PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
6-8 July 2022 Verona, Italy

Acoustic analysis of a well-preserved Renaissance music space: the Odeo Cornaro in Padua.

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ABSTRACT

The Odeo Cornaro (1534) in Padua is a Renaissance music space designed by the architect Falconetto for the private palace of the Venetian entrepreneur Alvise Cornaro. Inspired by the classicism of Roman "villae" described in Cicero's letters, this octangular hall may be included in the "loci consonantes" Vitruvius' category, where the sound propagation isaccentuated, and the voice supported. In order to analyse these acoustic features through a contemporary approach, a campaign of in situ acoustic measurements allowed an accurate analysis of such a well-preserved space through objectiveroom criteria. Moreover, the acoustic role of the umbrella vault and the niches in the sidewalls has been evaluated througha numerical model tuned on the measurements' outcomes. The main results show that the neat modal behaviour of the symmetrical environment is also accentuated by the moderate volume and the lack of furniture. This effect contributes to supporting the voice of the singers without losing the intimacy of the music performance, proving the Odeo to be an outstanding music place of the past.

Keywords: Renaissance music space, well-preserved octangular hall, central-planned architectures, acoustic heritage.

1. INTRODUCTION

Central-plan buildings assumed a predominant role in the High Renaissance philosophical and artistic framework. The most leading architects, such as Bramante, Leonardo, Brunelleschi, Alberti, used to glimpse the idea of the divine perfection behind symmetrical shapes, also according to Aristotle and Plato's views and the *De Architectura* by Vitruvius [1,2]. Indeed, the geometrical features of centrally planned halls significantly affect the acoustics of the environments [3,4].

The aim of the present work is investigating the acoustic properties of a well-preserved Renaissance music space: the Odeo Cornaro in Padua (Italy). The Odeo Cornaro belongs to one of the most interesting Venetian architectures dating back to the XVI Century [5]. Designed by the architect Falconetto for the patron of arts Alvise Cornaro, the *ottangulo* (from latin "octangular" place) was probably conceived as a music space for the nobleman's villa (Figure 1), while the surrounding communicating rooms were intended for erudite symposia [6,7]. The presence of instruments and a choir is explicitly mentioned by the writers of the same period (1537-1542). However, the moderate volume of the *ottangulo* suggests that it was a hall reserved to small groups of erudite people [8,9,10]. What is also mentioned in historical evidence is the support given by the hall to the human voice, which was attributed to the niches and the shape of the hall [11]. During the study historical references have been useful not only to know the intended use of the distinct parts of the architecture but also for the comprehension of the materials employed during the construction [12].

Figure 1 – Interior view of the Odeo Cornaro (Padua).

10.58874/SAAT.2022.208

2. ACOUSTIC MEASUREMENTS

In February 2022 the authors carried out a geometrical and an acoustic survey of the Odeo Cornaro. The aim was, respectively, to create a reliable 3D virtual model of the hall and to investigate the acoustics of such a unique well-preserved place. Main geometrical features of the octangular hall are provided in Table 1.

Table 1 – Main geometrical features of the octangular hall.

Feature	Quantity
Volume [m^3]	220
h_{max} [m]	6
h_{mean} [m]	5.5
Floor [m^2]	40
Niches [n°]	4

The most significant room criteria have been collected by in situ measurements in compliance with ISO 3382. Acoustic measurements were performed within the central hall and the surrounding rooms. Two points were selected for the location of the omnidirectional sound source (dodecahedron); twelve receiver points (monoaural receivers) were employed: nine within the octangular hall and three in the main communicating room. Experimental results are reported in Table 2.

3. NUMERICAL MODELS

Since the Schroeder frequency of the Odeo is around 225 Hz (V = 220 m^3, $T_{500\text{-}1k}$ = 2.8 s) two distinct simulation approaches are required [14]. A ray-tracing time dependent approach was adopted for the analysis of acoustic coupling effects and the free path distribution (ODEON Room Acoustics). A wave-based approach was applied for the steady state response under a sinusoidal monopole source distribution at low frequencies (COMSOL Multiphysics).

