The coupled rooms of Odeo Cornaro (1534) as support for Renaissance musicians and soloists

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ABSTRACT
The Odeo Cornaro in Padua (Italy) is a well-preserved XVI Century octangular music space (from Latin the *ottangulo*) surrounded by communicating smaller halls. Inspired by Roman classicism, the Renaissance architect Falconetto designed such coupled volume system for the private villa of the Venetian nobleman Alvise Cornaro. With the aim of assessing the acoustics of the Odeo by means of a contemporary approach, acoustic measurements were performed, and the room acoustic criteria were derived from the acquired impulse responses. Experimental results were employed to quantify the acoustic coupling effects throughout the environments and to outline the acoustic features of the central space. Numerical models were used to assess the free path distribution and the support given by the *ottangulo* to the singers' voices. The main outcomes confirm the different use of the spaces suggested by historical research: while the main hall was probably employed for singing and playing instruments, the adjoining rooms were intended for erudite conversations and symposia. The symmetrical shape and the moderate volume of the central octangular space contribute to creating a neat modal behaviour that accentuates the sound propagation, highlighting the outstanding value of the Odeo as one of the "loci resonantes" of the past.

Keywords: Coupled volumes, Renaissance music space, 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, while the surrounding communicating rooms were intended for erudite symposia (see Fig. 1) [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 literate 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 work, historical references have been useful not only to study the intended use of the distinct parts of the architecture, but also for the comprehension of the materials employed during the construction [12]. The present work proposes a method to exploit the advantages of different simulation approaches to investigate specific acoustic aspects in outstanding music spaces of the past [13, 14, 15].

Figure 1. Plan of the Odeo Cornaro building (left); interior views of the octangular hall (centre) and the main adjacent room (right).

2 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 COUPLED VOLUMES

The acoustic phenomenon of coupled spaces is often analysed through sound decay curves derived from the measured room impulse responses (RIRs) [16, 17]. Multi-rate sound decays are generally assessed for significant source-receiver pairs placed in the different volumes of the architecture of interest [18, 19, 20]. In order to investigate the potential multi-slope decay curves between the coupled rooms, the Bayesian analysis was carried out on the measured room impulse responses (RIRs) [21]. Double-decay curves were detected for the sound source in the *ottangulo* and the receiver in the adjacent room (Fig. 2). Figure 2 shows the results for the sound source in the *ottangulo* and the receiver in the adjacent room. According to the following expression:

$$H_s(\mathbf{H},\mathbf{T},t_k) = \sum_{i=0}^{2} H_i e^{-13.8 t_k / T_i} \tag{1}$$

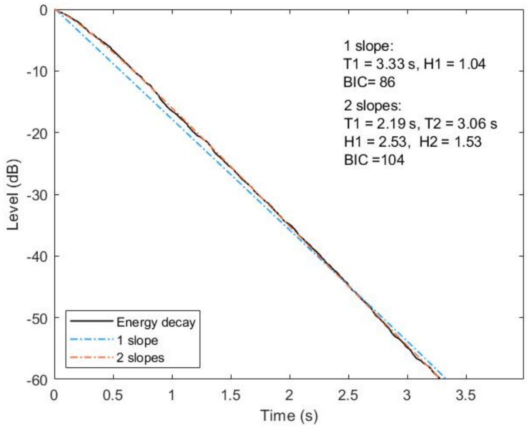

Figure 2. Multi-decay analysis of measured IR at 1000 Hz with the sound source in the octangular hall (S in hall 1) and the receiver in the adjacent room (R in hall 2), as it is shown in Fig. 1. Two slopes prove to be more accurate (higher BIC value for T_1, T_2, H_1, H_2) than the single slope (lower BIC value for T_1, H_1), demonstrating the occurrence of acoustic coupling effects [22, 23].

