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FEM for the Acoustic Modeling of Eigenmodes: Case of the Cultural Heritage Monument of Neoria, Crete

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ABSTRACT

Eigenfrequencies inside a space significantly affect its acoustic characteristics, especially below the Schroeder frequency in the low-frequency range. In Architectural Acoustics, accurate detection and visualization of eigenmodes can be particularly useful in practical applications. One of the most important landmarks in Chania, Greece, is Neoria, a cluster of 16th-century Venetian shipyards. One existing Neoria will be converted and used as a multipurpose hall. For this objective, acoustic modeling and various measurements were performed in the space. One of the purposes of the measures and modeling was the investigation of the eigenfrequencies and the eigenmodes of the area. Finite Element Method (FEM) was used for the acoustic modeling, while the acoustic measurements were performed in various positions according to ISO 3382-1. Impulse responses were measured, and frequency responses of the space were extracted using Fourier analysis. The measurements and the acoustic modeling results show that the frequencies with the most significant effect on the area are 86.1 Hz, 150.7 Hz, and 204.6 Hz. Eigenmodes of the frequencies are visualized with the application of FEM and especially the positions of nodes and antinodes, which can be utilized appropriately for the optimum placement of absorbers and diffusers in the space.

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1. Introduction

Proper acoustics is important for a variety of reasons [1]. Acoustic interventions are becoming more common in cultural heritage monuments [2, 3]. In addition, Archaeoacoustic studies examine the acoustics of various cultural heritage spaces [4], while studies assess and recover the acoustics of even extinct major religious heritage spaces [5, 6].

However, renovating cultural heritage sites can be challenging from an acoustic standpoint. Numerical methods are usually employed, with the most common ray tracing [7]. The ray tracing method is a simple implementation of the geometrical room acoustics approach by tracing energy rays around acoustic space [8, 9]. Although easy to program, it has difficulties in the acoustic modeling of a room in the low-frequency area since wave-based considerations are required below the Schroeder Frequency [10]. The finite-difference time-domain (FDTD) method [11] is another method of computing the acoustics of a space. The explicit formulation makes the computation efficient, and the computational effort increases linearly about the number of discretization cells. However, in many cases, the architectural space boundary shape is simulated by a staircase approximation, which is a disadvantage of the FDTD method because a room's shape is an important factor in determining acoustic behavior.

Recent years have witnessed the widespread application of FEM to solve the wave equation in acoustics. The method can be applied in architectural and environmental acoustics [12, 13]. FEM can be used in the frequency domain for Eigen frequency analysis [14] and in the time domain for calculating the impulse response of space [15-17]. However, these approaches usually entail considerable computational costs for analyzing sound fields in architectural space with practical dimensions and useful frequency ranges. In recent years the emergence of low-cost, high-speed computers has made those approaches accessible. With the rapid progress of computer technology, FEM is becoming even more applicable for conducting acoustical investigations and carrying out design processes.

Neoria is one of Crete, Greece's most important cultural heritage monuments. Neoria monument is situated in a central location in the old port of Chania and consists of seven buildings. The memorial was built in the 16th century when the fleet of the Venetians ruled in the Mediterranean. Neoria in Greek (Νεώρια) means shipyards for warships (while Neorio is a single shipyard). Neoria is a large stone structure made mainly from sandstone with an arched facade, approximately 45-50 meters long, 9 meters wide, and 10 meters high.

The present study is part of the renovation works for the monument of Neoria in the city of Chania (Fig. **1**). One of the Neoria (from the cluster of seven) will be converted and used as a multipurpose hall. Various acoustic

Figure 1: Monument of Neoria, Chania, Crete.

measurements were performed for renovation, and acoustic models were created. Eigen frequencies (or resonant frequencies) inside a space significantly affect its acoustic characteristics and the reproduction of music, significantly below the Schroeder frequency in the low-frequency range. Detection and visualization of Eigen modes are particularly important, as acoustic treatments such as acoustic diffusers and absorbers can be applied appropriately inside space to minimize their negative effect. For this study, acoustic measurements of Eigen frequencies (resonant frequencies) and acoustic modeling of Eigen modes using FEM were performed.

