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THE ACOUSTIC DESIGN AND REQUALIFICATION OF AN AUDITORIUM IN A CHURCH AND OF A HISTORICAL THEATER

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Abstract. Environmental sustainability is the ability to keep ecological processes within an ecosystem and its biodiversity in the future and, together with economic and social sustainability, contributes to the definition of well-being and progress. In this frame, circular economy and holistic approach in planning urban areas and designing public and private buildings play a decisive role. In the case of restoration, it can even be critical to achieve the best compromise between the desired acoustic quality and the architectural constraints imposed by the structure being restored. Software for simulating sound response in enclosed spaces can help to solve this issue.
The paper reports the numerical-experimental method used for the acoustic design and main results obtained in the acoustic requalification design of a church and a historic theater, both located in Tuscany (Italy). In the first case study, a requalification procedure was devoted to transform the church of Rispescia in a multifunctional auditorium by using sustainable materials. The study and design are referred to a building with a significant volume of approximately 1300 m^3, where the presence of finishing materials and reflecting furniture determined a high acoustic discomfort, making the hall difficult to use for events like lectures and concerts. After the implementation of the designed interventions, the church has been regularly used for different functions.
In the second case study, the proposed method has been applied for the acoustic restoration of the historic theater of Monsummano Terme by modifying its former acoustic design and thus extending its use to include concerts in addition to theatrical performances.

1. Introduction

Sensitive aspects of historical buildings concern restoration and renovation. In fact, in the case of the restoration of historic theaters and churches for example, it is not possible to create prototypes and negative results would be catastrophic [1-4]. Moreover, it can even be critical to obtain the desired acoustic quality when some architectural constraints imposed by the structure being restored are present. The use of the hybrid numerical-experimental acoustic design method proposed in this paper enables accurate calibration of the theater and church model so that any errors may be detected prior to restoration, thereby eliminating costly and most times, unsatisfactory retrofits, attempting to minimize the sound prediction uncertainties and the differences in the actual and simulated acoustic responses.
Referring to the design phase of possible solutions, sustainable growth to be referred to the three aspects of environment, economy and society, is the greatest challenge of the 21st Century. In this frame, circular economy and holistic approach in planning urban areas and designing public and private buildings play a decisive role. Circular economy is an economic system that can regenerate its own. In a circular economy,

material flows are of two types: biological ones, capable of being reintegrated into the biosphere, and technical ones, destined to be revalorized without entering the biosphere.

Holistic designer of urban areas and buildings try to apply to their designed works the idea that the whole is more than merely the sum of its parts, in theory, and above all, in practice. In the frame of circular economy, holistic design is also based on the attenuation of impacts by using materials characterized by reactive intelligence, as a coherent composition of natural and artificial materials which well adapts to the characterization of works in delicate contexts.

In the first example shown in this paper this specific matter of effectiveness has been applied by the designers in the acoustic requalification of the Rispescia Auditorium, located in a church. In fact, the proposed acoustic solutions have been designed keeping in mind the virtuous constraint of sustainability for all selected construction materials and artefact in order to create an eco-compatible and aesthetically attractive space. Moreover, only natural materials have been used, being them recycled and/or recyclable.

2. Methodology and parameters for the acoustic design

In this Paragraph the hybrid numerical-experimental acoustic design method useful to accurately calibrate the acoustic model adopted by both the case studies is presented. The advantage of using a model in this frame is to be able to detect errors and to minimize the sound prediction uncertainties and the differences in the actual and simulated acoustic responses prior to a potential restoration, thereby eliminating costly, and most times, unsatisfactory retrofits [5-9]. To method consists of the following steps:

Step 0. Definition of geometric and acoustic scenario and of design objectives, with reference to the various possible destinations of the building.

Step 1. Experimental measurements of sound pressure levels, reverberation time and impulse response with a previously characterized sound source.

Step 2. Construction of a three-dimensional geometric model simulating actual internal conditions.

Step 3. Calibration procedure which guides the user in modifying the absorption coefficient of each surface, starting from the most uncertain one. This step is especially critical, since, if the absorption coefficients are improperly assigned, the model could anyway be calibrated according to the reverberation time determined on the basis of previously acquired experimental data, but the error would render it worthless for representing the building’s acoustic response and incapable of simulating structural modifications.

Step 4. Simulation and verification of the current acoustic conditions.

Step 5. Simulation of the design proposals and selection of the solution(s) to be implemented.

Step 6. Repetition of the experimental measurements carried out during Step 1 in the post-operam scenario and comparison with those collected during the ante-operam one.

