

A virtual acoustic restitution of St. John's Baptistery in Pisa

Anna ROVIGATTI⁽¹⁾, Elena ROSSI⁽²⁾, Giulia FRATONI⁽³⁾, Dario D'ORAZIO⁽⁴⁾, Massimo GARAI⁽⁵⁾

⁽¹⁾University of Bologna - Department of Industrial Engineering, Italy, anna.rovigatti2@unibo.it

⁽²⁾University of Bologna - Department of Industrial Engineering, Italy, elena.rossi56@unibo.it

⁽³⁾University of Bologna - Department of Industrial Engineering, Italy, giulia.fratoni2@unibo.it

⁽⁴⁾University of Bologna - Department of Industrial Engineering, Italy, dario.dorazio@unibo.it

⁽⁵⁾University of Bologna - Department of Industrial Engineering, Italy, massimo.garai@unibo.it

Abstract

Virtual acoustics is a useful tool for studying ancient environments now part of our cultural heritage. The acoustic restitution of an existing building, or even of a no more existing building, allows understanding its acoustic and architectural evolution. St. John's Baptistery is located in Piazza dei Miracoli (Pisa), which is a homogenous architectural ensemble including the Leaning Tower and the Cathedral. Due to the succession of different masters, the Baptistery was built in stylistic disagreement with the earliest design, resulting in the actual architecture that provides interesting acoustic peculiarities. This work presents the virtual acoustic restitution of potential first designs, based on previous studies. The accurate calibration of the existing Baptistery model enables us to achieve a believable acoustic restitutions through the auralisation techniques. More in details the acoustic coupling between the volumes of the building – respectively the dome, the matroneum and the ambulatory – was studied with measurements and numerical simulations. Furthermore, the layout of a Gregorian soloists in the choir part of the Baptistery was simulated according to musicological researchers, both in unoccupied and occupied conditions.

Keywords: Cultural-Heritage, Virtual Acoustics, Worship Acoustics, Sound Energy Distribution

1 INTRODUCTION

The virtual acoustics provides a significant benefit for learning how the acoustic and architectural evolutions of a place could have been, in order to consciously operate for its preservation. It is extremely relevant for worship places, in which the historical investigations can not separate acoustic assessment from architecture analysis. This is the case of churches, which are considered the place of the music birth and growth for the western society [1] and for that reason characterized by a deep relationship between architecture features and the provided acoustics [2]. Indeed the historical analysis about the relationship between the building and its acoustics, has to highlights the importance of considering the “intangible” cultural heritage (e.g. acoustic peculiarities) as remarkable as “tangible” cultural heritage (e.g. the architecture) [3]. Several studies about famous places applied the virtual acoustics techniques, giving a significant assistance to the preservation workflow. On one side, when the study cases are about ruins or destroyed buildings, the reconstruction of the acoustics by means of virtual methods can support the archeological research and moreover improve the public interactive applications [4, 5]. On the other hand, numerical simulations provide to predict acoustic parameters as result of material adjustments - due to occasional change of use - or required restorations, so that the renovation actions do not destroyed the original acoustics of historical places, which is part of our intangible cultural heritage [6]. Moreover with the techniques of virtual acoustics it is possible to investigate how the different sound source positions and the distribution of sound absorbing materials affect the speech intelligibility and the music quality perceived. This is especially interesting for the case of ancient churches which are mostly composed by hard and reflective surfaces and a non-uniform arrangement of absorbing elements, and characterized by long reverberation times, focusing effects and poor speech clarity. For such reasons, the evaluation of the acoustic behaviour of churches includes the analysis of the spatial distribution of the sound energy according to the acoustic energy models

for churches [7, 8]. A special case is represented by baptisteries, rotundae and mosques, which are all based on a central plan design. The sound field inside such places results in peculiar effects as flutter-echoes and “whispering galleries” due to the high symmetry of the. This paper provides the results of a virtual acoustic restitution of the St. John’s Baptistery in Pisa, which is part of the monumental complex of *Piazza del Duomo* included in the UNESCO World Heritage Site [9]. Based on central plan design, the Baptistery is a significant example of Medieval architecture, composed of the central volume at the ground floor, with the baptismal font, the Pulpit and the altar; the ambulatory delimited by arches and cross vaults; and the matroneum at the first floor, which is size-comparable to the ambulatory. Due to its long-term construction and the union of styles coming from different masters, different hypotheses about how the first design should have been, exist [10]. So that, also the acoustic simulations of such hypotheses were carried out and auralisations of a Gregorian chant inside the Baptistery were done in order to recreate the perceptive atmosphere of its acoustics.

