COMPUTER ASSISTED METHODS AND ACOUSTIC QUALITY: RECENT RESTORATION CASE HISTORIES

Alessandro Cocchi *, Angelo Farina**, Lamberto Tronchin*

* Technical Physics Institute, University of Bologna, Viale Risorgimento 2, 40136 BOLOGNA (Italy)
** Industrial Engineering Dept., University of Parma, Via delle Scienze, 43100 PARMA (Italy)

I. INTRODUCTION

When the restoration of an existing concert hall has to be undertaken, the architect has many possible choices of which it is difficult to evaluate the acoustic performance. For this, in the most recent years a number of numerical simulation programs has been realised, making it possible to obtain the most useful acoustic parameters from a 3D CAD model of the room. However, the good practice demands for 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 this computer assisted method of evaluating the acoustic restoration design has been applied to three different rooms, namely the church S.Domenico in Foligno, the church S.Lucia in Bologna and the Teatro Comunale in Gradisca D’Isonzo. In one of these cases a comparison was made between two different acoustic numerical models, based on similar approaches.

The results show that this method can produce useful information in a reasonably little 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 room, the study has been carried out by the following steps:

- Binaural measurements were performed in the hall before any alterations 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 like listening level, ITDG, reverberation time, IACC and many others, and to map their values;

- Calculation of Ando’s quality maps of preferences, with reference to two different kinds of musical signals (Mozart, τ_e=38ms and Haydn, τ_e=65ms) was accomplished from experimental measurements;

- Software simulation of the geometrical configurations of the internal surfaces of the halls was performed and the acoustic characteristics of different materials have been chosen in such a way to approximate 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 auralisation were also made, to compare subjectively the proposed treatments with the original situation.

The results of these comparisons and the influence of the right configuration of some parameters in impulse response prediction by pyramid and/or cone tracing are here explained.

II. MEASUREMENT TECHNIQUE

The measuring system has been used basically to obtain the binaural impulse responses in each listening point. For this, an omnidirectional loudspeaker was used, being fed with the Maximum Length Signal produced by a MLSSA board, installed in a portable PC. The signal period was 65535 samples, and the sampling rate varied between 22.05 kHz and 44.1 kHz. The acoustic signal was sampled through a dummy head (Sennheiser MKE2002set), connected with the MLSSA board through a wireless system (NADY VF-701). The measure was repeated for each ear, thus enabling the computation of the Inter Aural Cross Correlation (IACC) through a dedicated post-processing program, in addition to the wide range of other acoustical parameters computed by the MLSSA software. Fig. 1 shows a scheme of the measuring system.

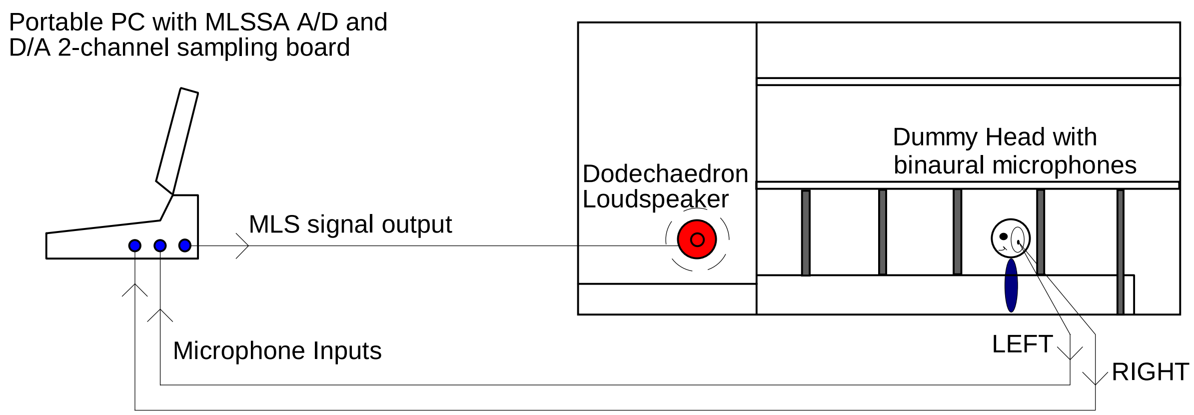

Fig 1 - The measuring system

III. NUMERICAL SIMULATION PROGRAMS

Two commercial room acoustics programs were employed for this work. The first, used for the three cases presented, is a pyramid tracing code [1], suited both for noise evaluation in workplaces, for the simulation of loudspeaker coverage and for concert hall acoustic quality evaluation. The particularity 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 Sabinian spaces with a little number of pyramids (typically 256). However some problems are present for very regular spaces: considering always specular reflections also for high order reflections, the late part of the tail becomes very uneven as clearly shown in [2].