2. Methods

The methodology applied in this study can be divided into two parts. The first part consists of the relevant acoustic measurements applied to the monument of 'Neoria' and the second part of the acoustic modeling of the space. These are presented separately below.

2.1. Acoustic Measurements

Acoustic measurements were performed according to ISO 3382-1 [18]. The impulse responses at various points were measured as depicted in Fig. (**2**). An omnidirectional dodecahedral loudspeaker (Type DO12; 01 dB-Stell) was placed at the height of 1.5 m for the measurements. In general, an omnidirectional source is necessary for such measures [19]. However other sources could be utilized [20, 21].

For the measurements with the dodecahedron speaker, the ESS signal was used [22]. The sampling frequency of the measure was 44.1 kHz. The excitation signal was preferred because of the low background noise [23, 24]. A microphone (Type 4190; Earthworks) was placed 1.2 m above the floor for each measurement. An appropriate sequence length and time constant for the ESS signal were chosen according to the expected reverberation time. Three iterations were performed for each of the measurement points. Averaging was used for a better signal-to-noise ratio and to reduce the temperature fluctuation effect. The variations of temperature and hence the sound velocity with time and position must be considered. Still, the effects which are caused by these in-homogeneities can be deemed to be small. An example of an impulse response to the space obtained is depicted in Fig. (**3**).

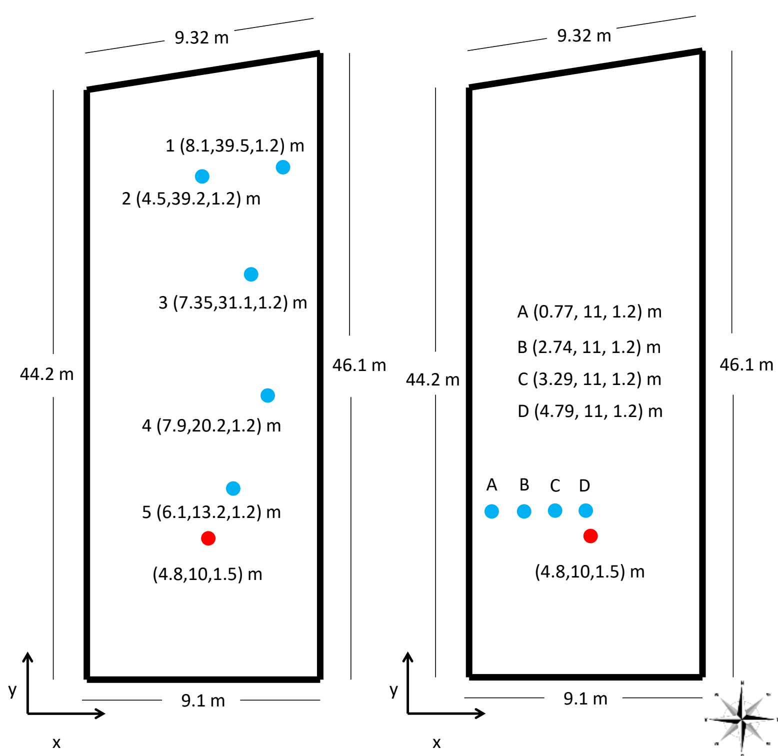

Figure 2: Measurement positions (Red, source, and Blue, receiver positions).

Regarding the positions of the measurements, the selection was made according to ISO 3382-1. Measurements were also performed in positions perpendicular to the parallel walls to detect the existence of specific resonant frequencies in all measurements. The purpose was to detect the most dominant resonant frequencies in future listener positions.