2 RESEARCH METHODOLOGY

In order to deeply investigate the acoustic behaviour of St. John’s Baptistery and virtually reproduce the sound inside such a worship place, the followed methodology was applied. A first step was consisted on analysis of its current acoustics through *in situ* measurement campaign carried out according to the ISO standard about performance spaces [11], then the virtual model was shaped and a rigorous calibration process was completed. The numerical simulations allowed to obtain reliable Room Impulse Responses (RIR) of the Baptistery as it was and still is, and as it should had looked following the original design according to some historical studies. Finally auralisation techniques were used to achieve realistic virtual acoustic restitutions.

2.1 Acoustic measurements

The acoustic measurement campaign was carried out during closing time of the Baptistery in order to measure the RIRs in unoccupied conditions. The workflow of measure followed the recommendations of the ISO 3382-1 and the guidelines about acoustic measurements in a worship place [12]. 7 positions of sound sources were selected spread over the ground floor and the matroneum level at the first floor (2 located on the principal symmetry axis in the altar, 1 near to the pulpit, 2 in the interior and exterior circular of the ambulatory, and 2 placed on the matroneum) and 16 receiver points were identified for the RIRs recordings and two Bruel & Kjaer 4181 and one Schoeps KFM6 stereo microphone were utilized. Exponential Sine Sweeps ESS were used as excitation signals using high-SPL sound sources [13]. A proprietary software was used for both signal generation and impulse responses acquisition [14]. All the environmental conditions were monitored during the measurement session and registered an average temperature and relative humidity of 18°C and 58 % respectively. In the table 1 the measured values, averaged for each sound sources, inside St. John’s Baptistery are reported.

Table 1. Measured values, spatially and spectrally averaged, of the ISO 3382-1 acoustic parameters.

	EDT_M (s)	$T_{30,M}$ (s)	$T_{s,M}$ (ms)	G_M (dB)
Altar (S1)	12.6	12.8	909	15.9
Pulpit (S2)	12.8	12.8	994	14.3
Matroneum (S3)	12.2	13.0	954	12.7

2.2 Acoustic modeling and calibration

A 3D model of the Baptistery was shaped with an approximate interior volume of 24000 m^3 and in accordance with the Geometric Acoustics techniques. In order to avoid the increases of the computational time more than necessary, the complexity of the geometry was strongly reduced and the final model was composed of about 6300 surfaces. The acoustic simulations were provided by hybrid GA software [15]. A transition order equal to 2 was used to achieve reliable results for early reflections which are responsible for the perceptual acoustic

response of the room ($TO=2$; number of early rays=23518; IR length=20000 ms). The model of the Baptistry has been calibrated according to the acoustic measurements and 3 out of 7 source positions were selected for the entire process (two at the ground floor - one on the altar (S1) and the second one on the pulpit (S2) - and one placed in the matroneum (S3)). The positions of the receivers were subdivided into three groups according to their placing compared to the ambulatory or the center volume or the matroneum. The calibration workflow

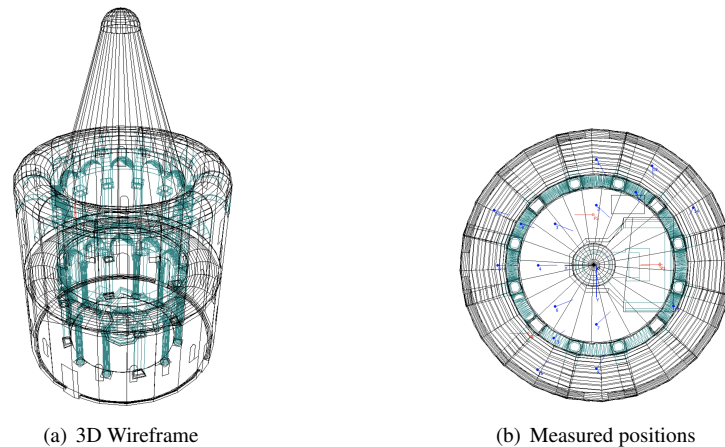


Figure 1. 3D wireframe of the calibrated model and the positions of the sources and microphones selected for the acoustic measurements.