3.1 Geometrical Acoustics (GA)

The 3D virtual model of the *ottangulo* and the adjacent room was created according to the geometrical acoustics (GA) state-of-the-art (see Figure 2) [13]. The calibration of the model was achieved by considering a single material for all the surfaces involved: the marble. The α coefficient in octave bands are provided in Table 2, along with the comparison between measured and simulated T_{20}. The scattering value was set equal to 0.3 for the upper part of the niches, and equal to 0.02 for the remaining surfaces. A transition order equal to 2, an impulse response length of 4 s, and 40 k rays were used during the simulation.

Table 2 – Measured and simulated T20 values along with the absorption coefficient of the marble.

	125	250	500	1k	2k	4k
T_{20} (Meas.)	3.49	3.23	2.92	2.70	2.36	1.69
T_{20} (Sim.)	3.32	3.20	3.02	2.69	2.31	1.61
α_{marble}	0.013	0.014	0.014	0.015	0.015	0.016

The calibrated model was employed to investigate the potential multi-slope decay curves between the coupled rooms [15]. The Bayesian analysis was carried out on the measured and the simulated room impulse responses (RIRs): mono-decay curves were detected for the receivers located in the octangular hall whilst dou- ble-decay curves were detected for the points located in the adjacent room (Figure 3).

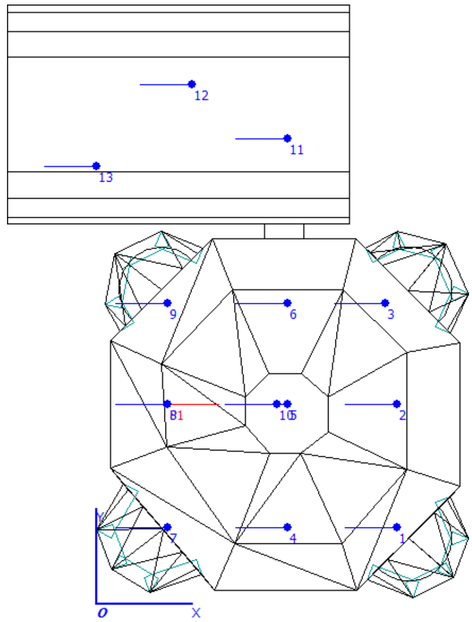

Figure 2– 3D model of the Odeo Cornaro (ODEON).

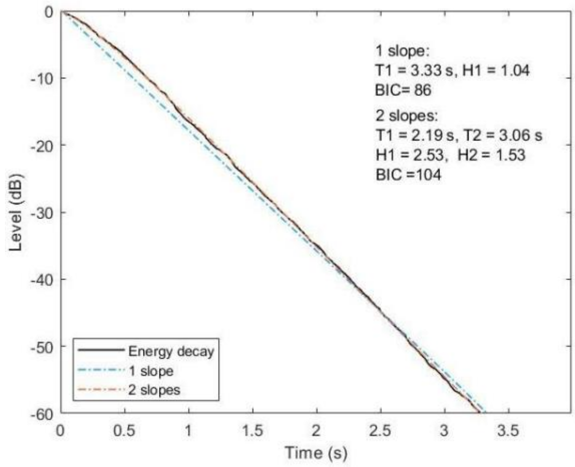

Figure 3–. Multi-decay analysis of measured IR at 1000 Hz with the sound source in the octangular hall and the re- ceiver in the adjacent room [16].

Figure 3 shows the results for the sound source in the *ottangulo* and the receiver in the adjacent room. According to the following expression [16]:

$$H_s(\mathbf{H},\mathbf{T},tk) = \sum_{S=1}^{2} H_s e^{-13.8tk/T_s}$$

where H_s is the Schroeder curve, **T**= T_1, T_2, and **H** = H_1, H_2 are the decay parameters, the combination of two slopes proves to be more accurate (higher BIC value for T_1, T_2, H_1, H_2) than the single slope (lower BIC value for T_1, H_1).