3. The acoustic design of an auditorium into a church

3.1 Introduction

The study and design reported in this Paragraph are referred to the Legambiente Auditorium, located in the church of Rispescia, in the area of the National Centre for Sustainable Development "The Sunflower" [10] in western Tuscany. The church has a rectangular plant of about 8x19 m and variable height from a minimum of 8.86 m to a maximum of 9.92 m, in correspondence with the ridge line. The cover is made of two layers supported by wooden trusses. The room is equipped with an altar area currently used as a speaker zone when used for conferences and as stage for concerts and plays. The plastered masonry walls are provided of windows (1x2.82 m). The bottom wall has a large entrance with 1.90x 3.5 m wooden door of and two 0.78 x 1.5 m windows. The volume of the church is approximately 1300 m^3 and finishing materials and reflecting furniture (marble floor, plastered walls, stone in the altar area, cover bricks in the soffit tiles, wooden exterior carpentry and single glazing, wooden interior doors, metal benches drilled) are present. These aspects determined conditions of perceived acoustic discomfort that made difficult to use the hall for events including listening of speech and music and Festambiente, the Italian National festival of the environments. Moreover, the church, or parts of it, weren’t easy to use neither for simple exhibitions, lectures and other cultural events.

3.2 The acoustic design

According to Step 0 of the method, the main objective of the acoustic project was to create a comfortable sound and a versatile environment for the different types of expected functions. This goal has been reached through the creation of variable solutions, able to guarantee for each intended use a proper acoustic performance, keeping in mind the virtuous constraint of sustainability for all selected construction materials and artefact in order to create a space that is eco-compatible and aesthetically attractive as well. Moreover, only natural, recycled and/or recyclable materials have been used (plants, wood, recycled rubber from discarded tires, polyester from recycled PET bottles).

3.2.1 Considered parameters

For the improvement of the acoustic performance of the space, with reference to its various possible destinations, the parameters reverberation time (TR), clarity (C50) and speech transmission (STI) have been selected. For the choice of target values for these parameters, the optimum ones defined in the Appendix C of the Italian Standard UNI 11367 [11] have been referred to. According to Step 1 of the method, the TR of the Auditorium has been measured according to the ISO3382 [12], while the optimum reverberation time in the frequency domain has been calculated according to the UNI 11367 [11]. However, since one of the project goals was the creation of optimal characteristics conditions for a multi-functional environment, a more general reference for TR has been established to a specific performance range (Table 1).

Table 1: Comparison between measured TR, optimal TR according to ISO 11367 and to a more general reference.

f [Hz]	125	250	500	1000	2000	4000
Measured TR [s]	3.54	3.53	3.47	3.52	2.75	1.89
Optimal TR [s] UNI 11367	1.23	1.23	1.03	1.03	1.23	1.23
Optimal TR [s] more general reference	1.3÷1.8		1.0÷1.2	1.0÷1.2	1.0÷1.2	

From Table 1 it can be noticed that the measured TR was far above the considered optimal values for the project. For the background noise, the ISO NR30 curve has been considered (Table 2).

Table 2: Background Noise according to NR30 curve.

f [Hz]	125	250	500	1000	2000	4000
NR30 [dB]	48	40	34	30	27	25

3.2.1.1 Validation of the acoustic model and designed solutions

The 3D model representing the current characteristics of the church has been created making use of Ramsete© 2.5 software. The model has been calibrated by comparing the TR measured in significant environmental points with the simulated TR in the same locations. With reference to Step 3, the sound absorption characteristics of materials were obtained via the iterative process of model calibration based on TR. The good validation of the model is proved by verifying that deviations in absolute value of the measurement and simulated average reverberation time data are lower than 0.1 s.

According to the main objectives of the acoustic design, the project of acoustic correction of the church involved design and construction of three integrated solutions summarized below, to be simulated during Step 5:

1. sound-absorbing evergreen plant coating for the improvement of absorption on the back wall;
2. sound absorbing curved acoustic panels suspended from the ceiling (36 baffles arranged in six parallel rows);
3. mobile network of double-face reflecting/absorbing panels on wheels for acoustic separation in different configurations of sub-areas.

Depending on their position and side, the reflecting/absorbing panels curved panels can perform a double function:

- sidewalls lining panels that are sound-absorbing or reflecting and diffusing sound, depending on the side facing the interior of the church;
- acoustic separation elements between different sub-areas of the hall.

