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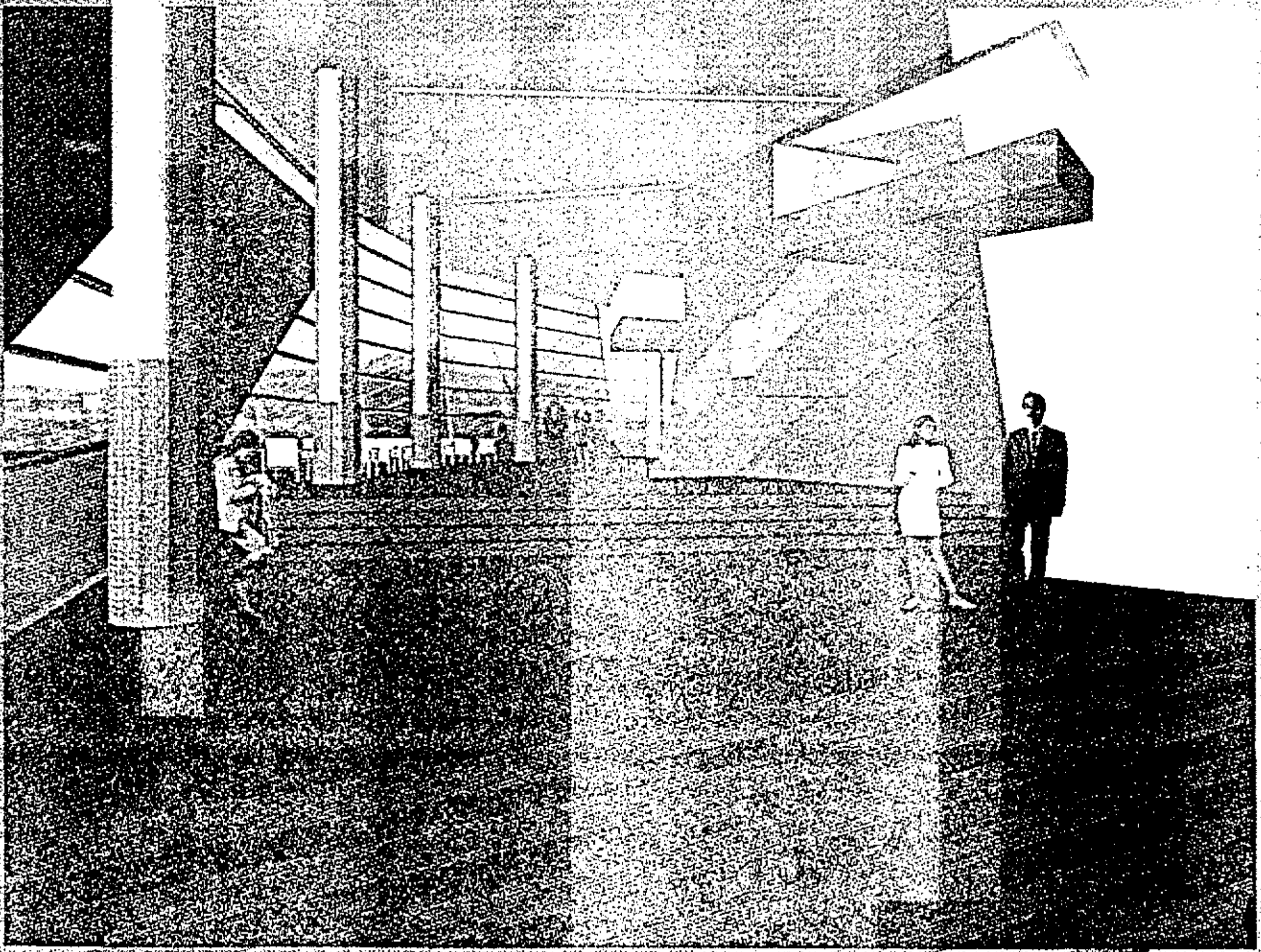

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Computer assisted methods and acoustic quality: recent application cases

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INTRODUCTION

While planning a new concert hall, the architect is generally free from any cultural constraints and can design looking only at the best compromise between architecture and acoustics; the peculiar characteristic of restoration works is that almost always the hall shape is already defined and sometimes also the architectural look cannot be changed.

However, when the restoration of an existing concert hall has to be undertaken, the architect has, in general, some choices whose acoustic importance is difficult to evaluate. In recent years a number of numerical simulation programs have been realized, making it possible to obtain the most useful acoustic parameters from a 3D CAD model of the room. However, good practice demands an initial calibration of the numerical model based on experimental measurements, from which a reliable estimation of the effects produced by the proposed modification can then be obtained.

In this work a numerical prediction method specially fitted for working on existing halls will be presented together with the results obtained in four cases related to different kinds of restoration:

- the S.Lucia church in Bologna, where only very few intrusive elements are admitted, owing to historical constraints. even for the color of the walls:

- the S.Domenico church in Foligno, where there are also historical constraints, but where only some paintings are present on the walls;
- the Teatro Comunale in Gradisca D'Isonzo, which represents the case where the architect and the acoustician can work together in an existing building shell and can really give a new look to an existing hall;
- the Teatro Alighieri in Ravenna, where a comparison between two different experimental conditions has been made with exactly the same computer assisted experimental methodology to state the real performance of an existing cavity under the orchestra pit.

The results show that this method can produce useful information in a reasonably short time, provided that measurements are carried out with the most advanced digital techniques and that a fast computation model is used: in this case the MLSSA measuring system and pyramid tracing or cone tracing programs were used.

For each hall, the study has been carried out by the following steps:

- binaural measurements were performed in the hall (before any alteration in the original condition) using the impulse response technique and a dummy head located at different listening positions: so it has been possible to evaluate the main acoustic parameters according to Ando's theory (such as listening level, ITDG, reverberation time, IACC and many others), and to map their values;
- calculations and mapping of Ando's preference values, with reference to two different kinds of musical signals (Mozart, $\tau_e = 38$ ms and Haydn. $\tau_e = 65$ ms) were accomplished from experimental measurements;
- software simulations of the geometrical configurations of the halls were performed, then the acoustic characteristics of the different wall materials were chosen in such a way as to converge on the measured values of the most important objective parameters, particularly EDT;
- the model, so calibrated, was used to evaluate the opportunity of introducing changes in the original configuration (shape and materials), computing in any situation the aforementioned objective parameters; some listening experiments with auralization were also made, to compare subjectively the proposed treatments with the original situation.

The results of these comparisons, and the influence of the correct choice of some parameters in impulse response prediction, by pyramid and/or cone tracing, are explained.

