (r) values of the cylindrical domain through which the acoustic field is applied are indicated in the legend of the figure. As observed in Fig. 8, three notable peaks are observed at the vicinity of 50, 488, and 816 Hz. The first peak at 488 Hz confirms the initial results obtained from the impedance tube measurements and many higher modes are also observed as expected (Fig. 9).

Analyses of the first mode and the other detected eigenmodes of the clay pots are shown in Fig. 10. While calculating the eigenvalues with FEM, the complete analysis model is used to have consistency with the sound absorption results since the region above the neck modifies the boundary condition for the eigenvalue analysis. Therefore, the cylindrical domain attached to the aperture of the pot is kept present in eigenmode analysis. As represented in Fig. 10, the modes occurred at the fundamental frequency and the first mode of the clay pot [Figs. 10(a) and 10(b)] that the examinations are based upon are axial modes. On the other hand, the mode shapes at the higher frequencies

TABLE II. The sound absorption coefficients of the materials employed in ray tracing simulations.

	Sound absorption coefficients over 1/1 octave bands						
Materials	125	250	500	1000	2000	4000	Scattering coefficients
Stone surfaces	0.05	0.05	0.06	0.09	0.11	0.11	0.20
Carpet	0.02	0.12	0.23	0.38	0.55	0.58	0.10
Plastered surfaces (current plaster) and dome without the clay pots	0.13	0.09	0.06	0.02	0.03	0.04	0.10
Dome with clay pots	0.13	0.09	0.87; 0.24[a]	0.02	0.03	0.04	0.30
Glass surfaces	0.18	0.06	0.04	0.03	0.02	0.02	0.05
Marble surfaces	0.01	0.01	0.01	0.01	0.02	0.02	0.05
Wood surfaces	0.10	0.07	0.05	0.04	0.04	0.04	0.10
Gypsum decorations	0.29	0.10	0.05	0.04	0.07	0.09	0.50
Copper decorations	0.12	0.08	0.02	0.01	0.01	0.01	0.50

[a]Absorption coefficient at the effective frequency of the pot is obtained both from Phase 2 numerical simulations and the impedance tube measurement results.

[Fig. 10(c)] are observed as tangential modes in the pressure maps.

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. In Phase 2 of numerical simulations, a narrow step sized sweep is also held at the vicinity of the observed peaks of 488 and 816 Hz. The latter examination at the 816 Hz is only acquired from the shell model due to the higher computing power required for the other models.

An overall comparison of the numerical analysis and experimental measurements is given in Fig. 11. As seen in the results of the impedance tube measurements and following numerical analysis, peaks occur at 488 and 819 Hz.

An important result of the examinations is that the effective frequency range of the clay pots is 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 cylindrical domain is varied to ensure that at least one full wavelength is present during the study (Table I). In these setups, the sound absorption coefficient of the pot at the related frequency ranges varies, but the effective frequency ranges of clay pots remain the same.

C. Ray tracing simulations

The numerical simulations are followed by the ray tracing simulations in which T_{30} values with and without the pots embedded in the dome are examined. The comparison basis on the 500 Hz octave band as the first elastic mode of the pot is revealed to be around 500 Hz, both in the impedance tube measurements and the FEM simulations. Nevertheless, according to the numerical simulations, the high sound absorption performance of the pots is only observed in a narrow frequency band. Owing to the limitations on averaging the sound absorption values in FEM model, two different sound absorption coefficients at 1/1 octave 500 Hz central frequency band are employed in ray tracing simulations. These values are obtained from Phase 2 numerical simulations and the impedance tube