Specifically, panels have radius of curvature of 3.5 m, height 2 m and a thickness of 106 mm, some with sound absorbing concave side and other with sound absorbing convex side. The system is supported by a wooden structure and floating through the use of wheels provided of brake system for a total weight of about 80 kg. In Figure 1 some pictures of the church are shown, according to the implemented solutions.

Figure 1: The church of Rispescia with the new designed implemented acoustic solutions.

3.3 Results

With respect to Step 6, in the post-operam scenario some sets of reverberation time measurements were carried out in several configurations, obtained changing the position and the orientation (side) of the double-face reflecting/absorbing panels on wheels. As first set of tests, the church has been considered as a whole auditorium and the effectiveness of the following three solutions has been considered:

a) only suspended sound-absorbing panels;
b) suspended sound-absorbing panels, evergreen coating and double-face panels in the minimum sound absorption configuration;
c) suspended sound-absorbing panels, evergreen coating and double-face panels in the maximum sound absorption configuration.

From the comparison of the results of measurements with the range of optimal values for speech derives that project objectives are fully respected.
Figure 2 shows how the configuration a) represents a huge improvement where compared with the ante-operam reverberation and how double-face movable panels and evergreen plants coating (b and c) have resulted in a further reduction of approximately 0.5 s at all frequencies for the reverberation time, compared to the configuration of only suspended panels.
Moreover, specific Sound Pressure Levels (SPL) measurements have been performed to assess the distribution of sound along the church, starting from an omnidirectional normalized source placed in a central position at the altar (stage), and in some places corresponding to listeners possible positions.
The results show levels varying from a maximum of 92.4 dB(A) at the receiver position closest to the source, to a minimum of 88.7 dB(A) at one of the more distant receiver.

The maximum difference between two measured level is therefore equal to 2.7 dB(A), in accordance to what calculated for this configuration.

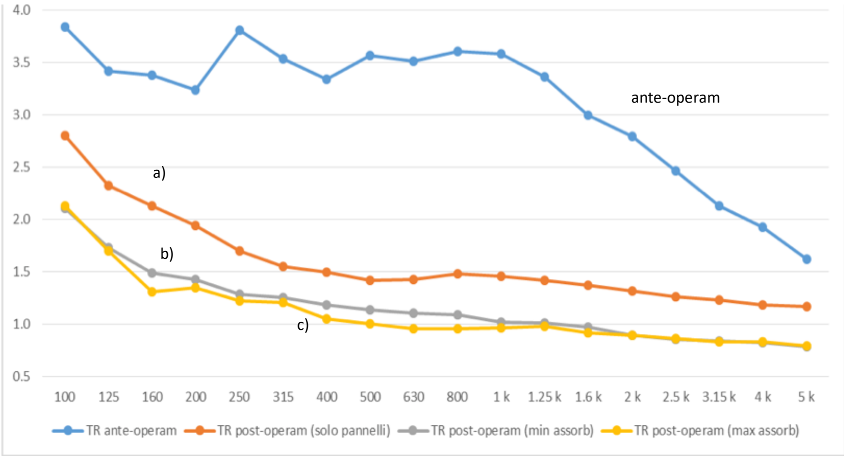

Figure 2: reverberation times in configurations a), b), c) and comparison with ante-operam.

The double-face panels can also be used as elements of separation and insulation between the different subareas of the room. This is particularly important when the room hosts several working groups operating simultaneously. The effectiveness of mobile acoustic panels as separation elements between adjacent sub-areas has been tested, carrying on SPL measurements aimed at identifying the acoustic attenuation determined by the presence of the panels in some of the catalogued configurations. A normalized sample source (dodecahedron) and receivers (sound meters) have been placed in different areas of the hall at ear height of a seated person. The SPL measurements have made possible to evaluate the differences present in the considered receivers points in both the basic configurations (panels at wall) and in workshop settings (panels as separating walls). The presence of the panels determines in the workshop schemes reductions in SPL from 5 dB to a maximum of almost 12 dB (A) in correspondence of all the receiver points in the sub-areas different from those in which the source is located. Conversely an increase of almost 1 dB (A) is measured in the receiver point located in the same sub-area where the source is.

4. The acoustic design of a historic theater in Monsummano Terme

4.1 Introduction and objectives

The historic Italian theater G. Giusti was built in the late nineteenth century in Monsummano Terme, approximately 25 miles northwest of Florence. Although it had been in disuse since the 1950s, it was considered an outstanding example of the horseshoe-shaped “teatro all’italiana” [13-15]. According to the Step 0 of the method described in Paragraph 2, the aims of the restorers were to return the building to its former glory while respecting current safety regulations and to improve on its original acoustics so that it could be used for concerts as well as theatrical performances. To accomplish this, it was necessary to improve its overall acoustic quality by distributing the sound uniformly throughout the building and optimizing the acoustic parameters in accordance with predetermined reference values [16-17].