MEASUREMENT TECHNIQUE

The measuring system has been used primarily to obtain the binaural impulse responses at each listening point. For this, an omnidirectional loudspeaker was used, being fed with the Maximum Length Signal produced by a MLSSA

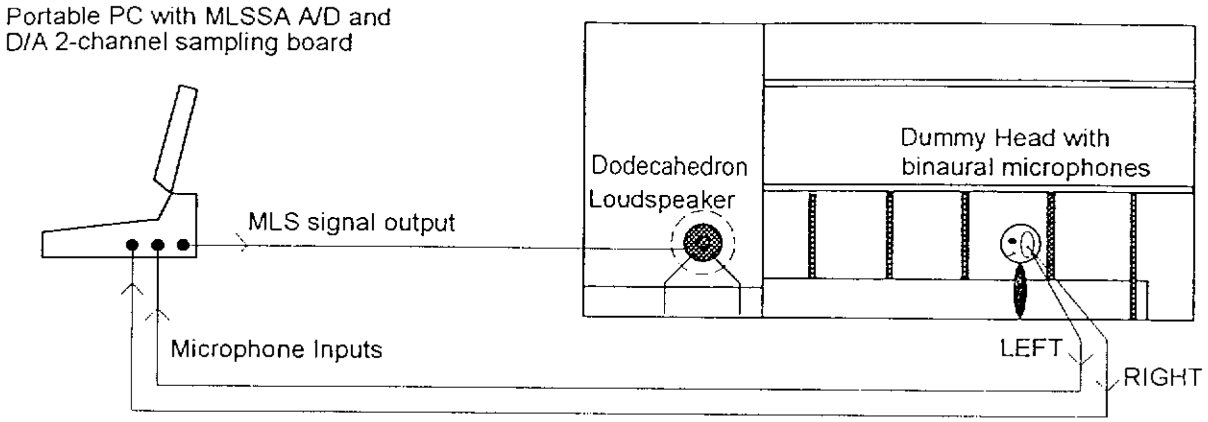


Fig. 8.1 The measuring system.

board, installed in a portable PC. The signal period was 65 535 samples, and the sampling rate varied between 22.05 kHz and 44.1 kHz. The acoustic signal was sampled through a dummy head (Sennheiser MKE2002 set), connected with the MLSSA board through a wireless system (NADY VF-701). The measurement was repeated for each ear, thus enabling the computation of the interaural cross correlation (IACC) through a dedicated post-processing program, in addition to the wide range of other acoustical parameters computed by the MLSSA software. Figure 8.1 shows a scheme of the measuring system.

NUMERICAL SIMULATION PROGRAMS

In the first case presented, two commercial room acoustics programs have been employed. The first, used for the three cases presented, is a pyramid tracing code,[1] suitable for noise evaluation in workplaces, for the simulation of loudspeaker coverage and for concert hall acoustic quality evaluation. A notable feature of this program is the fact that it is not hybrid: each pyramid is followed (without split-up) for the whole time length of the impulse response. Then a multiplicative correction is applied to the response of each receiver, enabling the study also of non-Sabine spaces with a small number of pyramids (typically 256). Until now however, problems arise for very regular spaces: by always considering specular reflections as well for high-order reflections, the late part of the tail becomes very uneven, as shown clearly by Dalenback.[2]

The second program, used for comparison in one of the three cases, is a hybrid cone tracing program,[3] in which initially the cone tracing is used for evaluating deterministically the early reflections (by identifying the corresponding image sources), and then a reverberant tail is appended, computed by advanced statistics on the history of the rays. It can also handle diffuse reflections, producing smooth late tails, provided that a sufficiently large number of cones is employed.

In the case where both programs were used, it was possible to verify the

In the case where both programs were used, it was possible to verify the difference between the results obtainable with the two different approaches, and also the sensitivity of the two programs to the variation of the input data (absorption coefficient of the surfaces).

THE S.LUCIA MAIN HALL IN BOLOGNA

The University of Bologna has its main hall located inside an unused building, an ancient church originally devoted to S.Lucia, restored and opened to the public in 1988. The aesthetic appearance of the hall is impressive: the architectural complex comprises three naves, a semicircular apse and a high, vaulted roof; the walls and the ceiling are finished with a clear, hard plaster. Lightly upholstered seats occupy the floor of the main nave, surrounded by a wooden balcony. Figure 8.2 shows a perspective view of the room, with the proposed acoustic treatment.

Due to the large dimensions of the hall, to its large and empty volume and to the sound reflecting finishing of almost all surfaces, the listening quality in the hall is very poor. Therefore, a thorough acoustical study was undertaken, in order to give to the hall an acceptable acoustical quality, for both speech and music; the experience reported in this paper is a study oriented toward the second goal (music).

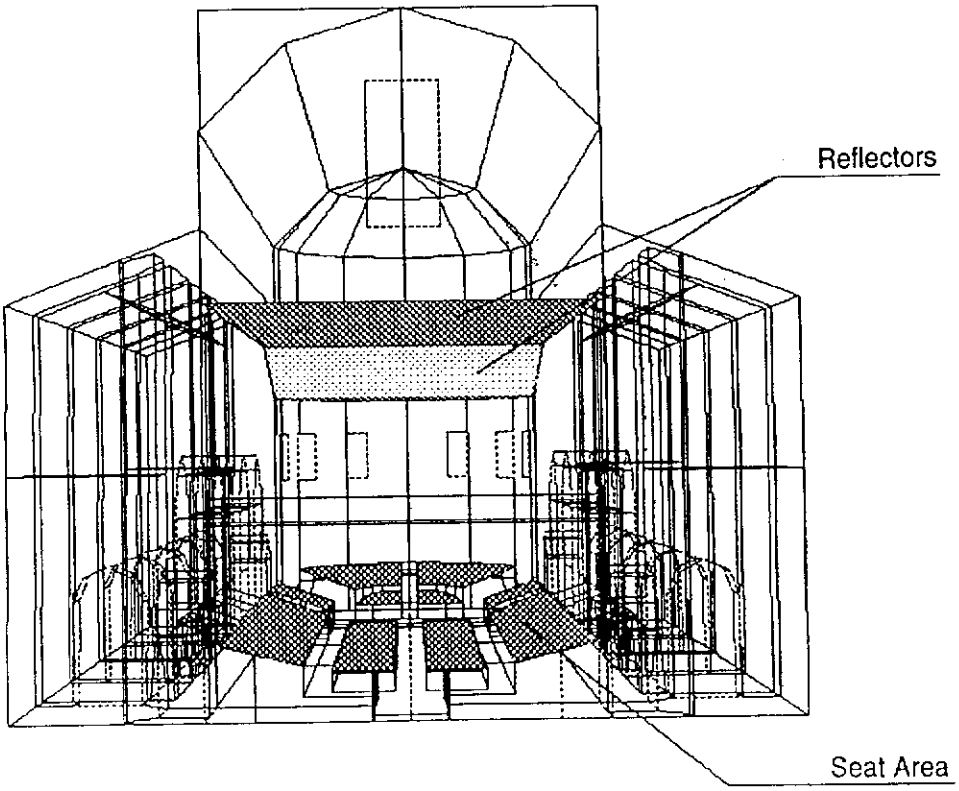


Fig. 8.2 Proposed acoustic treatment of S.Lucia church.

The experimental data clearly showed that the poor acoustic quality is due to the lack of early reflections, to the very slow sound decay (too much reverberation) and to the strong and late reflections from the vaulted roof and from the rear wall.

The proposed acoustic correction, not fully satisfying from the aesthetic point of view but surely useful for the comparison of the two numerical programs, is based on sound reflecting, optically transparent panels which exclude a considerable part of the upper volume, block the negative influence of the lateral naves and redirect the sound energy to the only strongly absorbing surface: the seating area.