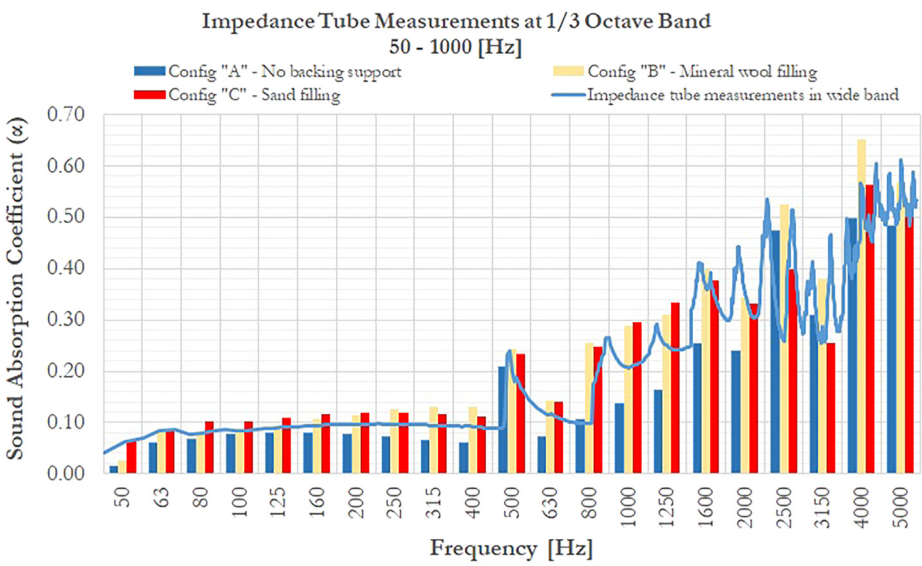

FIG. 7. (Color online) Sound absorption coefficients measured with the impedance tube at 1/3 octave bands and impedance tube measurement results plotted for individual frequencies from 50 to 5000 Hz.

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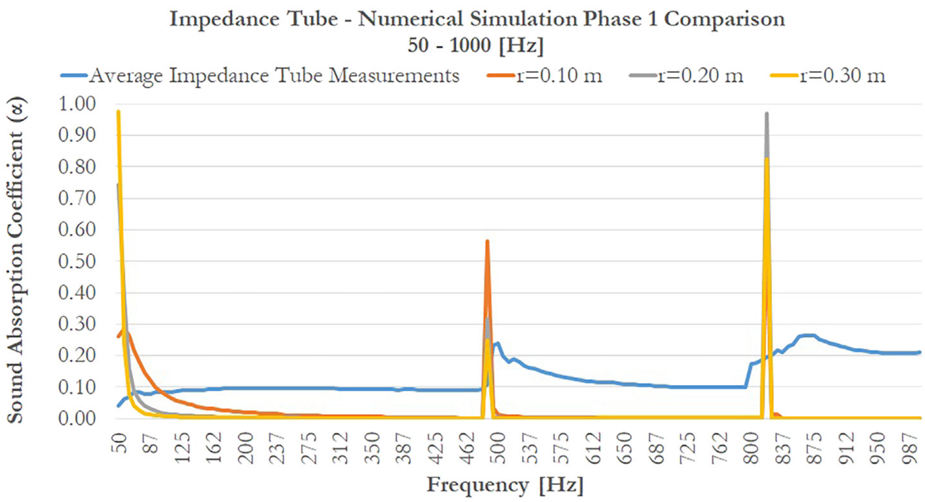

FIG. 8. (Color online) Sound absorption coefficients simulated in Phase 1 numerical analysis and comparison with the impedance tube measurement results at 50–1000 Hz.

measurements. The purpose behind such application is to compare the sound absorption performance of the pots with their peak sound absorption coefficient that is effective only at a narrow frequency band and with a rather averaged value of a wider bandwidth that is closer to its actual performance in the edifice.

First, sound absorption value obtained at 488 Hz from 11.25° models of Phase 2 numerical simulations (Table III) is employed as the absorption coefficient at 500 Hz central frequency band for ray tracing simulations in which the acoustic model with the clay pots is aimed to be virtually reconstructed. It is observed that the increased sound absorption area provided with the clay pots in the dome surface bring 2 s drop in T_{30} value at 488 Hz. The T_{30} analysis conducted with ray tracing simulations requires alpha values at 1/1 octave bands for the assigned materials. Therefore, it should be kept in mind that the sound absorption performance of the clay pots is obtained in a finer sweep, meaning that the 2 s decrease in T_{30} value is only localized at the vicinity of 488 Hz. In the second ray tracing simulation, sound absorption coefficient of the dome surface containing pots is derived from the experimental measurement results provided in Fig. 8. "Configuration c" of the impedance tube measurements is utilized in ray tracing simulations. In a wider bandwidth, the pots contribute to an approximately 0.7 s decrease in T_{30} value (Fig. 12).

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 IV, T_{30} values recorded in different field measurements exhibiting the acoustical states of Süleymaniye before and after the restoration works are provided.