The second program, used for comparison in one of the three cases, is an hybrid cone tracing [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 an advanced statistics on the history of the rays. It can handle also diffuse reflections, producing smooth late tails, provided that a number of cones high enough is employed.

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

IV. THE TEATRO COMUNALE IN GRADISCA D'ISONZO

The town of Gradisca D'Isonzo (GO) has a municipal Theatre, located inside the main square of the village. Actually the building is dismissed and it is being restored.

The architectural complex comprises three order level of seats, one at the mail level and two semicircular floors, as shown in fig. 2.

In order to establish the acoustic behaviour of the theatre, and to give to the hall an acceptable acoustical quality, for both speech and music, a thorough acoustical study was undertaken, in collaboration with the architectonic 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 high reverberation) and to the lack of loudness in the farthest seats. The proposed acoustic correction is based on sound reflecting panels which redirect the sound energy to the only strong absorbing surface: the seating area.

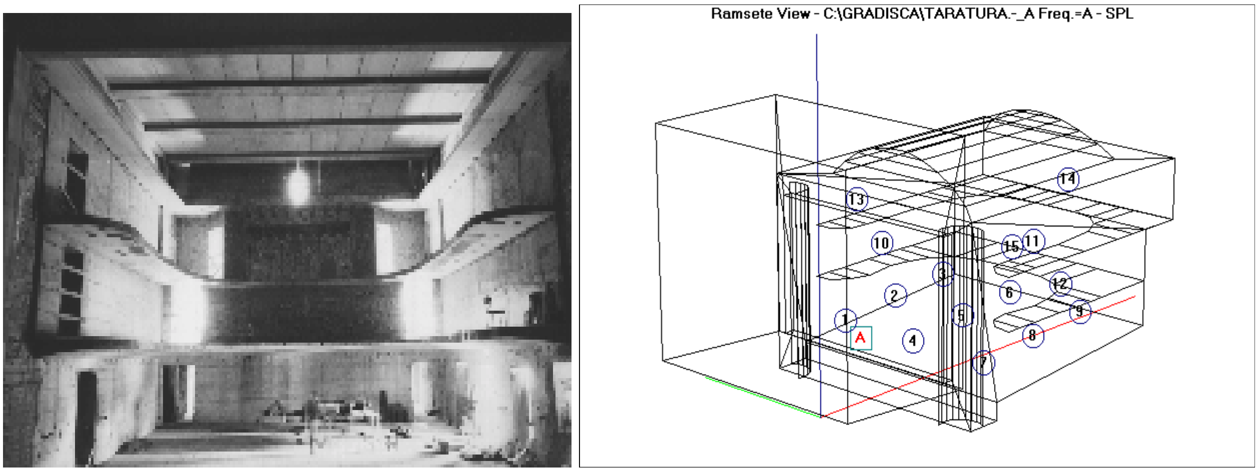

Fig. 2 - Photographic view of the hall and CAD drawing of the model used for the validation

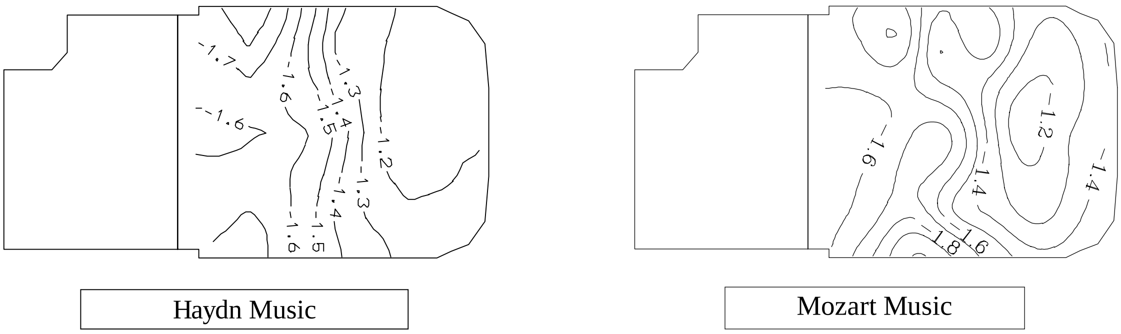

Fig. 3 - Ando's total preference index.