2.2. FEM Modeling

For this study, the FEM was applied in the frequency domain to detect eigenfrequencies and visualize eigenmodes. The software Comsol Multiphysics v.6.0. (Comsol inc., Burlington, USA) was utilized for the models. The method can also be applied in the time domain to calculate the acoustic parameters of space [25]. For the FEM modeling, the Galerkin method was employed, and the Multifrontal Massively Parallel Sparse (MUMPS) direct solver was utilized [26]. The rule of thumb λ/h=5 was applied for mesh creation, where λ and h denote the wavelength of the upper limit frequency and the maximum nodal distance. A model of the mesh for Noeria is presented in Fig. (**4**) and consists of 5113566 domain elements, 78132 boundary elements, and 3203 edge elements. Number of degrees of freedom solved for is 6888325. For mesh creation, a different approach should be considered if the method is applied in the time domain [27]. FEM was used to model the inhomogeneous Helmholtz equation.

$$\nabla\left(-\frac{1}{\rho_c}\nabla p\right)-\frac{k^2 p}{\rho_c}=Q_m \tag{1}$$

The Inhomogeneous Helmholtz equation is obtained from the inhomogeneous wave equation if we assume a time-harmonic wave, for which the pressure varies with time as:

$$p(\boldsymbol{x},t)=p(\boldsymbol{x})e^{i\omega t} \tag{2}$$

A monopole sound source was applied.

$$Q_m=\frac{4\pi}{\rho_c}S\delta^{(2)}(\boldsymbol{x}-\boldsymbol{x_0}) \tag{3}$$

$$S=e^{i\varphi}\sqrt{\frac{\rho_c c_c P_{rms}}{2\pi}} \tag{4}$$

Finally, the finite element formulation was obtained by testing the linearized inhomogeneous Helmholtz equation using the Galerkin method.

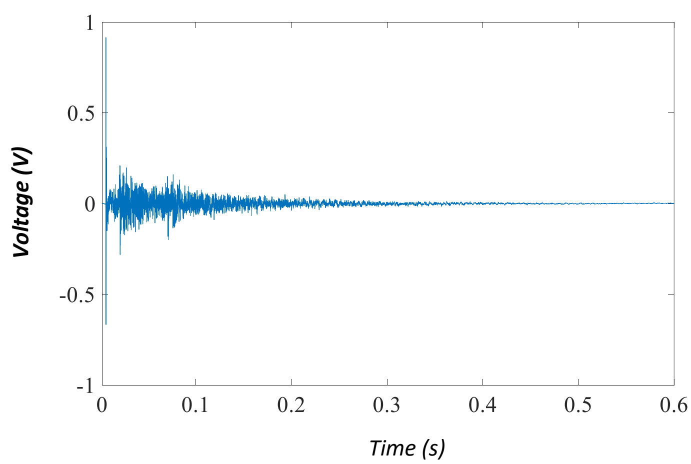

Figure 3: Impulse response measured (Position A).

3. Results

Impulse responses of the space were measured according to the source and receiver points presented in Fig. (**2**). An example of an impulse response of the space obtained is depicted in Fig. (**3**) (receiver position A).

Frequency responses were extracted from the impulse responses using Fourier analysis for the perpendicular measurement positions (positions A, B, C, D). Accordingly, any position or position could have been chosen to measure the impulse responses and then extract the frequency responses. The frequencies most significantly affect all measurement locations are 86.1 Hz, 150.7 Hz, and 204.6 Hz. Different colors have been placed on the spectrum for these frequencies to make them more visible (Fig. **5**).