The results reveal the positive effect of the recent restoration works especially at the 500 Hz octave frequency band. In an earlier study (Sü Gül, 2019), the 2 s drop in the

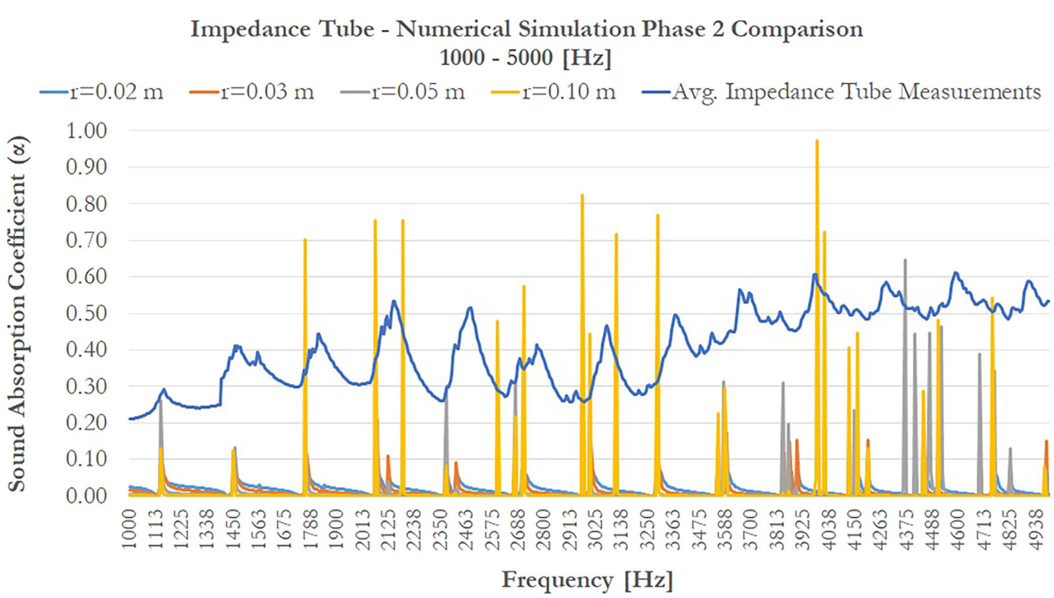

FIG. 9. (Color online) Sound absorption coefficients simulated in Phase 2 numerical analysis and comparison with the impedance tube measurement results at 1000–5000 Hz.

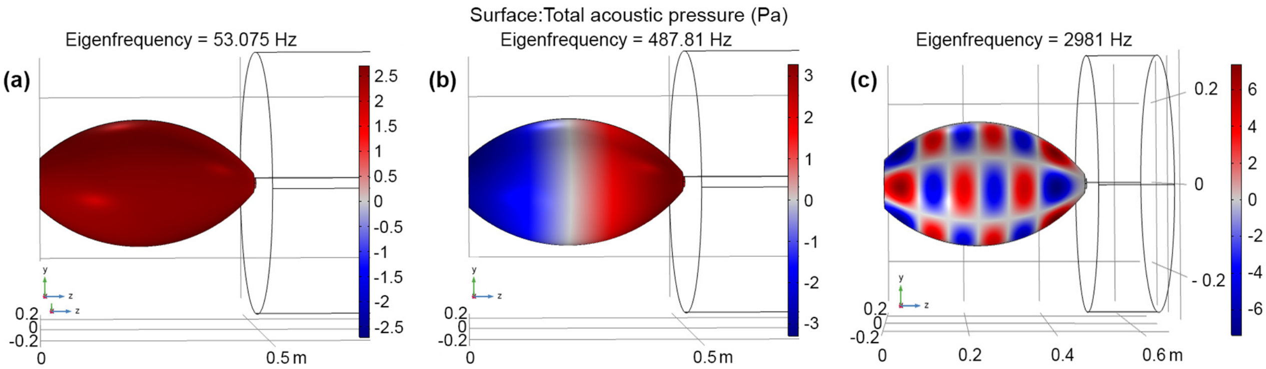

FIG. 10. (Color online) Eigenfrequency analysis of the simulated resonance peaks.