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

A. 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 16384 pyramids, followed until the time limit, so it was possible to model the environment without any other hypothesis. The program always requires to set in advance the time resolution for the impulse response computation: it was set to 10 ms.

B. 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 the position in the hall was taken into account selecting the calculation points distributed along the whole theatre. The choice of the most suitable criteria for the task were restricted to *EDT*, C_{80} and centre time t_s [4]. The validation was made in two steps:

- starting with the model just imported from the CAD program, the value of the sound power level of the source was selected, comparing the *SPL* 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* agreed.

The first step was only a matter of shifting the resulting *SPL*, in a straightforward and simplified way, in order to set the simulated value of *SPL* to the measured ones.

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. At the end of the iterative procedure, the values of *EDT* obtained from the simulation resulted very close to the measured ones.

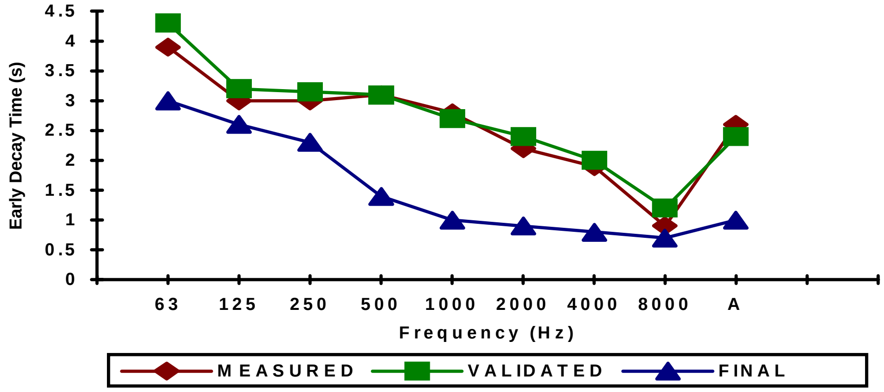

Fig. 4 - Comparison of experimental EDT with computed values before and after the treatment

It should be noted however that the computed C_{80} values resulted very different from the measured ones, although their spatial variation is close to the reality. This suggests that at present, even with a room model more accurate than in current practice, the Clarity is not a reliable criterion for acoustic simulations, because the geometrical simplifications and the physical approximations needed to make the program work affect too much the Clarity values [4].

C. Design Of The Acoustic Correction

The acoustic correction was simulated in two steps.

At first, a set of reflective glasses was introduced over the proscenium; this reflectors shall redirect many sound rays toward the sound absorbing seating area.