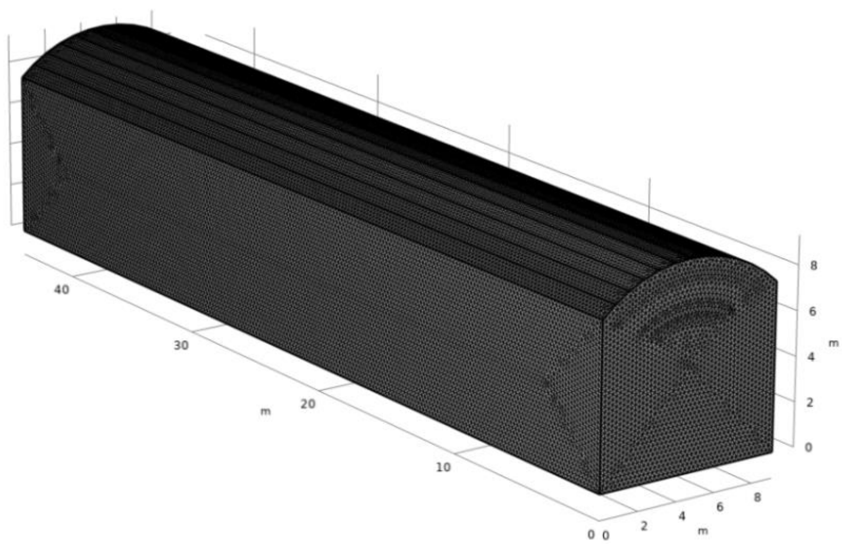

Figure 4: FEM mesh model of Neoria.

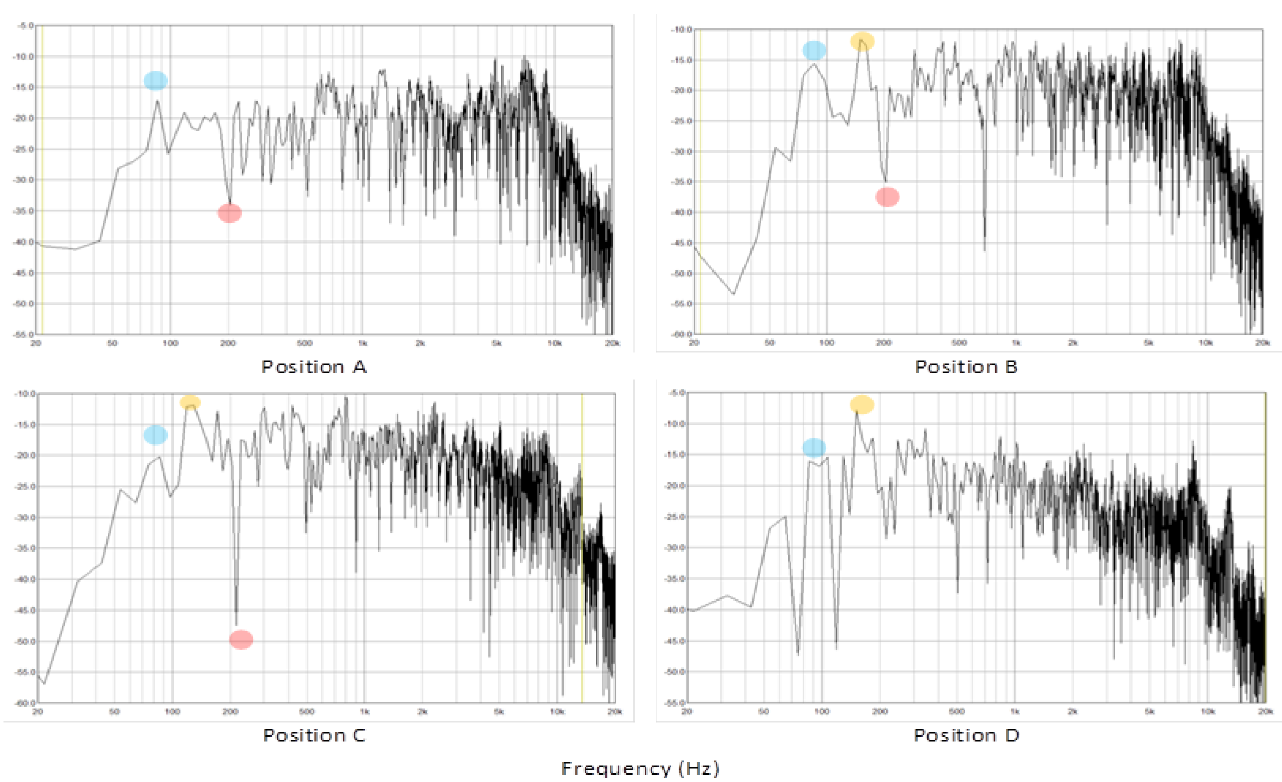

Figure 5: Frequency responses in different perpendicular positions (blue: 86.1 Hz, yellow: 150.7 Hz, red: 204.6 Hz).