Choice of the calculation parameters

The measured reverberation time was always smaller than 8 s in each frequency band of interest; therefore the simulations were limited to 8 s.

With an auxiliary procedure of the cone tracing program a volume $V = 45\ 900\ \mathrm{m}^3$ and a total surface $S = 12\ 500\ \mathrm{m}^2$ were estimated. Using those data a mean free path $l = 14.7$ m and an average number of reflections for a ray $k \leqslant 200$ were computed. Thus it was decided to make the cone tracing program generate 10 000 rays to be followed till the 200th reflection. The pyramid tracing program generated 8192 pyramids (this number must be a multiple of $8 \cdot 2^n$, n integer), followed until the time limit.

The diffusion coefficient required by the cone tracing program was set to 1 as suggested in reference 3, and the transition order from deterministic to statistical reflections was set to 5

Validation of the models

In order to evaluate the accuracy of the two models, a comparison was made between the computed values of some acoustical criteria and the corresponding experimental values.

The variations of the criteria with the position in the hall were taken into account by selecting an array of eight reference points distributed along the main nave. The choice of the most suitable criteria for the task was restricted to those criteria common to both programs: SPL, EDT, C_{80} and center time t_s. The validation was made in two steps:

- starting with the model imported from the CAD program, the value of the sound power level of the source was selected, comparing the SPL values computed in the reference points with the measured ones;
- with an iterative procedure, the sound absorbing coefficients of the materials were modified until the measured and simulated EDT values agreed.

The first step was only a matter of shifting the resulting SPL, in a straightforward and simplified way, because the cone tracing allowed the assignment to the model of a global sound power level, but not of the spectrum shape of the actual source.

The second step involved only the EDT because, among the above mentioned criteria, this is the most sensitive to the sound absorption of the hall. The measured EDT values are very close to those of T_{15} and T_{20}.

It should be noted that the values of C_{80} computed with both programs are very different from the measured ones, although their spatial variation is close to the measurements. This suggests that at present, even with a room model more accurate than in current practice, clarity is not a reliable criterion for acoustic simulations, because the geometrical simplifications and the physical approximations needed to make the program work affect the clarity values too strongly.

In practice, the validation procedure was based on the variation of the sound absorption coefficient of the plaster, which is by far the most abundant material inside the room. Table 8.1 reports the initial, intermediate and final values used in the two programs.

For every acoustic criterion x (in the present case EDT), if x_{si} is the value computed during the simulation for the ith point and x_{mi} is the corresponding measured value, the prediction error is $(x_{si} - x_{mi})$; as an index of the accuracy of the model, the RMS value of the prediction error over the eight reference points was taken. Figure 8.3 shows the RMS error values affecting the results obtained with the two programs at the end of the iterative adjusting procedure.

As can be seen, with cone tracing a reasonable accuracy can be obtained, except in the 125 Hz octave band (probably a lower diffusion coefficient should be selected at low frequency). On average, pyramid tracing achieves a better accuracy than cone tracing, with the exception of the 4000 Hz octave band, where a bias error occurs in the computation of the sound absorption of air.

The absolute error values are small, as can be seen in Figure 8.4. The optimizing values of the absorption coefficient are such that almost exact correspondence between the computed and experimental values of EDT occurs.

Table 8.1 Plaster sound absorption coefficient in three validation runs of the programs.

	Plaster sound absorption coefficient for 1/1 octave bands					
	125	250	500	1000	2000	4000
Cone Tracing 1	0.03	0.03	0.03	0.02	0.03	0.02
Cone Tracing 2	0.05	0.03	0.01	0.02	0.02	0.02
Cone Tracing 3	0.05	0.03	0.018	0.018	0.018	0.02
Pyramid Tracing 1	0.04	0.035	0.03	0.02	0.03	0.04
Pyramid Tracing 2	0.045	0.04	0.02	0.02	0.03	0.05
Pyramid Tracing 3	0.045	0.035	0.02	0.02	0.03	0.06

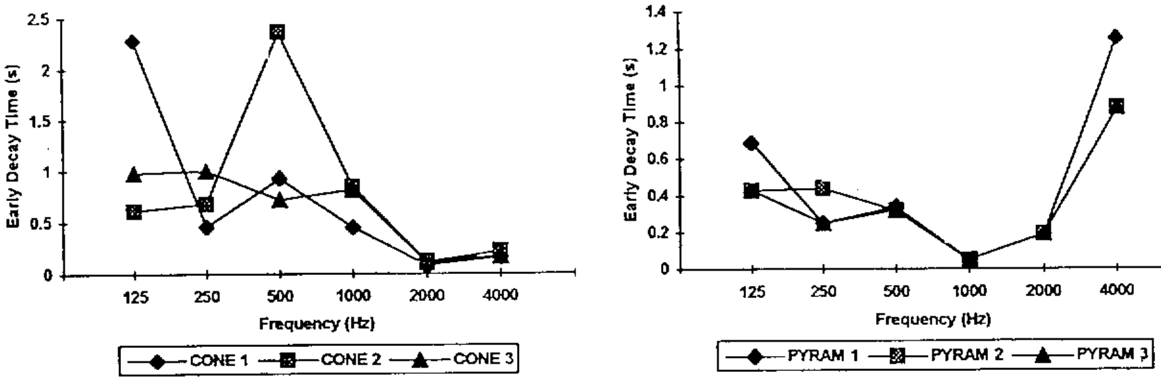


Fig. 8.3 RMS error of the parameter EDT for the two computer models.

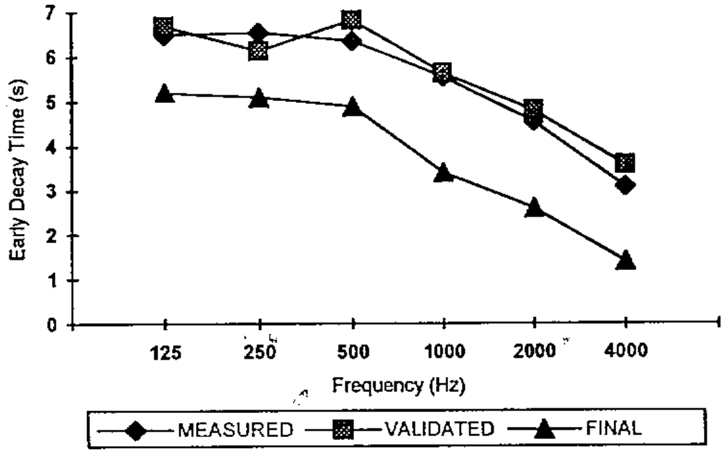


Fig. 8.4 Comparison of experimental EDT with values computed with pyramid tracing before and after treatment.

Design of the acoustic correction

The visual analysis of the ray paths, possible with the cone tracing program, confirmed the strong non-Sabine behavior of the hall and revealed the different (and critical) role of the high vaulted roof, the lateral naves and the vertical wall in front of the apse. The suggested acoustic correction was then designed in three steps.