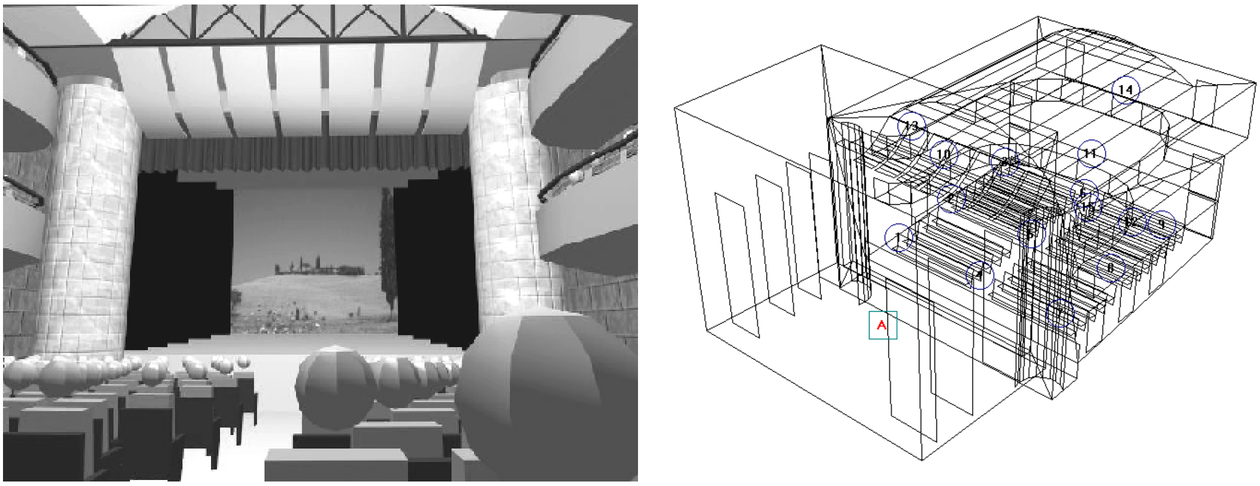

Fig. 5 - Proposed solution: rendered view (left) and wireframe CAD model (right)

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 an equal behaviour of the theatre either for music than for speech.

Fig. 4 also shows the reverberation times obtained with the proposed acoustic treatment. Fig. 5 shows the final appearance of the room with the proposed acoustic reflectors. Fig. 6 shows the improvement in STI obtained with the proposed treatment.

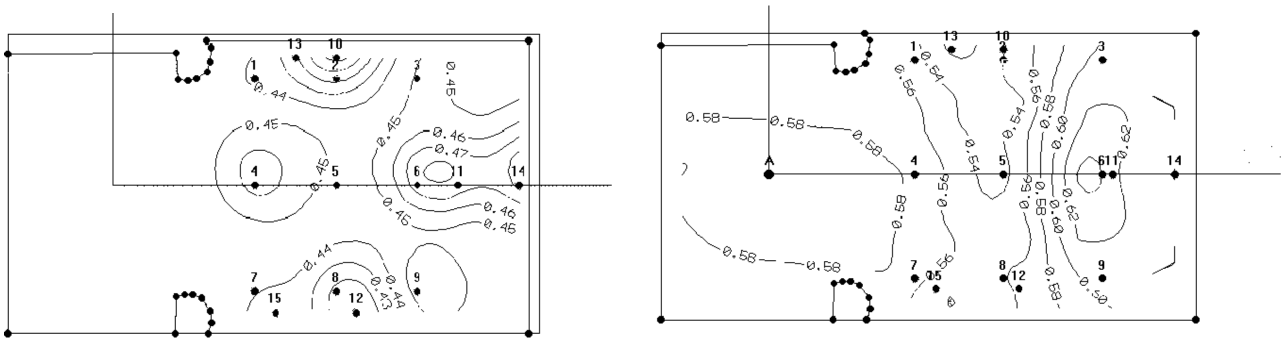

Fig. 6 - Comparison of STI map before (left) and after (right) the proposed restoration

V. THE AULA MAGNA "S.LUCIA" IN BOLOGNA

The University of Bologna has a main hall ("Aula Magna"), located inside an unused building which is an ancient dismissed church ("Santa Lucia"); it was restored and was 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. Fig. 7 show a perspective view of the room, with the proposed acoustic treatment.

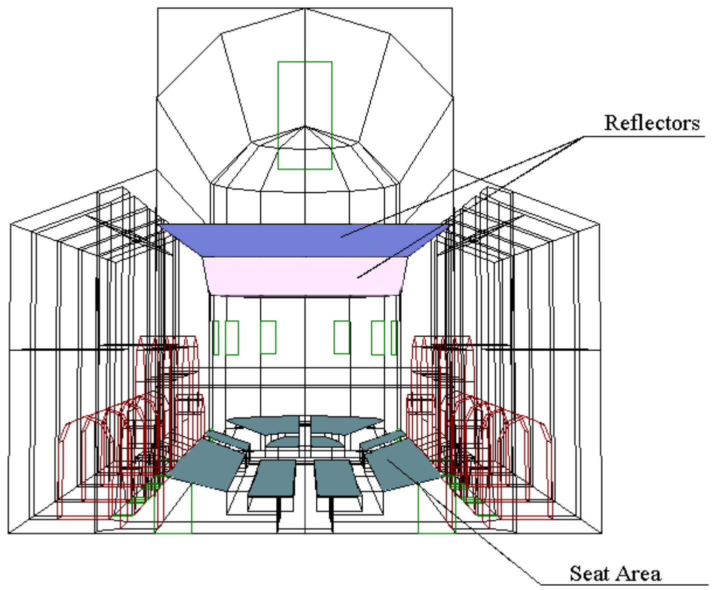

Fig. 7 - proposed acoustic treatment of "S.Lucia" church

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 regards the study oriented toward the second goal (music).