H_s is the Schroeder curve, $\mathbf{T} = T_1, T_2$ is the decay time associated with the logarithmic decay slope of individual exponential decay terms, and $\mathbf{H} = H_1, H_2$ is the linear amplitude parameter related to the level of individual exponential decay terms [22, 23]. Two slopes prove 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), demonstrating the occurence of acoustic coupling effects. The similarity with the "plateau-type" curve rather than the "cliff-type" curve is probably due to the lack of strong early reflections in a highly reverberant sound field, leading to early decay time values longer than the reverberation time values [24]. Therefore, the current acoustics of the main adjacent rooms proved to be too reverberant for the intended use mentioned by historical documents, i.e. erudite conversations. This may suggest the presence of furniture - not preserved today - in the halls surrounding the *ottangulo*.

Another index quantifying the acoustic coupling between volumes is the coupling factor k_c defined by Cremer and Muller's theory [25]. The coupling factor k_c was calculated 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):

$$k_{c12} = \frac{S_c}{S_c + A_2} \simeq 0.44 \quad k_{c21} = \frac{S_c}{S_c + A_1} \simeq 0.33 \tag{2}$$

where $S_c = 1.33\,\mathrm{m}^2$, $A_1 = 2.69\,\mathrm{m}^2$, $A_2 = 1.68\,\mathrm{m}^2$. These values indicate that coupling effects between the *ottangulo* and the adjacent room are not neglectable, meaning that there is a considerable sound energy exchange between the coupled volumes, suggesting that the music performances in the main hall and the erudite symposia in the remaining rooms did not happen simultaneously. Moreover, the influence of the octangular hall's acoustics on the listener's experience in the adjacent room is higher than the influence in the opposite configuration ($k_{c12} = 0.44$ vs $k_{c21} = 0.33$).

4 NUMERICAL MODELS

Since the Schroeder frequency of the Odeo is around 225 Hz ($V = 220\,\mathrm{m}^3$, $T_{20,500-1k} = 2.8\,\mathrm{s}$) two distinct simulation approaches are required. A ray-tracing time dependent approach was adopted for the analysis of 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).

4.1 Geometrical Acoustics (GA)

The 3D virtual model of the *ottangulo* and the adjacent room was created according to the geometrical acoustics (GA) state-of-art (see Fig. 3) [26, 27]. 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.