Moreover, the coupling factor *kc* was calculated according to the Cremer and Muller theory [17] considering the coupling surface, S_c, and the equivalent absorption area of the receiving space (A_2 when the sound source is in the octangular hall, A_1 when the sound source is in the adjacent room):

$$k_{c12} = \frac{S_c}{S_c + A_2} \approx 0.44;\; k_{c21} = \frac{S_c}{S_c + A_1} \approx 0.33 \qquad (1)$$

where Sc = 1.33 m2, A2 = 2.69 m2 A2 = 1.68 m2. Such values indicate that coupling effects between the *ottangulo* and the adjacent room are not neglectable.

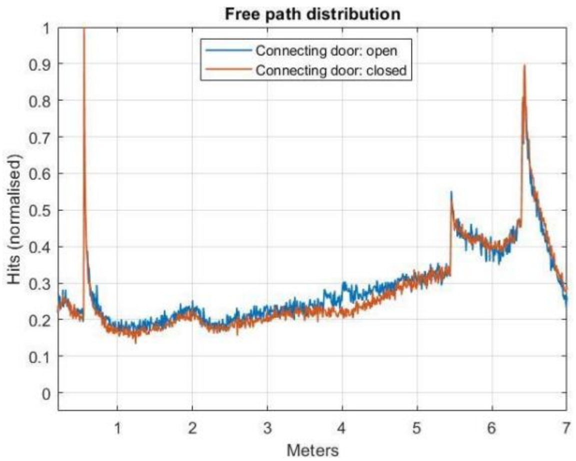

Figure 4 – Free path distribution in two configurations depending on the connecting door: open and closed.

A further analysis concerns the free path distribution in two distinct configurations depending on the connecting room (open or closed). Figure 4 provides the results in terms of normalised frequency of surface hits versus the distance of free paths in meters. It is possible to notice that no significant discrepancies are detected suggesting that the free path distribution in the main octangular hall is independent from the configuration of the door and the presence of the adjacent hall.

3.2 Finite Element Method

The sound energy behaviour at low frequencies has been assessed through COMSOL Multiphysics, in which the 3D model of only the octangular hall was built from the scratch. The *Pressure Acoustics, Frequency Domain* module embedded in the software was used to explore the effects of eigenfrequencies of the hall on the signal emitted by an omnidirectional sound source (*Monopole point source* placed at 1.5 meters above the floor). A single *air* domain was defined for the whole geometry by employing the linear elastic model. As a first approximation, no specific boundary conditions were set except for the *Sound Hard Boundary Wall* condition on all the surfaces involved. The mesh of the geometry has been set according to the rule of thumb of 6 elements for the minimum wavelength of interest (considering f_{max} = 400 Hz in FE analysis).

Figure 5 shows the steady state response under a monopole source distribution (P_{rms} = 1 W) in terms of total acoustic pressure distribution at f = 110 Hz, f = 130 Hz, f =150 Hz. These results confirm that the voice – which is here preliminarily approximated as omnidirectional and has the first energy contribution in the 125 Hz octave band – is effectively supported by the hall. Moreover, such kind of study also suggests that the behaviour of the *ottangulo*'s response at low frequencies is moderately affected by the presence of the niches, in contrast with the historical statements. Therefore, in the first place it is possible to consider the steady state response of the octangular hall similar to that one of cylindrical halls [11].

4. CONCLUSIONS

The present work investigates the acoustics of a well-preserved Renaissance music space in Padua (It- aly). A campaign of acoustic measurements allowed for the collection of the ISO 3382 room criteria, while two different numerical models have been used for a contemporary approach to the acoustic analysis of such unique hall.

The preliminary results clarify the relationship between the central octangular hall and the surrounding rooms (GA software) and show the response under a monopole source at low frequencies (FE software). The multi-decay analysis on measured and GA impulse responses proved that the adjacent halls work with acoustic coupling effects (double-decay curves) when the sound source is in the octangular hall and the receiving points are in the adjacent room. Furthermore, the FE results show the considerable sound reinforcement obtained with a source located where singers were supposed to be (at one side of the *ottangulo*). Finally, the present study proposes a method to exploit the advantages of different simulation approaches to investigate specific acoustic aspects in well-preserved historical music spaces.

ACKNOWLEDGEMENTS

This work has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme Grant agreement No. 950084 NEMUS. Also, the authors would like to thank Riccardo Russo and Virginia Tardini for their kind support during the acoustic measurements and the 3D model creation.