mainly consists of an iterative process which involves the acoustic material proprieties, as absorption and scattering coefficients, and thus the selection of these values is responsible of the reliability of the simulations. A data collection for credible values of absorption coefficients was carried out basing on the scientific literature on this matter, according to both the material typologies and historical context [6, 16, 17]. Where necessary some values were slightly adapted according to the specific case and conditions (e.g. elements which were simplified or even not modeled), according to similar procedures [20]. About the lacking of complex small details in comparison to the main volumes was fixed by assigning particular scattering proprieties. The occupied condition was simulated and analyzed basing on previous researches on this topic [16, 21]. Considering that the applied sound absorption coefficients depend on the occupancy density, it was decided to adopt a condition with 1 person per square meter and a scattering coefficient of 0.7 as well. The numerical models were calibrated taking into account the measured values of Early Decay Time EDT , reverberation time T_{30} and center time T_s . The calibration process was considered completed once the simulated values were inside the JND values.

Table 2. Absorption (α) and scattering (s) coefficients for all the materials involved in the simulation.

Materials	Surface %	α						s	Ref.
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz		
Marble	71	0.01	0.01	0.01	0.02	0.02	0.02	0.30	[18]
Plaster	20	0.07	0.07	0.05	0.03	0.04	0.05	0.05	adapted [18]
Furniture	6	0.12	0.12	0.10	0.04	0.02	0.02	0.70	adapted [17]
Windows	2	0.35	0.25	0.18	0.12	0.07	0.04	0.10	[19]
Wood	1	0.10	0.15	0.18	0.20	0.20	0.20	0.15	[18]
Faithfuls	1.5	0.16	0.29	0.55	0.80	0.92	0.90	0.70	[16]

2.3 Numerical simulations of the historical models

The perceptible difference between the Baptistery and the external context gave rise to a long debate on what was the form originally thought by the designer Diotisalvi. Three significant historical studies have been selected for this paper proposes: De Fleury's proposal (DF), Boeck's proposal (BO) and Manenti Valli's one (MV) [10]. The first two studies were focused on the figure of a cusped dome open on the top with heights corresponding to the current building. DF's model was also composed of a lower matroneum than BO's model and the actual one. MV model appears considerably reduced compared to the current aspect due to the reduction of the matroneum height and the hemispherical dome placed on the inner ring.

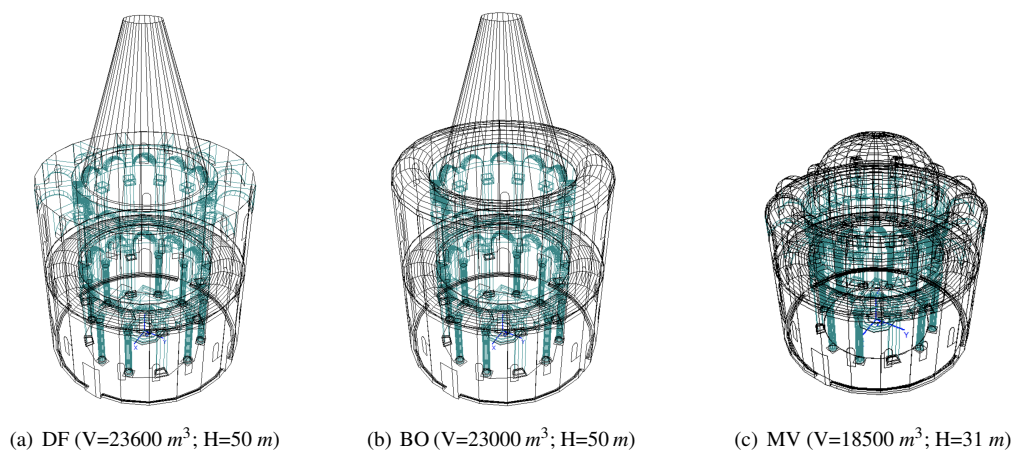


Figure 2. 3D Wireframes of the historical hypotheses about the early design of the Baptistery.