relevant octave band is linked to the replacement of cement-based plasters with the historically compatible Horasan plaster. In the light of the present knowledge, employment of the pots might also have an effect on the sound energy decay pattern at the 500 Hz central frequency octave band in addition to the renovated plaster. 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 may provide benefit for the acoustical control in the space especially at a narrow bandwidth. Therefore, the results support the long-standing acoustical myth behind the pots of Süleymaniye Mosque. In addition to their sound absorption performance, their placement in the large concave surface of the grand 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 led to low intelligibility. Asymmetry and irregularity created with the substantial number of pots in the large concave surfaces of the dome are likely to aid the scattering of sound. This helps to provide a diffuse sound field by enlarging the dome's reflection zone (Sü Gül and Çalışkan, 2014). 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 sound content in historic structures if pots of changing volumes are equally distributed over the related octave band. Nevertheless, in the light of the current resources and present empirical data on the matter, the authentic intent of Sinan the Architect Laureate behind placing these pots remains unknown.

V. CONCLUSION

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

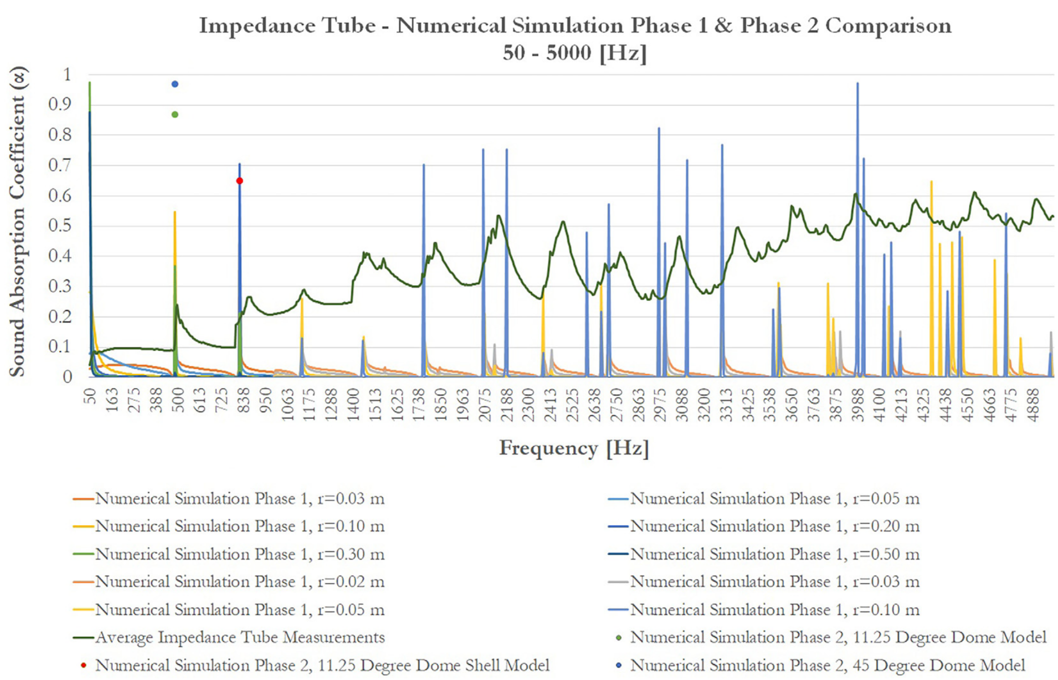

FIG. 11. (Color online) Sound absorption coefficients acquired from the numerical analyses and an overall comparison with the impedance tube measurement results at 50–5000 Hz.

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TABLE III. Sound absorption coefficients acquired from the Phase 2 numerical analysis of dome models for detected frequency bands.

11.25° model		11.25° shell model		45° model	
Frequency band	α	Frequency band	α	Frequency band	α
487.8–491.0	0.87	487.2–491.0	0.87	487.8–491.0	0.97
—	—	816.2–819.2	0.86	—	—

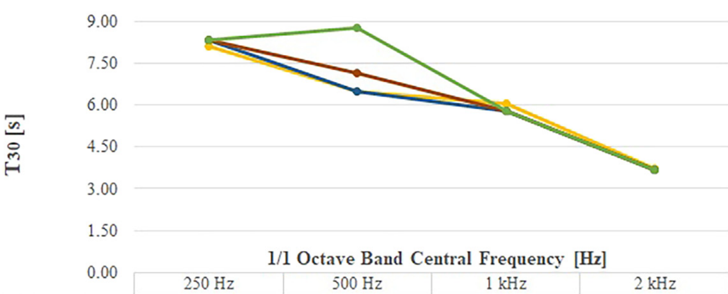
TABLE IV. Reverberation times at 1/1 octave bands from previously published field measurements held in Süleymaniye Mosque.