4.2 Experimental measurements

In relation to the Step 1, for calibrating the simulation model, TR and SPL were experimentally measured. The TR was measured according to ISO3382 [12] prescriptions for the interrupted noise method and, although the standard prescribes a minimum of eighteen measurements to ensure proper coverage, twenty-one measures were carried out, three for each microphone position. Thanks to the symmetric configuration of the hall, it was necessary to carry out the measurements on only one side of the orchestra. Seven receiver points were selected in relation to the seating arrangement, the hall geometry and the ISO-imposed conditions of a minimum reciprocal distance of two meters and a minimum surface lateral distance of at least one meter. The microphone was positioned on a tripod 1.2 m above ground level. Three positions for the sound source enabled coverage of the whole theatrical area and verification of the symmetry of the configuration have been chosen:

- Source CS was positioned at centre stage at approximately two meters from the edge.
- Sources RS and LS were positioned four meters away from source CS, one on the right and one on the left side of the stage.

SPL at eleven positions in the orchestra and six positions in the balcony were also measured to provide the full coverage (Figure 3). The sound source used to perform reverberation time and sound pressure measurements in the theater was previously characterized. In particular, the sound source power spectrum and directivity were determined by performing SPL measurements in outdoor environment according to ISO 3744 [18].

4.3 Three-dimensional model designing and calibration

With reference to Step 2 of the procedure defined in Section 2, A three-dimensional geometric model was built aimed to duplicate the theater's actual acoustic conditions. The hall was reproduced with maximum definition levels in the balcony, orchestra, and stage sections. By accurately duplicating the volumes and solids, an object dimension accuracy of 30-40 cm was achieved (Figure 4). The surface absorption coefficients present in the hall were mostly set on the basis of indications available in the literature [19]. Nevertheless, some surface like the coverage was difficult to characterize, so, in this case, the sound absorption was firstly defined as a trial value to be optimized in the calibration phase (Step 3 of the procedure defined in Section 2) according to the measurements results.

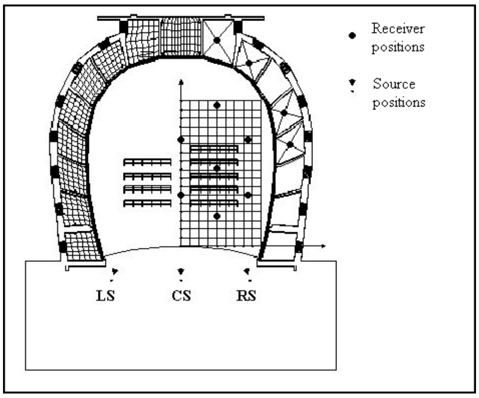

Figure 3: Positioning of the sources and the microphones.

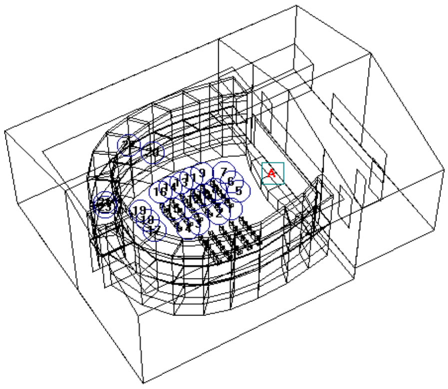

Figure 4: 3D model with sound source and microphones.

The source was set on the stage in the off-centre position previously selected for the SPL measurements. This setup was suitable for comparing the SPL and TR, since reverberation did not significantly vary in relation to the sound source position. Consequently, some receiver positions were defined in the 3D according to the receiving positions considered in the measurements of TR and SPL.

The model was calibrated so that its response would duplicate the actual acoustic conditions as closely as possible. It was decided to adopt the TR as calibration index, in particular it was felt advisable to refer to decay intervals such as T20 that did not involve a long period of sound response [20]. Finally, the model was checked in relation to the SPL. The calibration procedure [21] compared the simulated and measured T20 values by using the SD index:

$$SD = \sqrt{\frac{\sum_{1}^{n}\left[T_{20}(p,f)_{mis} - T_{20}(p,f)_{sim}\right]^2}{n}}$$

where:

n= number of measuring points per frequency band numbers

$T_{20}(p,f)_{mis}$ = reverberation time measured at position p and relative to frequency f

$T_{20}(p,f)_{sim}$ = reverberation time simulated at position p and relative to frequency f

To establish a priority of interventions, a weighted index was assigned to each surface that would allow accounting for:
- uncertainties in identifying the type of surface and in estimating its acoustic absorption;
- uncertainties in measuring the area of the surface;
- inaccuracies in geometric surface representation;
- effects of the acoustic absorption of the surface on the total environmental absorption.