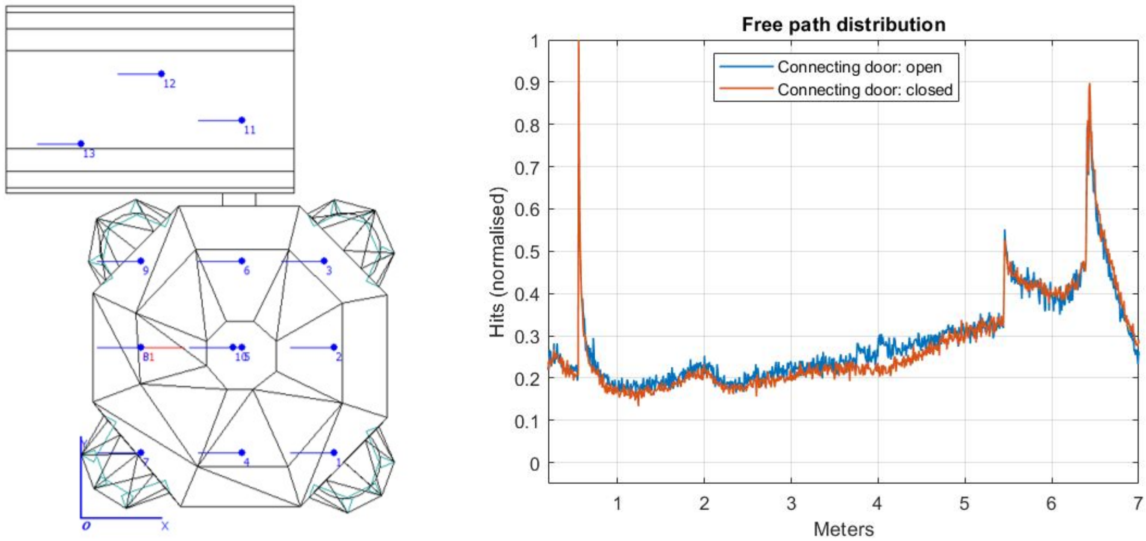

Figure 3. On the left 3D model of the Odeo Cornaro (ODEON). On the right free path distribution (sound source in the *ottangulo*) in two configurations depending on the connecting door: open and closed. Results are provided in terms of normalised frequency of surface hits versus the distance of free paths in meters.

The ray-tracing approach was adopted for an accurate analysis of the free path distribution. The analysis of the free path distribution has been done in two distinct configurations depending on the connecting room (open or closed). Figure 3 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 when the sound source is in the main octangular hall no significant discrepancies are detected in the free path distribution, confirming that the ottangulo is more acoustically indepedent from the presence of adjacent rooms.

Table 2. Measured and simulated T_{20} values, the percentage differences, and the absorption coefficient of the marble are provided.

	125 Hz	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz
T_{20} (Measured)	3.49	3.23	2.92	2.70	2.36	1.69
T_{20} (Simulated)	3.32	3.20	3.02	2.69	2.31	1.61
Difference	4.8 %	0.9%	3.4 %	0.4 %	2.1%	4.7%
α_{marble}	0.013	0.014	0.014	0.015	0.015	0.016

4.2 Finite Element Method (FEM)

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 (see Fig. 4). 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 wave-length of interest (considering fmax = 400 Hz in FE analysis). Figure 5 shows the total acoustic pressure field at 150 Hz along a horizontal and a vertical slice passing through receiver R2 ($x = 0$, $y = -2$, $z = 1.5$). Moreover, the frequency response for a sinusoidal monopole source ($P_{rms} = 1W$) located at S1 ($x = 0$, $y = 2$, $z = 1.5$) and the receiver located at R2 ($x = 0$, $y = -2$, $z = 1.5$), R5 ($x = 0$, $y = 0$, $z = 1.5$) is provided. These results confirm that the voice – which has the first energy contribution in the 125 Hz octave band – is effectively supported by the hall, especially in the positions where the audience is expected to be located (R2).

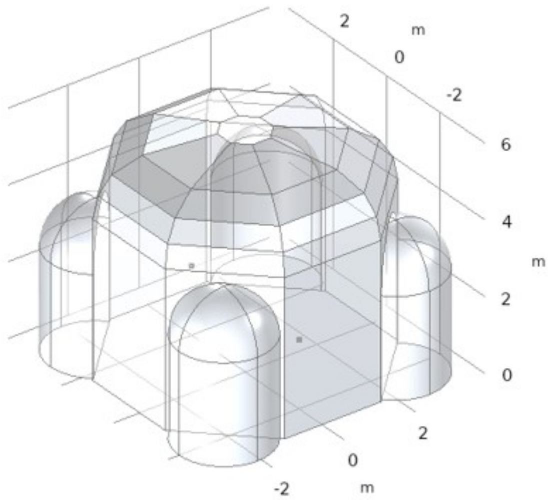

Figure 4. 3D model of the octangular hall in Comsol Multiphysics.

5 CONCLUSIONS

The present work investigates the acoustic coupling effects of a well-preserved Renaissance music space in Padua (Italy). 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 multi-decay analysis on measured 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. The numerical 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). Furthermore, the FE results show the considerable sound reinforcement obtained with a source located where singers were supposed to perform (S1). 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.