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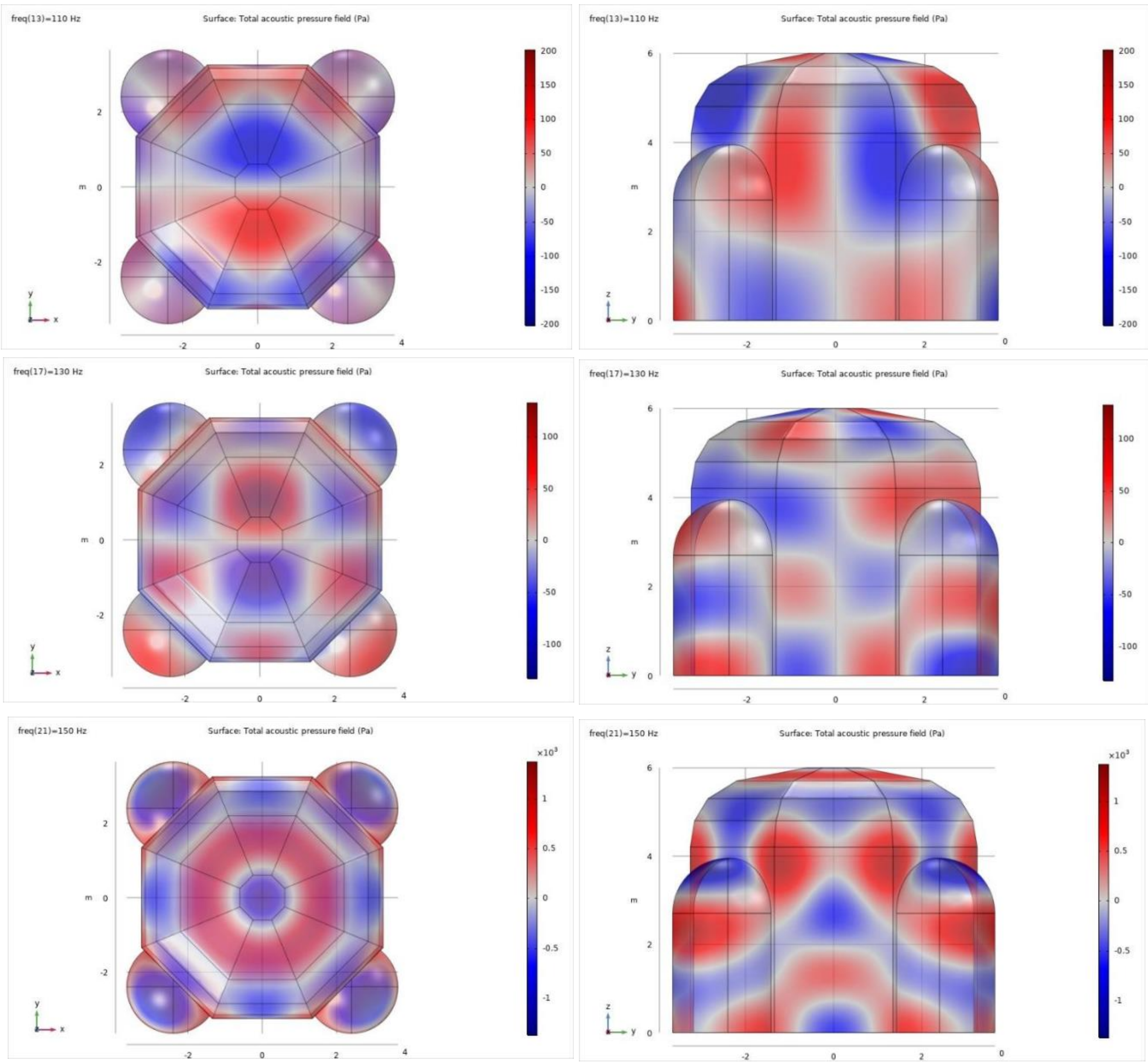

Figure 5– Steady state response under a sinusoidal monopole source distribution located at (x=0, y=2, z=1.5) with input frequency as indicated in each panel (COMSOL).

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