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 high reverberation) and to the strong and late reflections from the vaulted roof and from the rear wall.

The proposed acoustic correction is based on sound reflecting 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 strong absorbing surface: the seating area.

A. 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 $V = 45900\ m^3$ and a total surface $S = 12500\ m^2$ were estimated. Using those data a mean free path $l = 14{,}7$ m and an average number of reflections for a ray $k \leq 200$ were computed. Thus, it was decided to make the cone tracing program generate 10000 rays to be followed till the 200^{th} reflection. The pyramid tracing program generated 8000 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 [3], and the transition order from deterministic to statistic reflections was set to 5.

B. 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 was taken into account 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 common to both programs: *SPL*, *EDT*, C_{80} and centre time t_s. The validation was made in two steps:

- starting with the model just imported from the CAD program, the value of the sound power level of the source was selected, comparing the *SPL* 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* 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 assignement to the source model of a global sound power level, but not of a spectrum shape according to 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 reality. This suggests that at present, even with a room model more accurate than in current practice, the clarity is not a reliable criterion for acoustic simulations, because the geometrical simplifications and the physical approximations needed to make the program work affect too much the clarity values.

In practice, the validation procedure was based on the variation of the sound absorption coefficient of the plaster, which is by far the most common material inside the room. Table 1 reports the initial, intermediate and final values used in the two programs.

Tab. 1. Plaster sound absorption coefficient in three validation runs of the programs. Values for 1/1 octave bands.

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

For every acoustic criterion x (in the present case the *EDT*), if $x_{s,i}$ is the value computed during the simulation for the *i*-th point and $x_{m,i}$ is the corresponding measured value, the prediction error is ($x_{s,i}$ - $x_{m,i}$); therefore as an index of the accuracy of the model the RMS value of the prediction error over the eight reference points was taken.

Fig. 8 shows the RMS errors obtained for the two programs at the end of the iterative adjusting of the input data.

Fig. 8 - RMS error of the parameter EDT for the two computer models

As it can be seen, with the Cone Tracing a reasonable accuracy can be obtained, except of 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.

Anyway the absolute errors are little, as it can be seen in fig. 9: the optimised values are capable of producing almost exact correspondence between the computed values of EDT and the experimental ones.

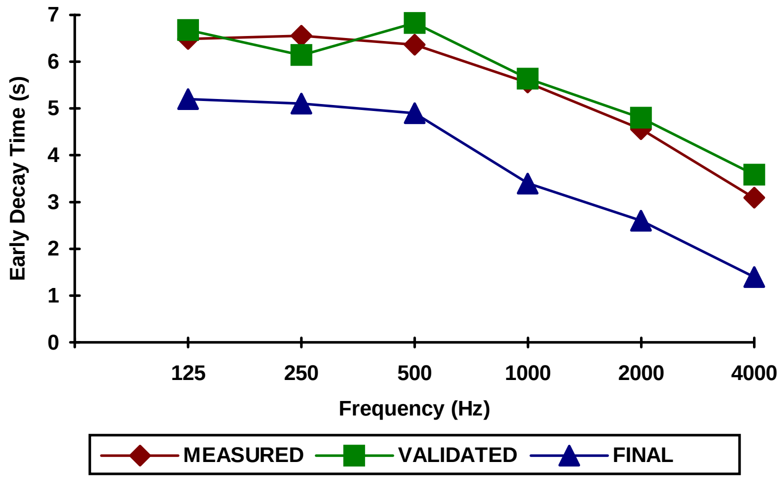

Fig. 9 - Comparison of experimental EDT with values computed with Pyramid Tracing before and after the treatment

C. Design Of The Acoustic Correction

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

At first, a sound reflective ceiling was introduced over the audience, at a height considerably smaller than that of the vaulted roof (see fig. 8); this reflector shall redirect many sound rays toward the sound absorbing seating area and shall “cut-out” the reverberating effect of the upper volume. The material should be optically transparent, in order to not 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 help 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 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 fig. 9 the new EDT values are shown, that are significantly lower than in the actual case (however the reduction of T20 is not so large). In fig. 10 the contour maps of RASTI, computed with the Pyramid Tracing program, are compared; the improvement is on average of a factor 1.5. However a strong focalisation effect in the center of the apse can still be observed, which was not reduced by the proposed treatment.