First, a sound reflective ceiling was introduced into the simulation, over the audience, at a height considerably lower than that of the vaulted roof (see Figure 8.2); this reflector sends many sound rays toward the sound absorbing seating area and 'cuts out' the reverberating effect of the upper volume. The material should be optically transparent, in order not to change the appearance of the hall.

In the second step, the coupling with the lateral naves was prevented by inserting heavy curtains in the communication openings. Their sound absorbing surface helps to keep the reverberation as low as possible. It should be noted that, during the simulations, the lateral naves act as 'traps' for the sound rays, which often remain segregated in a little lateral volume and find the exit only

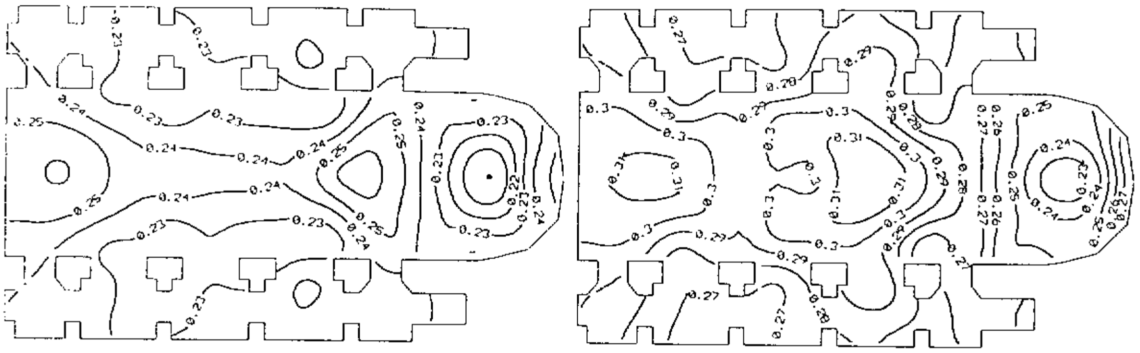


Fig. 8.5 Contour map of RASTI before (left) and after (right) the proposed treatment.

after a relatively long time; this effect, typical of rays rather than of waves, could lead to an overestimation of the negative role of the lateral naves.

The third step was the covering of the rear wall with a sound absorbing plaster, in order to avoid echo effects.

Optically transparent reflectors were also inserted over the apse and oriented in order to reinforce the early reflections perceived by the orchestra.

The overall effect of the proposed treatment is noticeable: in Figure 8.4 the new EDT values are shown to become significantly lower than in the actual case (however the reduction of T_{20} is not so large). In Figure 8.5 the contour maps of RASTI, computed with the pyramid tracing program, are compared; the improvement is, on average, good. However a strong focusing effect in the center of the apse can still be observed, which was not reduced by the proposed treatment.

THE S.DOMENICO CHURCH IN FOLIGNO

The city of Foligno (PG) does not have a concert hall suitable for large ensemble performances for a large audience. For this reason an ancient church, no longer used for religious purposes, was re-adapted and restored. It was not possible however to reduce the enormous volume, and so it was necessary to study an acoustic treatment of the room, with the aim of reducing the reverberation time, increasing the clarity and intelligibility and eliminating some echoes and focusing actually present.

Fortunately in this case the main nave is narrow and long, and the side walls produce many strong lateral early reflections, so the spatial impression is very good. The reverberation time was slightly lower than in the previous case, and it was possible to add some sound absorbing plaster on the walls, so that the reverberation can be controlled to within reasonable values in this case. A reflector was added over the orchestra pit to avoid echoes and focusing from the apse, and to send the reflected sound energy towards the rear part of the main nave, where the direct waves arrive attenuated by grazing incidence over the long seating area. Figure 8.6 shows the modelled geometry of the church with the proposed acoustic treatment, which is already partially executed.

Choice of the calculation parameters

In this case an accurate calibration of the computation parameters having an important role in the tail correction, as explained in reference 1, was performed, enabling very fast computation with just 256 pyramids. First a preliminary test was conducted, based on the comparison between the results obtained with two different runs with a different number of pyramids: 256 and 2048. Then, by a least squares best fitting, 'optimal' values were found, minimizing the difference between the two sound decays.

It was found that the sound field has a perfectly Sabine character in this room, as the number of reflections increase with the square of the time. The mean free path is lower than $4V/S$, due to the shape of this room, very narrow compared with its length, and due to the presence of some lateral chapels and other minor spaces. It must be noted, however, that this effect could also be caused by the lack of diffusion artificially introduced by the specular reflection assumption applied to all the reflections: in this sense the adjustment of the relevant parameters makes it possible to compensate for this bias error, removing one of the limitations to the accuracy of pyramid tracing.

For the simulation an impulse response length of 5 s and a time resolution of 10 ms were chosen.

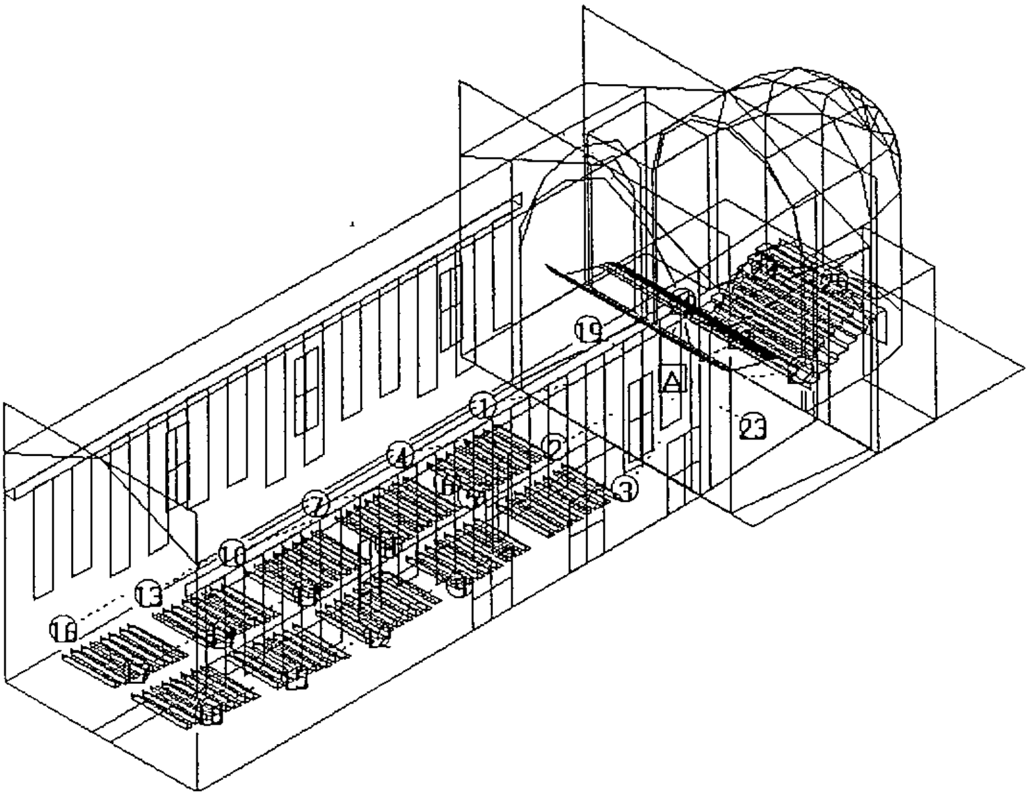


Fig. 8.6 The church of S.Domenico in Foligno.