Additionally, the eigenmodes of these frequencies were visualized with the use of FEM and are presented in Fig. (**6**-**8**), respectively. The locations of the nodes and antinodes of the Eigen modes can also be identified in Fig. (**6**-**8**). The knowledge of these positions can be useful in making appropriate acoustic interventions in space.

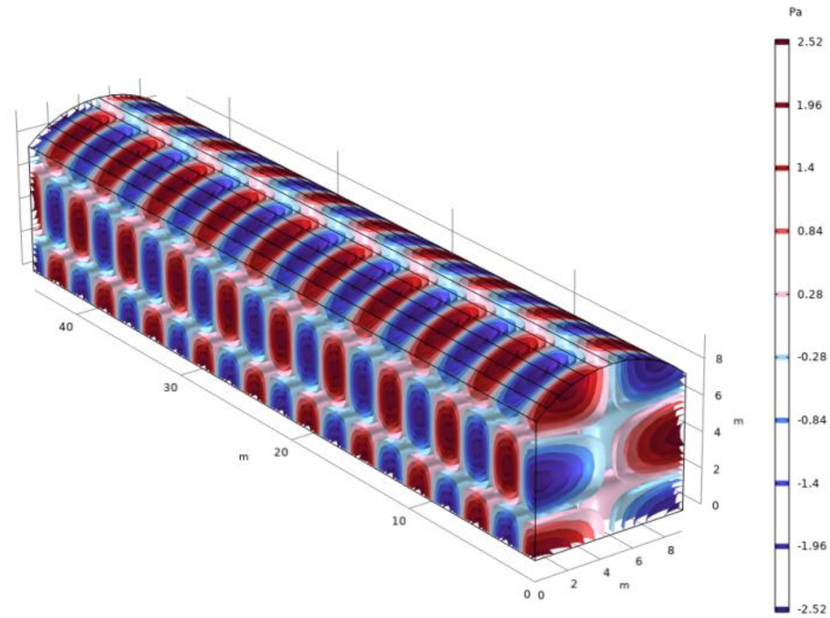

Figure 6: Eigenmode for the eigenfrequency of 86.1 Hz.

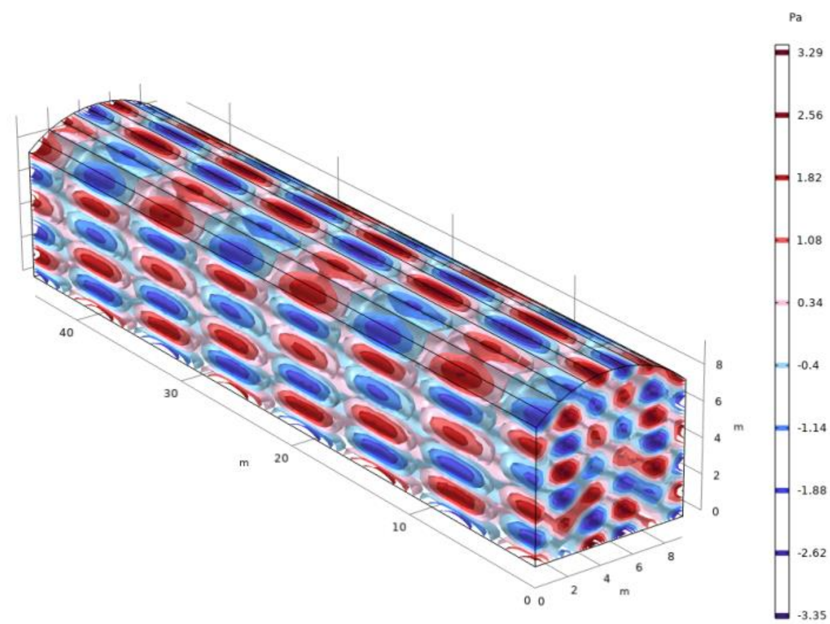

Figure 7: Eigenmode for the eigenfrequency of 150.7 Hz.