Starting from the surface with the most critical index, the absorption coefficients was modified for each frequency band whenever the simulated reverberation time fitted the measured one. To evaluate the effects of corrections, a new simulation was performed for each correction step and the SD parameter was evaluated. This iterative procedure was replaced until SD parameter stopped decreasing and stabilized. When stabilization was reached, the absorption coefficients for the most critical element could be considered correct. We then examined the next element on the uncertainty list and proceeded in the same manner. To enhance the accuracy of the analysis, we observed the variations in the SPL at every step in the calibration procedure, comparing the values with the experimental data on hand.

4.4 Current acoustic condition and design proposals

According to the simulations of current scenario (Step 4 of the procedure defined in the Section 2), parameters such as TR, SPL, Sound clarity (C80) and Center time (Ts) have been evaluated [22-23] and it was found that it would be necessary to reduce its mean absorption and increase its reverberation time, according to the project design and the legislative references (Figure 5).
Regarding the design of an acoustic solution for the theater, the possibility of installing a specific acoustic ceiling was investigated and the acoustic effects of the proposed restoration solution were numerically simulated and evaluated using the simulation model (Step 5 of the procedure defined in the Paragraph 2). According to the simulation, the acoustic ceiling would retain the original reverberation time and reduce, albeit slightly, the sound definition. In keeping with the greater dispersion of the reflections, the total integration of the direct and indirect sounds would decrease to produce an improvement in music capability without a significant loss in clarity (Figure 6).

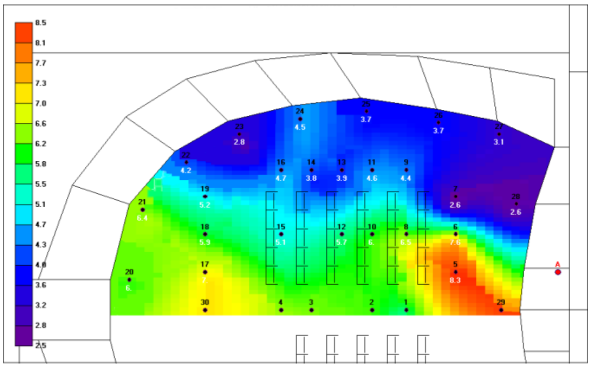

Figure 5: Map of sound clarity (C80).

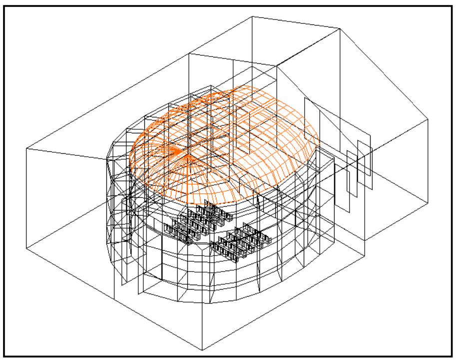

Figure 6: Monsummano Theater, designed solution.

Conclusions

A hybrid numerical-experimental acoustic design method can be considered as a precious instrument in order to obtain an accurate calibration of theaters and churches model so that errors may be detected and avoid prior to restoration. In this paper a numerical-experimental six-step method was described and applied to two pilot cases, respectively the church of Rispescia and the Monsummano Terme theater both located in the Tuscany Region, Italy. In the first case, after the application of the method, the church of Rispescia has been transformed in a real auditorium and in a multi-functional acoustic space as well. The reverberation time measured after design and construction shows full compliance with the project objectives, mainly aimed to create acoustic comfort conditions primarily in listening speech (conferences, lessons, workshops,

theatrical plays, cinema, expositions, etc.). The variable acoustics of the church, required to ensure optimal acoustic conditions in correspondence with the different uses is determined by the combination of three solutions and by the configuration of movable panels all using natural materials.
Concerning the theater of Monsummano Terme, the carried-out investigation showed that the theater was better suited to theatrical performances than concerts since, on the one hand, the acoustics characterized by deep lateral reflections combining with direct sound enhanced speech clarity and, on the other, the low reverberations rendered it unsuitable for music. The proposed acoustic ceiling produces a slight improvement in the overall musical quality through sound diffusion, without dramatically affecting the hall's acoustic properties.

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