Validation of the model

After the proper choice of the relevant parameters, many computations were performed by changing the absorption coefficient of the plaster, in such a way to obtain computed values of the reverberation time T_{20} as close as possible to the experimental values. This was possible as the computation time was only 4 min on a i486 DX2-66 PC, launching 256 pyramids for each simulation. The advantage of using a reduced number of pyramids, in addition to the speed obtained, is also that the tail correction algorithm corrects the late part of the tail, producing a numerical 'diffusion' effect, that is useful to avoid the oddities sometimes found in the simulation of long impulse responses with a 'specular-only' simulation code, as reported by Dalenback.[2]

Figure 8.7 shows the results of the validation process: the computed T_{20} values perfectly correspond to the experimental values. At lower frequencies the reverberation is very high, but it must be noted that the room was empty, and an audience of 1200 people will add considerable absorption, particularly in the low frequency range.

Design of the acoustic correction

The acoustic correction of the room is based on three steps: installation of sound absorbing plaster on the walls of the apse and transepts, large velvet panels suspended from the top of the lateral walls, and an acoustic reflector over the orchestra pit. All these modifications are shown in Figure 8.6. It must be noted, however, that these solutions are effective only at medium and high frequency; low frequency absorption could be obtained by the people seating in the stalls, but probably it will be necessary to add some resonant panels on the back wall to control the low end of the spectrum. This can be seen in Figure 8.7: the reduction of the reverberation time is noticeable at medium and high frequencies, but it is small in the low frequency range.

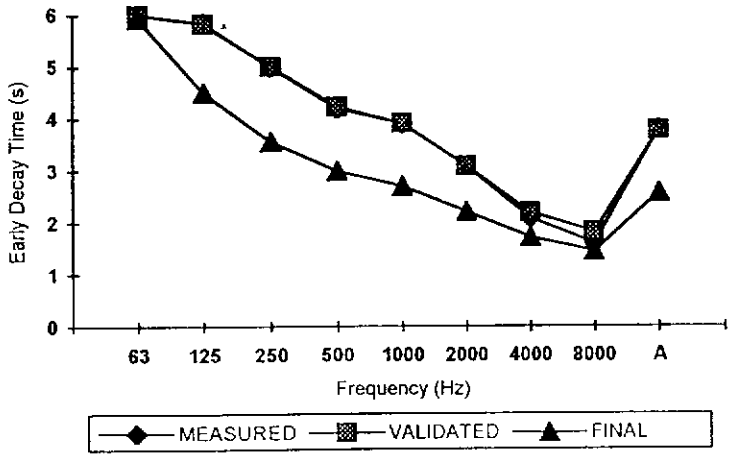


Fig. 8.7 Comparison of experimental EDT with computed values before and after the treatment.

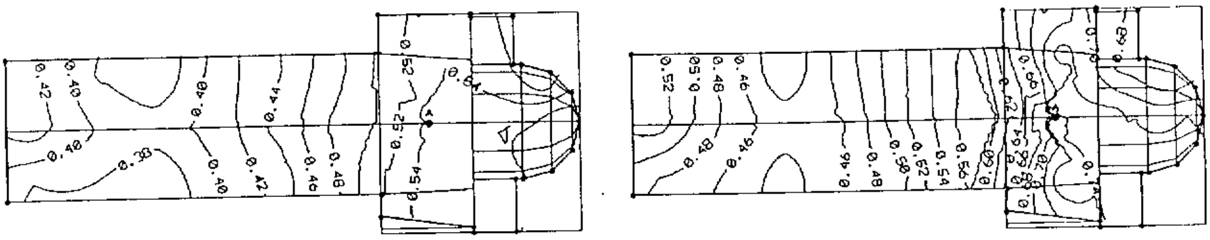


Fig. 8.8 Comparison between computed RASTI before (left) and after (right) the proposed treatment.

Figure 8.8 shows the comparison between the RASTI maps computed in the actual state and after the proposed treatment: there is an improvement to speech intelligibility, which will probably be beneficial also for music reproduction. The effect on music was evaluated by listening to convolved music samples, obtained using the convolution software Aurora[4,5] and anechoic samples from the DENON PG-6006 CD. Three convolutions were obtained for each sample, the first with an experimental impulse response, the second with the simulation in the original state (almost identical to the first) and the third after treatment to the room. The last exhibits better clarity, lower reverberation and wider spatial impression. A subjective validation of the auralization system was conducted including the comparison of the first two samples, as reported in reference 5; although the simulated sample was often distinguishable from the sample obtained by convolution with the experimental impulse response, the average subjective scores for the four most important parameters were not significantly different.

THE TEATRO COMUNALE IN GRADISCA D'ISONZO

The town of Gradisca D'Isonzo (GO) has a municipal theater, located in the main square. The building is currently under restoration.

The architectural complex comprises three levels of seats, one at the main level and two semicircular floors, as shown in Figure 8.9.

In order to establish the acoustic behavior of the theatre, and to give to the hall an acceptable acoustical quality, for both speech and music, a thorough acoustical study was undertaken, together with the architectural designer of the restoration.

The experimental data clearly showed that the poor acoustic quality was due to the lack of early reflections, to the slow sound decay (too much reverberation) and to the lack of volume in the farthest seats. The proposed acoustic correction is based on sound reflecting panels which redirect the sound energy to the only strongly absorbing surface: the seating area.

All curved surfaces were modeled with several planes; in particular, the thickness of the walls and of the columns cannot be neglected. Also the seating areas were modeled with realistic detail in the seat drawing, even if this caused an inevitable slowing of the program.