Additionally, in Fig. (**9**), the acoustic pressure (left) and the sound pressure levels (right) are presented in the shell of the Neoria monument for the eigenfrequency of 86.1 Hz.

4. Discussion

The purpose of this study was the application of numerical methods and, in particular, FEM for the acoustic modeling of the monument of Neoria so that the results can be used for its acoustic renovation. Usually, numerical methods, such as those presented in the introduction of this study, such as ray tracing, are used to calculate a space's impulse response and acoustic parameters. However, one aspect of numerical methods often needs to be addressed in acoustic studies of spaces is the identification and visualization of eigenmodes. This research aimed to focus on this point to find the most dominant eigenfrequencies and the corresponding eigenmodes in the Neoria monument.

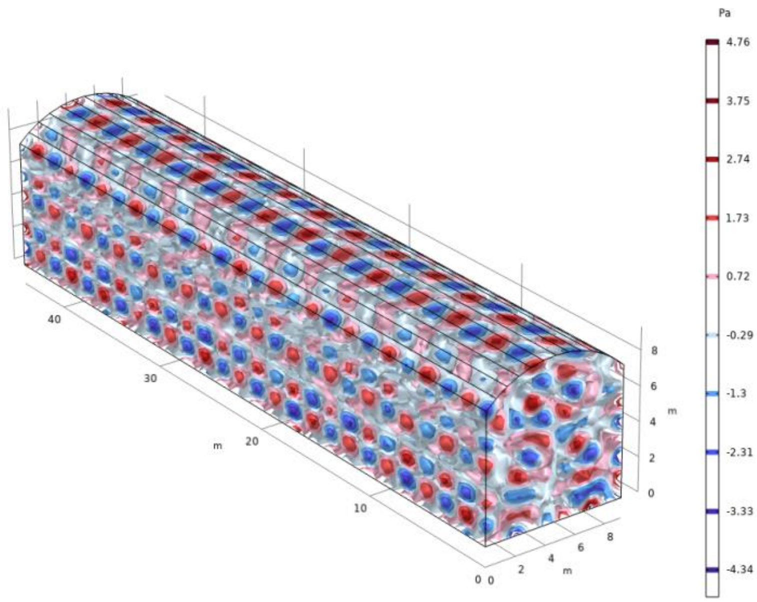

Figure 8: Eigenmode for the eigenfrequency of 204.6 Hz.