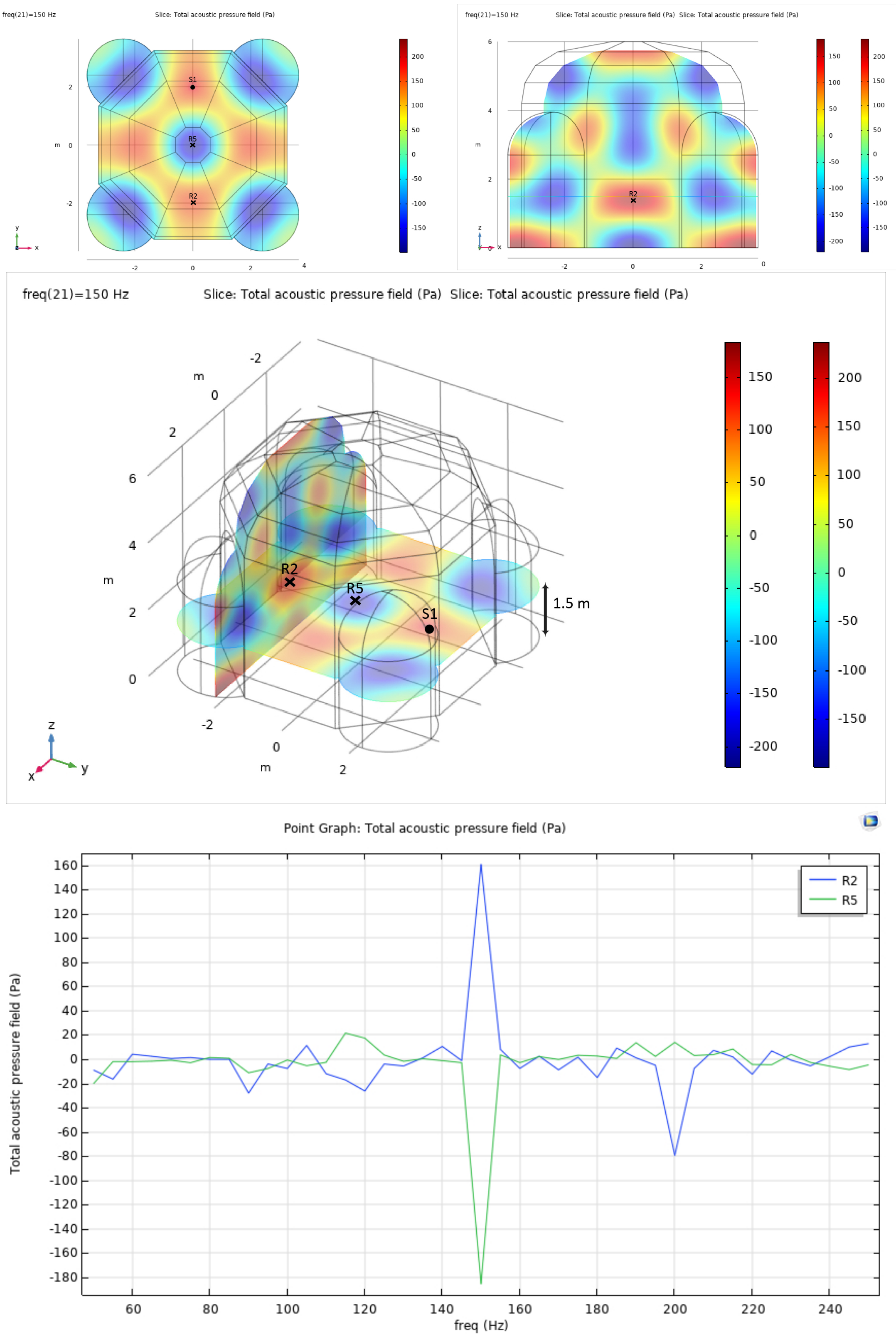

Figure 5. On the top total acoustic pressure field at 150 Hz along a horizontal and a vertical slice passing through receiver R2. On the bottom frequency response for a sinusoidal monopole source located at ($x = 0$, $y = 2$, $z = 1.5$) and receiver R2 ($x = 0$, $y = -2$, $z = 1.5$), R5 ($x = 0$, $y = 0$, $z = 1.5$).

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