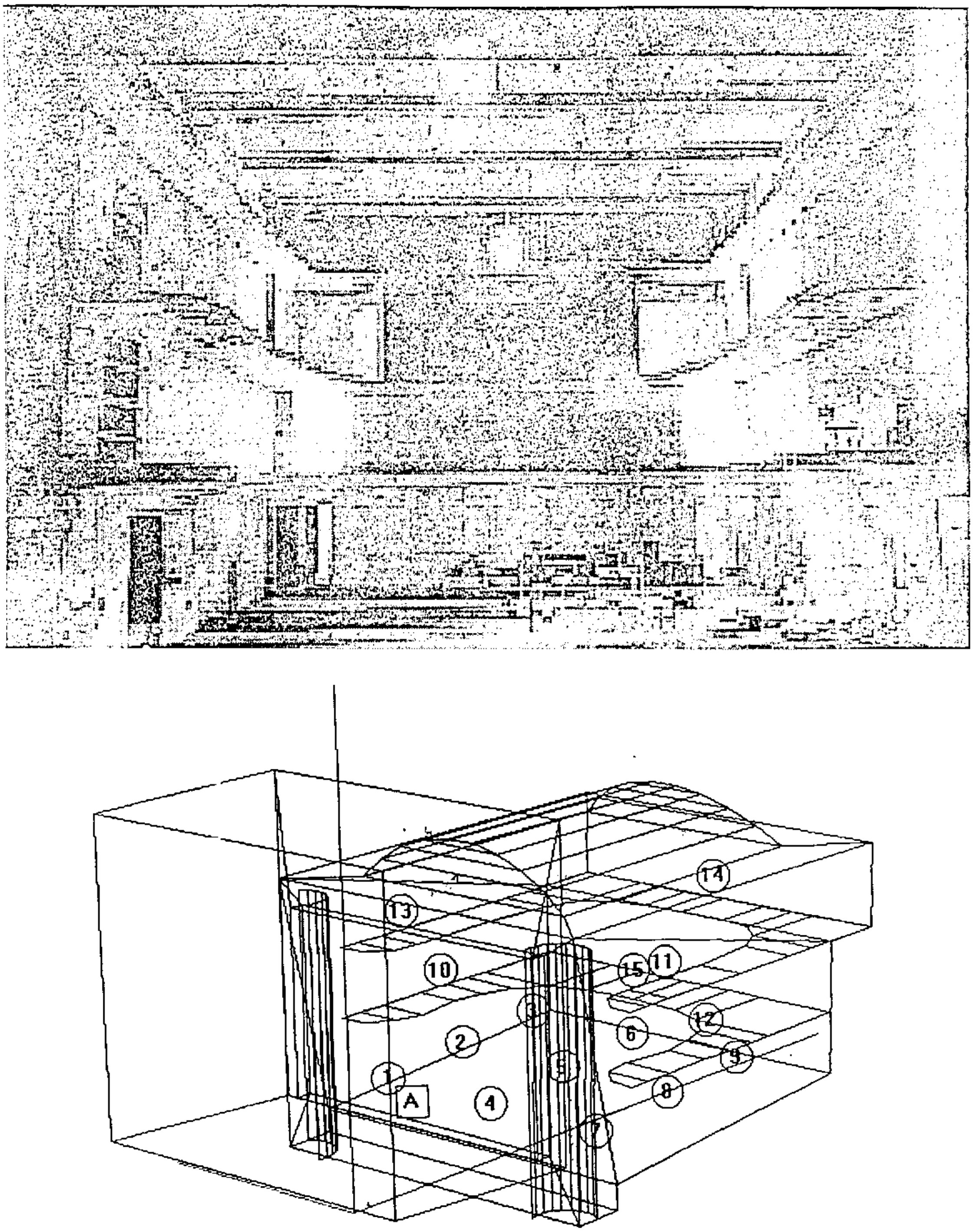


Fig. 8.9 Photographic view of the hall and CAD drawing of the model used for the validation.

Choice of the calculation parameters

The measured reverberation time was always smaller than 4 s in each frequency band of interest; therefore the simulations were limited to 4 s.

The computer code generated 16 384 pyramids, followed until the time limit, so it was possible to model the environment without further simplifications. The program requires selection in advance of the time resolution for the impulse response computation, which was set to 10 ms.

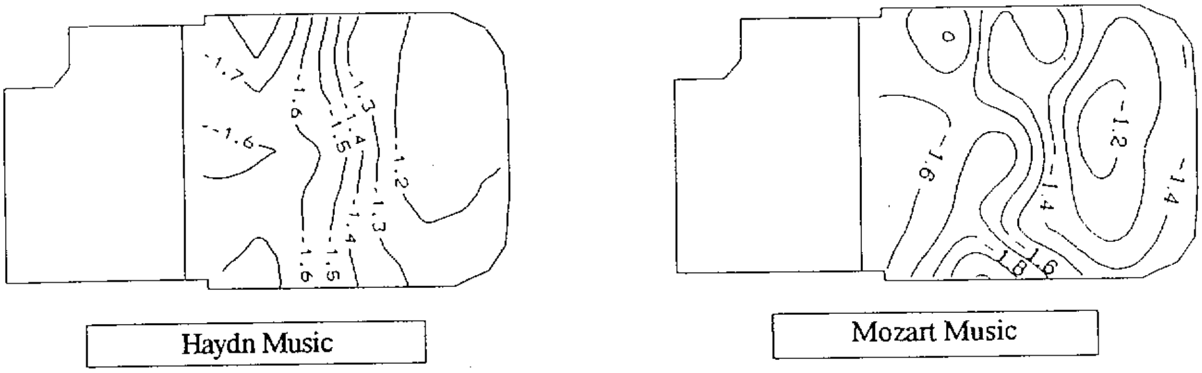


Fig. 8.10 Ando's total preference index.

Validation of the model

In order to evaluate the accuracy of the model, a comparison was made between the values of some acoustical criteria, either measured or resulting from the simulations.

The variations of the criteria with position in the hall were taken into account by selecting the calculation points distributed along the whole theater. The choices of the most suitable criteria for the task were restricted to EDT, C_{80} and center time t_s (unpublished work: Lam, Y.W.). The validation procedure has been the same as described above.

At the end of the iterative procedure, the values of EDT obtained from the simulation were very close to the measured ones, as shown in Figure 8.11.

Design of the acoustic correction

The acoustic correction was simulated in two steps.

First, a set of glass reflectors were introduced over the proscenium; these reflectors will redirect many sound waves toward the sound absorbing seating area.

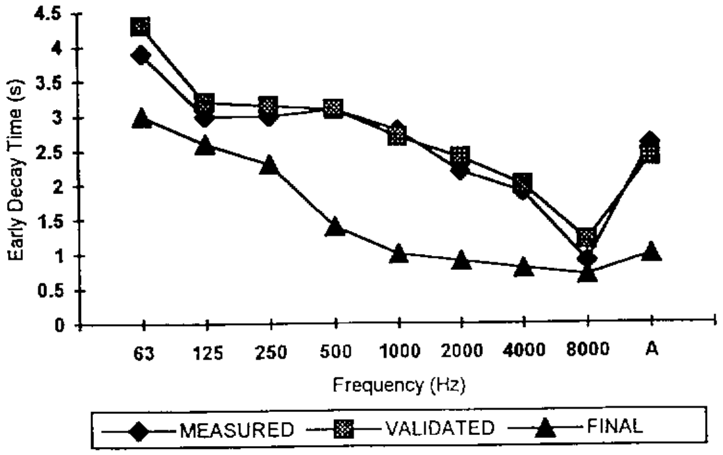


Fig. 8.11 Comparison of experimental EDT with computed values before and after treatment.

The second step was the covering of the ceiling and the rear wall with a sound absorbing plaster, in order to avoid echo effects, and obtain a smaller reverberation time; in fact the goal of the acoustic correction was to establish balanced behavior of the theater. either for music or for speech.