Considering these different hypotheses about the early design of St. John's Baptistery, the same methodology, described above, was adopted in order to reproduce the acoustics atmosphere inside. Three different GA models were shaped according to the historical studies and the materials properties (see fig. 3) used in the simulations were taken from the calibration of the actual model [22]. At the same manner the computational calculation was set up, taking into account the volume differences between the models, which involve the calculated effect of the air absorption and the number of rays used. The numerical simulations were ran using the same source-receivers configurations of the actual model based on the *in situ* acoustic measurements.

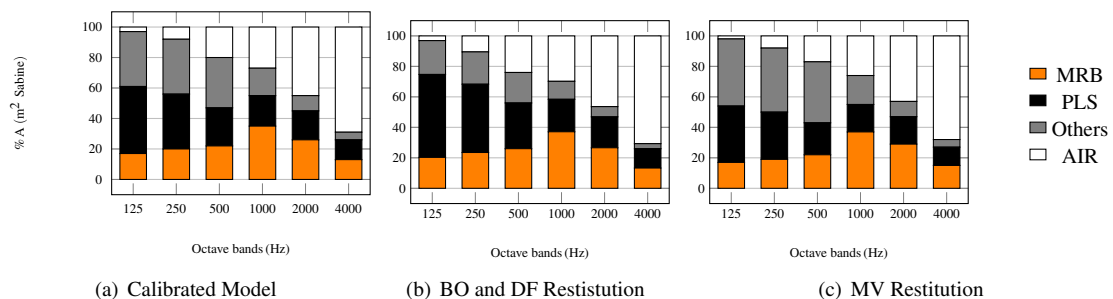


Figure 3. Percentage of equivalent absorption area of main materials for each octave band (MRB=Marble, PLS=Plaster, AIR=Air absorption, Others=all the remaining materials listed in table 2).

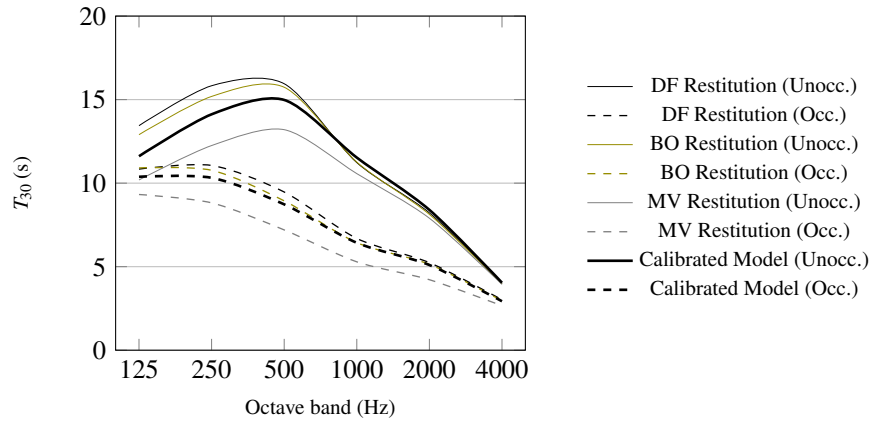


Figure 4. Values of T_{30} averaged over the receivers positions, in unoccupied and occupied conditions, for the Calibrated and Restitution models.