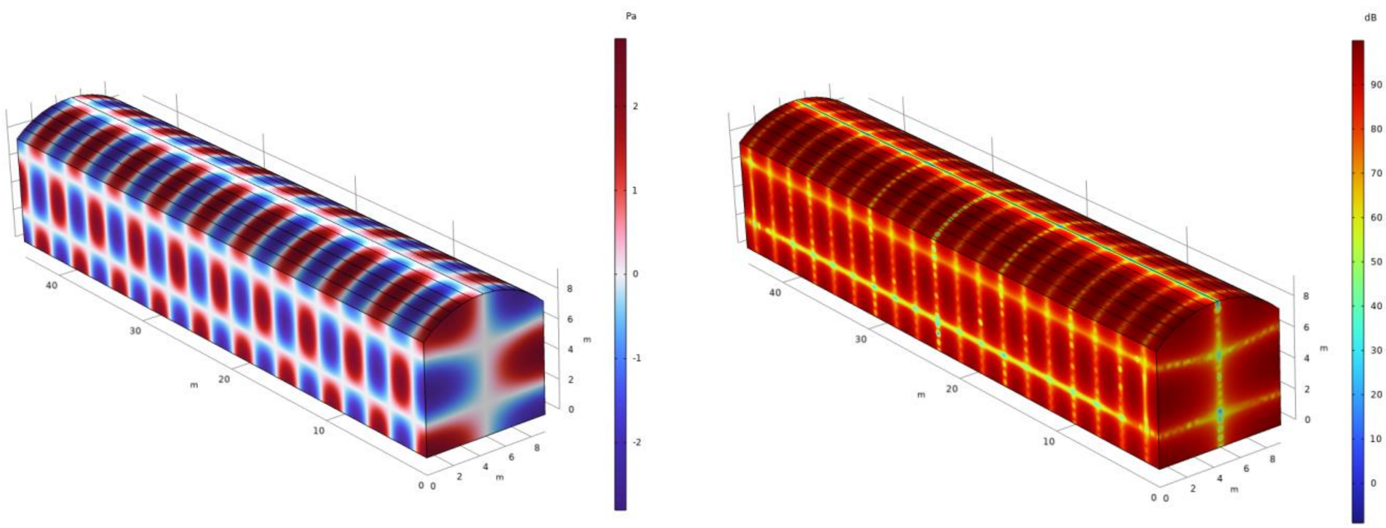

Figure 9: Eigenmode for the eigenfrequency of 86.1 Hz (left: acoustic pressure, right: sound pressure levels).

For this purpose, measurements were carried out, as well as acoustic modeling with the use of FEM, as presented in the previous section. In general, as waves travel along the same path but in opposite directions, they produce standing waves. An eigenmode may be characterized as a system of standing waves, which in turn, is characterized by nodes and antinodes. Where the oppositely traveling waves arrive in a pressure antiphase, pressure cancellation will occur, resulting in a pressure minimum called a node. Similarly, where the oppositely traveling waves arrive in the pressure phase, pressure amplification will occur, resulting in a pressure maximum called an antinode [28]. The locations of the nodes and antinodes of the eigenmodes can be identified in Fig. (**6**-**8**). Appropriate coloring in Fig. (**6**-**8**) clearly shows the areas where a maximum and a minimum of the sound pressure occurs and where the sound pressure is approximately equal to zero. Additionally, in Fig. (**9**), the acoustic pressure (left) and the sound pressure levels (right) are presented in the shell of the Neoria monument for the eigenfrequency of 86.1 Hz.

The knowledge of the space's eigenmodes, nodes, and antinodes can be useful for adequately placing absorbers and diffusers. In general, if we want to suppress a specific resonance 'through increased damping of a targeted acoustic mode, each resonator (or absorber) must be located near a pressure antinode of the mode [28]'. Various studies have addressed the optimal placement of absorbers and diffusers [29-31]. A study by Cucharero et al. [29] found that if the room modes dominate the sound field, the most efficient location for the sound-absorbing material should be at one of the surfaces causing the methods. There is likely to be an even more significant improvement in results if the positions of antinodes are chosen for the placement of absorbing material according to the approach of this study. In addition, the optimum placement of acoustic material depends on using space, e.g., for classrooms [32-34]. A similar approach can be applied when a combination of absorbers and diffusers is applied [31]. Some studies have also investigated the case of a particular distribution of diffusers, e.g. effect of periodic diffusers [35]. Finally, some studies have used the finite element method to investigate the optimum placement of acoustic elements [36, 37].

Especially for this study, the exact knowledge of the positions of the nodes and antinodes is helpful for the appropriate acoustic treatment. As the Neoria monument is to be redeveloped into a multipurpose hall, a stage, and appropriate seating will be added to the venue. The present approach is an important part of the acoustic design as it focuses on a neglected part of the acoustic study, which is the optimal application of acoustic elements in the space under study.

5. Conclusion

This study is a part of the acoustic renovation of the cultural heritage monument of Neoria in Chania, Greece. This study's measurements and acoustic modeling show that the frequencies with the greatest effect on the space are 86.1 Hz, 150.7 Hz, and 204.6 Hz. FEM was also utilized to visualize Eigen modes, nodes, and antinodes. Our approach could be applied to similar acoustic studies for cultural heritage monuments and more general acoustic studies. This study shows that FEM can be useful for detecting and visualizing eigenmodes. The identification and visualization of Eigen modes are crucial in architectural acoustics since they may negatively impact a space's acoustic features and the reproduction of music. This may be useful for applying suitable absorbent and diffuse elements to eliminate the effect of these resonances. The shape of antinode areas can be used to apply specific custom-made absorbers and diffusers. This study is a starting point for future investigations and acoustic interventions in the Neoria monument.

Acknowledgments

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