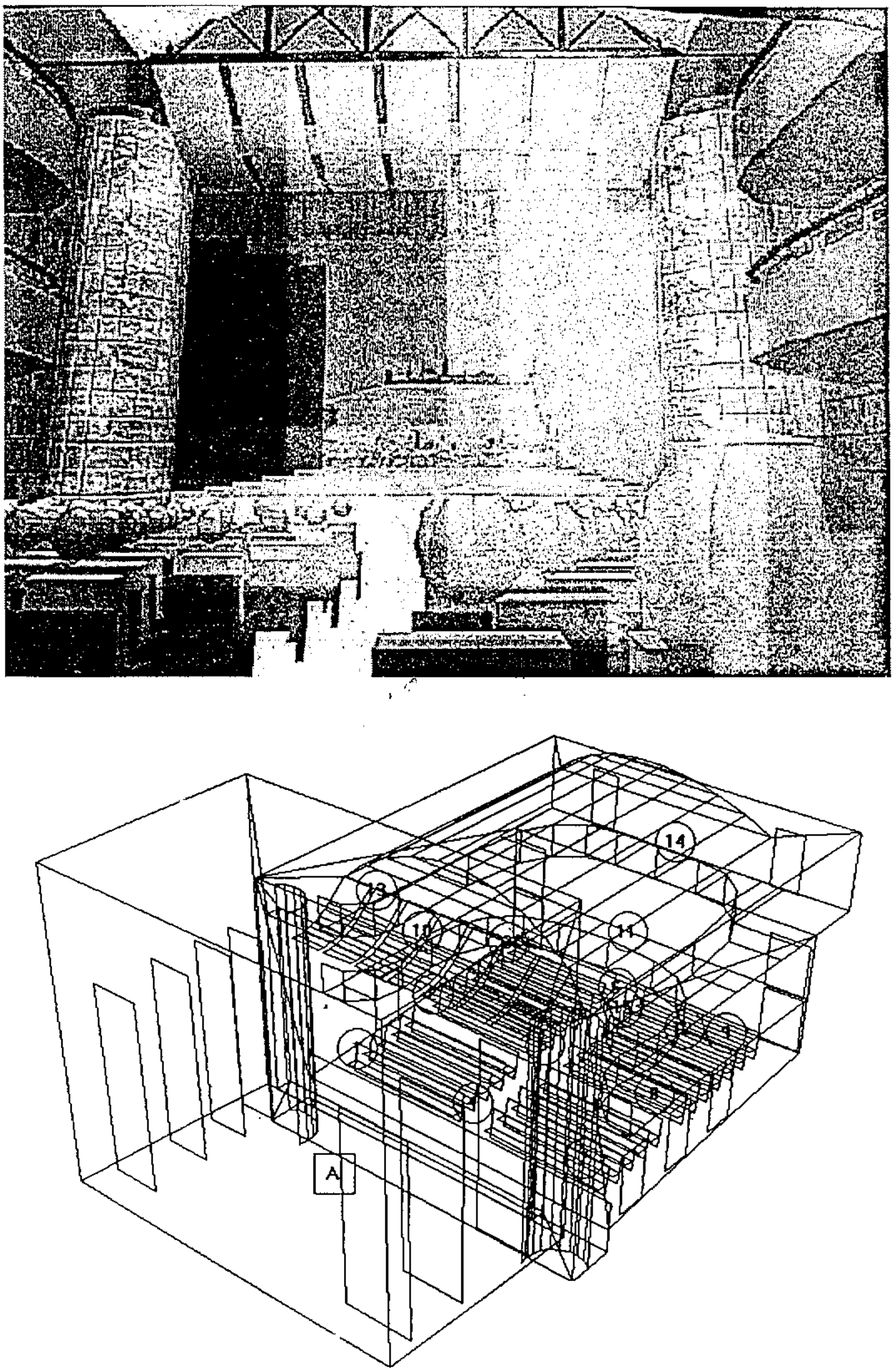


Fig. 8.12 Proposed solution: rendered view (above) and wireframe CAD model (below).

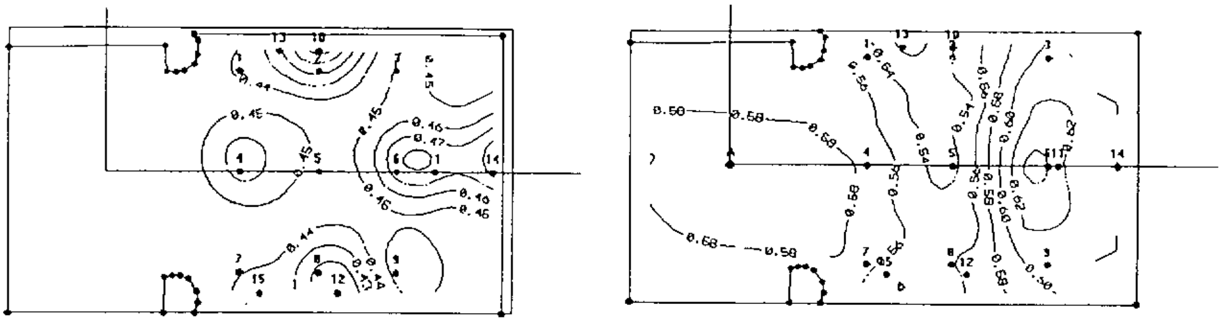


Fig. 8.13 Comparison of STI map before (left) and after (right) the proposed restoration.

Figure 8.11 also shows the EDT values obtained with the proposed acoustic treatment. Figure 8.12 shows the final appearance of the room with the proposed acoustic reflectors. Figure 8.13 shows the improvement in STI obtained with the proposed treatment.

THE DANTE ALIGHIERI THEATER IN RAVENNA

Introduction

In many Italian theaters it is still possible to find semi-cylindrical cavities under the orchestral pit.[6] Many European old opera houses had this cavity too, but almost all have been destroyed to provide a mechanical system that makes possible changes in the configuration of the stage in few minutes. while half a day is required for manual modifications.

In the Teatro Alighieri of Ravenna this wood cavity has a linear axis, and it was built by Venetian carpenters. For the first step, the subjective response was tested for both performers and musically educated people to the same musical program, performed first with an empty cavity and then with the same full of sawdust. From these responses, it was possible to understand that something in clarity and in spatial distribution of preference was changed, but the results were probably influenced, both for listening and the performers, by the musicians who adapted their performance to the acoustic response of the pit.

Experimental measurements

In order to quantify the effectiveness of the cavity on the acoustic quality of the theater a set of experimental measurements with an *empty* and then a polystyrene *filled* cavity was performed.

The study has been carried out by the previously stated steps, that is:

- binaural measurements were performed in the hall with both an empty and a filled cavity, using the impulse response technique and a dummy head located at different listening positions (29 referring to empty cavity, and

27 to filled cavity), changing the source position as well. An example is given in Figure 8.14.

- Calculation of Ando's preference values, with reference to two different kinds of musical signals (Mozart, $\tau_e = 38$ ms and Haydn, $\tau_e = 65$ ms). See Figure 8.15.