2.4 Auralisation

The first step on the MIMO (Multiple-Input-Multiple-Output) auralisation workflow was to put in the Baptistery the sound sources corresponding to each singer, so that a whole choir could be simulated. A virtual choir of four singers, which may be considered a reference for Gregorian Chant, was simulated. The choir configuration has been chosen following two displacements: the choir was placed in the ambulatory, directed orthogonally to the radius of the Baptistery; in the other configuration the choir was near the baptismal font. Such two positions correspond to different acoustic excitation of the Baptistery, considering the possible effects of sound focusing. In order to reproduce as close as possible the listening conditions achieved during the performances, several binaural receivers (multiple-output) are placed on the floor of the Baptistery and Binaural Room Impulse Responses (BRIRs) were calculated and filtrated with Head Related Transfer Functions (HRTF) for each virtual receiver. Indeed a set of BRIRs were extracted in occupied conditions in order to reproduce the effect of the presence of the faithfuls at the ground floor and the layer of the floor was replaced with the layer of the audience. For the aim of the present work an anechoic motif was recorded [23], which was *La missa de Notre Dame* di Guillaume de Machaut (1300–1377), a typical example of musical composition basing on *cantus firmus*. Four professional singers of Gregorian Choir, were selected and each singer at time played his part one after another, following a reference video of the conductor. The recording room was the listening room of the University of Bologna, treated with high density fiberform (80 kg/m^3). The porous materials and box-in-a-box structure made by gypsum board allow a negligible reverberation in a wide range of frequency. The microphone was placed at about 1.1 m from the soloist, within the critical radius of reverberation, allowing more than 10 dB of direct-to-reverberant ratio. Audio-Technica AT4050 microphone have been used thanks to the good recording capability and low noise characteristics. The microphone has been set in cardioid configuration and has been pre-amplified and A/D converted by a RME Micstasy.

3 DISCUSSION

In order to analyze the spatial distribution of sound energy inside the Baptistery, the Calibrated and MV Restitution models were selected leaving aside the other two hypotheses of restitution (see above). Such a selection was done considering which features would have resulted much more interesting to investigate. Indeed MV Restitution was opted for according to the significant differences in term of volumes (the matroneum volume is halved compared to the actual one) and shapes (i.e. hemispherical shaped vs tend shaped dome). So that the investigation was based on the comparison of the spatial distribution of sound energy with the analytical

prediction curves of Martellotta's model [7] and *generalised* μ model [8], elaborated for churches. For sake of brevity, detailed descriptions of models are not reported here. Seeing that inside the Baptistery the early reflections still remain after the typical value of 80 ms as limit between the early and late energy part, a time limit of 800 ms was assumed, according to the measurements and particular characteristics of sound field conditions. Consequently, the coefficient values introduced by the double-rate decay model [7] were chosen taking into account such a time limit and the geometric complexity of the space, as well as the absorption and scattering proprieties of the materials. The same considerations were made in order to fit the simulated values of sound strength in each measured position to the *generalised* μ model. A value of 0.4 was taken from [8] for the mean μ given the high complexity of the geometry of the Baptistery. In Figures 5 and 6, the simulated values of G_M and $T_{s,3}$ in unoccupied state are reported and compared to the prediction curves above mentioned.