Field measurements	250 Hz	500 Hz	1 kHz	2 kHz
METU–1996 (Topaktaş, 1996)	8.79 s	**8.44 s**	6.15 s	4.35 s
Mean values of DTU and UNIFE measurements (CAHRISMA, 2000)	8.35 s	**8.60 s**	6.25 s	3.85 s
Restoration Works, 2007–2011				
METU–2013 (Sü Gül *et al.*, 2014)	8.15 s	**6.50 s**	6.04 s	3.73 s

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 embedded in the dome structure of the edifice are investigated to understand their contribution to the characteristic acoustics of the space. Analytical, experimental, and numerical investigations are utilized in sequence for an in-depth analysis of the clay pot applications on the authentic acoustic features of historic structures. The main outcomes of the study are as follows:

- The initial analytical assessment indicates that the Helmholtz resonance of the clay pots (all having same dimension) employed in Süleymaniye Mosque is 52 Hz. The analytical analysis is followed by numerical modelings which verify the resonance frequency of 52 Hz of the clay pots.
- The pots have an effective absorption at the vicinity of 488 and 819 Hz. These elastic modes of the pots are both observed in the impedance tube measurements held with an original-sized sample clay pot and the numerical simulations which are comprised of two phases. The first phase includes the analysis of a single pot whilst in the following phase, the total effect of 224 pots over the whole dome is analyzed. The second phase of the numerical simulations, which cover the cumulative effect of the 224 pots embedded in the dome surface, further supports and strengthens the experimental measurements.
- The sound absorption coefficients obtained from the Phase 2 of the numerical model, as well as the impedance tube measurements, are applied in ray tracing simulations to study the effect of the pots on the sound energy decay pattern specifically around 500 Hz in the edifice. The *sebus*' sound absorption performance is studied at the close vicinity of their resonance frequency and at a wider bandwidth. The ray tracing simulations exhibit that the pots reduce the reverberation time (T_{30}) about 2 s in a narrow bandwidth at the close vicinity of 488 Hz, whilst they reduce T_{30} values approximately 0.7 s in a wider bandwidth (1/1 octave). The latter result exhibits a more realistic scenario considering that the actual Q-factor of the pots would be smaller, the peak would be less, and the bandwidth would be wider. This decrease at 500 Hz also supports the improvement in the results of the *in situ* measurements held in the edifice after the final restoration works dated 2011 in which the clay pots got repaired.
- According to the literature review, the clay pots embedded in the dome structure help lessen the dead weight of the dome. In addition to that historical information, current study supports the general belief of the clay pots utilization for tuning the acoustics of historical mosques, even if not for the full frequency spectrum.

The employment of clay pots for the acoustical correction of the space is a passed down tradition that has its roots reaching far back into the antiquity. Pots with changing quantity, size, and placement are spread in different pieces of architectural heritage in a wide geography from Europe to Asia. Such versatility reveals the evolution of the practice during its transfer through different cultural backgrounds. Changing sizes, number, and form of the clay pot applications observed in different areas of the world may be due to the distinctions between the Islamic and Christian liturgical services, different pottery practices, as well as the transformation of the practice during its geographical transmission. The sounding vessels of Vitruvius and its so-called continuation in medieval architecture still



	250 Hz	500 Hz	1 kHz	2 kHz
Field Test After Restoration (Sü Gül et al., 2014)	8.15	6.50	6.04	3.73
Simulation with the pots	8.36	6.50	5.80	3.69
Simulation without the pots (impedance tube measurements)	8.36	7.16	5.80	3.69
Simulation without the pots (numeric simulations)	8.36	8.78	5.80	3.69

FIG. 12. (Color online) Comparative T_{30} simulation results with and without the employment of clay pots in the edifice, alpha value of the dome surface is obtained from Phase 2 of FEM simulations, and impedance tube measurements.

remains to be an object of interest for the researchers. Their application in different structures built in the same period and their effect on the acoustics of the space remains to be answered as the subject of future studies.

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