Results of the experimental measurements and overview

From the experimental measurements, it was clear that the main value of the parameters, referring to the conditions with empty cavity and filled cavity, behave in the following way:

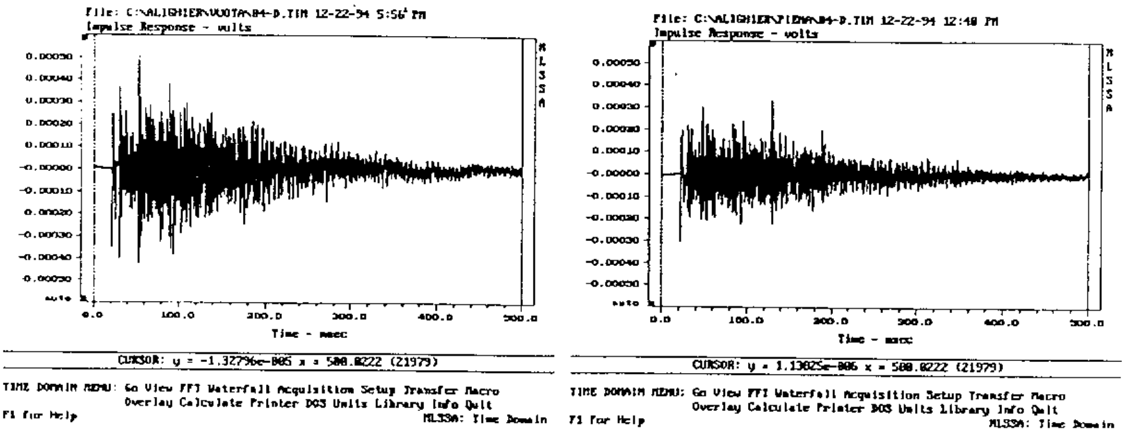
- the center time and the clarity (C_{50}, C_{80}) are far from the optimum values in each frequency bands – the empty cavity condition is better (Figure 8.16);
- the reverberation times (EDT, T_{15}, T_{30}) increase to 15–20% with the empty cavity (Figure 8.17);
- the listening level increases by 5–8 dB, for each frequency band, when the cavity is empty (Figure 8.18).

The spatial distributions of the Ando's preference indices, passing from the condition of filled cavity to that of empty cavity, are changed in this way:

- the preference index of ITDG is better in the rear of the room;
- the preference index of reverberation time is better in the whole theater;
- the preference index of listening level is worse in the seats at the front of the hall, but is better at the rear.

In the condition of *empty* cavity, the sound is reinforced, so the listening level and reverberation time preference indices are better, but the spatialization in the front seats of the hall is worse.

The results of the objective measurements are very close to the subjective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Impulse Response - volts
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Fig. 8.14 Impulse responses at point N.4, with empty and filled cavity, for the right channel.

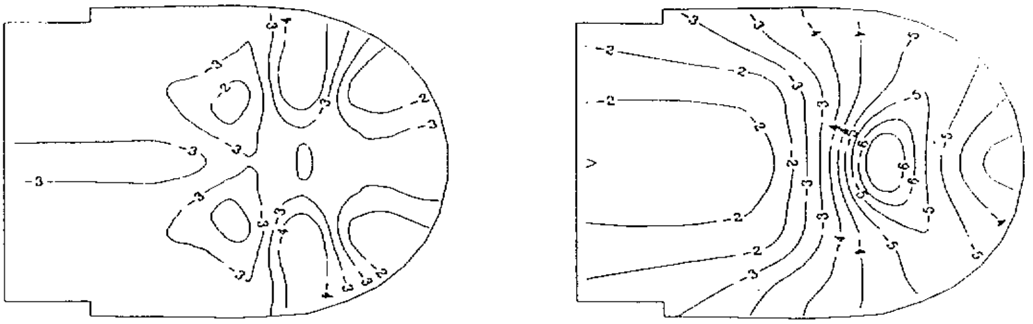

Fig. 8.15 Ando's total preference index: cavity empty (left) and filled (right), for Mozart's music.

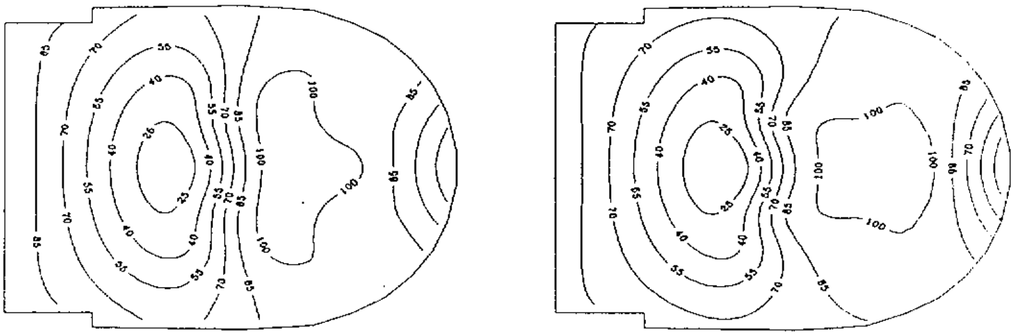

Fig. 8.16 Spatial distribution of center time with empty (left) and filled (right) cavity.

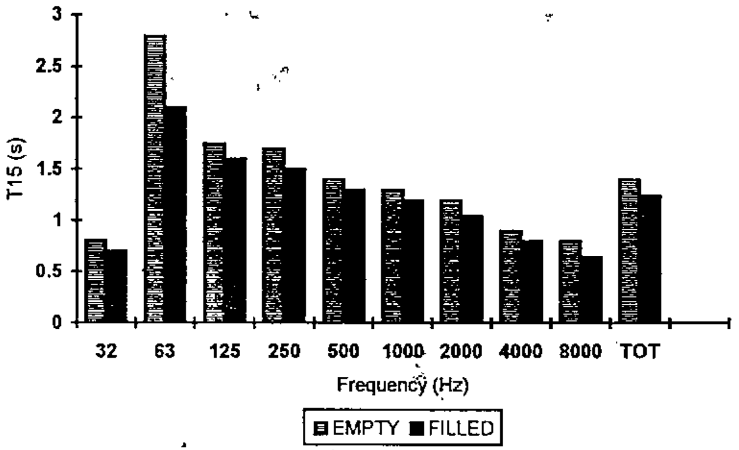

Fig. 8.17 Comparison of experimental T_{15} with empty and filled cavity.

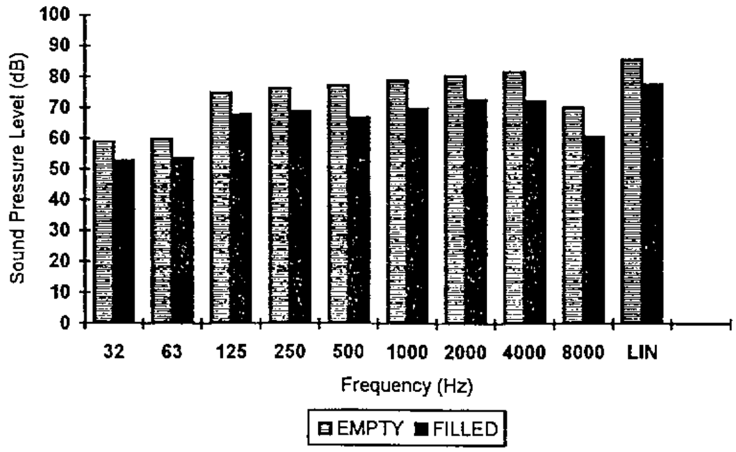

Fig. 8.18 Comparison of experimental SPL with empty and filled cavity.

evaluations already obtained from a large number of musicians in another psychoacoustic research project, in which the need for 'warmth' and 'liveness' was expressed.

Using the numerical technique already described, it will be possible to define the acoustic characterization of the theater in order to validate the possibility of using an acoustic chamber for better enjoyment of the hall.

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