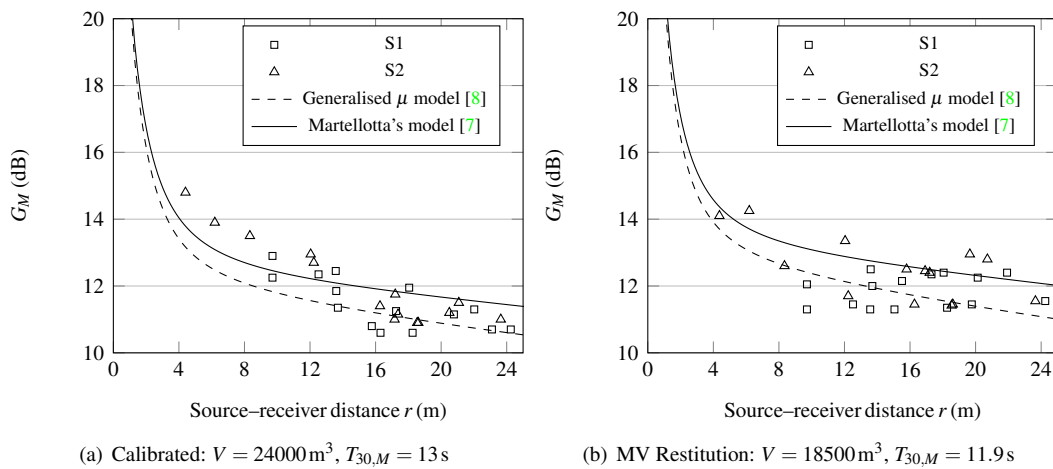


Figure 5. Simulated G_M values in unoccupied state, considering the actual layout (a) and the MV model (b) for S1 and S2 sound sources positions. “M” subscript identifies mean values over the central octave bands 500 - 1000 Hz. Simulated values are compared with analytical prediction curves: Martellotta's model (solid lines) [7] and Berardi et al.'s *generalised* μ model (dashed lines) [8].

Looking at the distribution of G_M along all the receivers (see fig. 5), both the analytical prediction curves give acceptable fitting, even if they have been applied to churches, which may not geometrically link to central base spaces as in the Baptistery. This works for both the Calibrated and MV Restitution models. In order to ensure the applying of such analysis, the distribution of $T_{s,3}$, similarly plotted as function of the source-receiver distance, was compared with the prediction curve of Martellotta's model (see fig. 6). In both the cases, the fittings are not achieved and the regression curves associated with the simulated values are shifted down. Moreover the change of the slope between early and late reflections may move down. According to these considerations, future efforts have to be made in order to verify the accuracy of the limit time between early and late reflections, which was approximated to 800 ms in the present work, and the applicability of the method of investigation used.

4 CONCLUSION

Throughout virtual acoustics techniques, the present paper investigates the sound of St. John's Baptistery in Pisa, which is included in a site of UNESCO World Heritage. The measurements inside the Baptistery enabled an accurate calibration of the virtual model corresponding to its actual status, which provided support to the analysis of spatial distribution of the sound energy inside the Baptistery compared to analytical prediction curves adapted for churches. Furthermore the calibrated model ensured numerical simulations of the three different

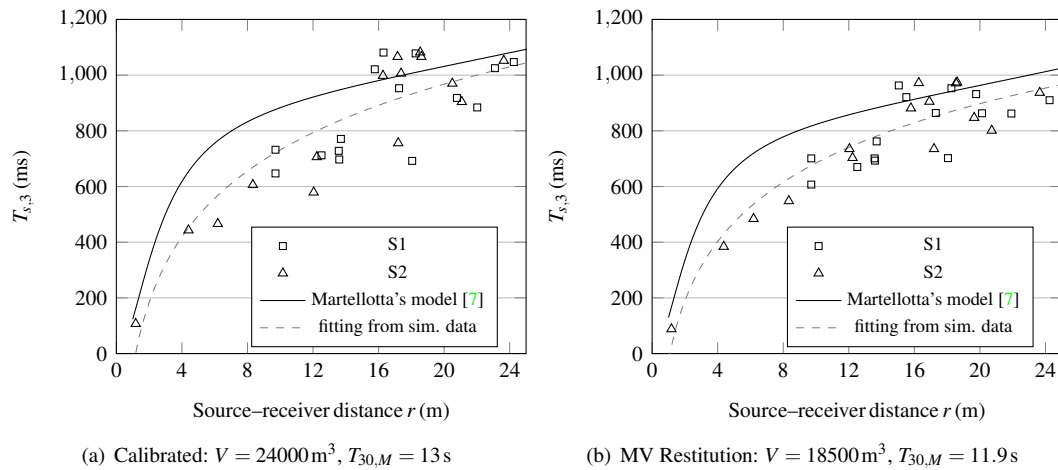


Figure 6. Simulated $T_{s,3}$ values in unoccupied state, considering the actual layout (a) and the MV model (b) for S1 and S2 sound sources positions. “3” subscript identifies mean values over the central octave bands 500 - 2000 Hz. Simulated values are compared with analytical prediction curve of Martellotta’s model (solid lines) [7] and fitting from simulated values (dashed line)

hypotheses about the original design, giving support to the historical research. Finally, the developing of MIMO auralisations of a Gregorian Choir placed into two potential configurations gives back the acoustic render of such a place, which is significant in terms of both intangible and tangible Cultural Heritage.

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