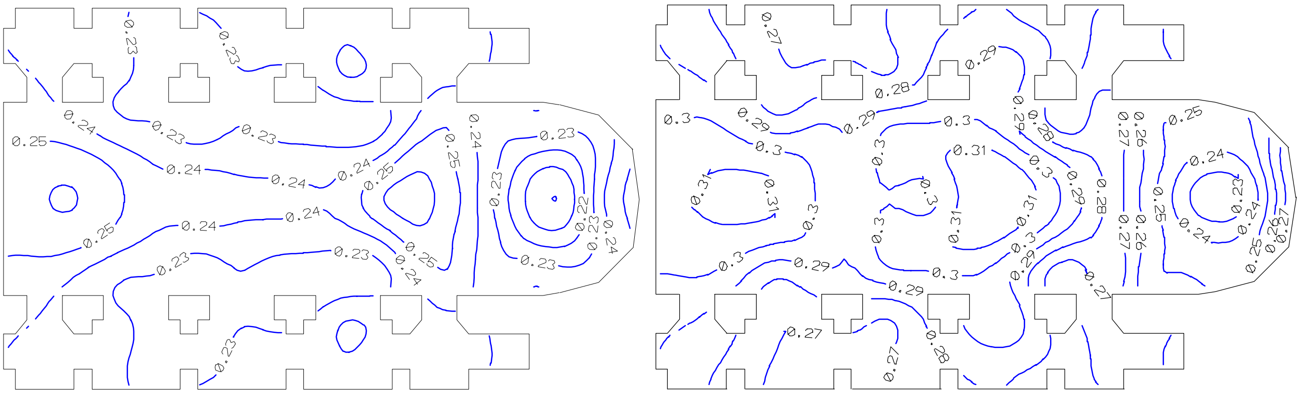

Fig. 10 - Contour map of RASTI before (left) and after (right) the proposed treatment

VI. THE CHURCH "S.DOMENICO" IN FOLIGNO

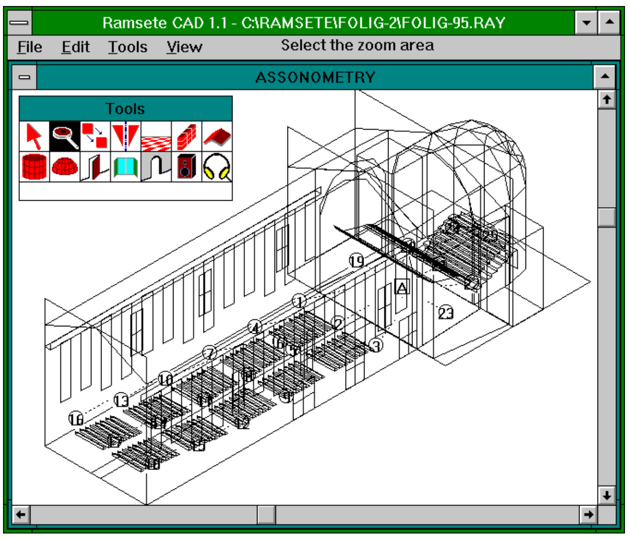

Fig. 11 - The church "S.Domenico" in Foligno

The city of Foligno (PG) does not have a concert hall suitable for large ensemble performances with a wide number of listeners. For this reason an ancient church, no more used for religious tasks, was re-adapted and restored. However it was not possible 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, to increase the clarity and intelligibility and to eliminate some echoes and focalisations actually present.

Fortunately in this case the main nave is narrow and long, and the side walls produce a lot of strong lateral early reflections, so the spatial impression is very good. The reverberation time was a bit lower than in the previous case, and it was possible to add some sound absorbing plaster on a part of the walls, so that the reverberation can be controlled to reasonable values in this case, Then a reflector was added over the orchestra pit, to avoid echoes and focalisations from the apse, and to redirect the reflected sound energy towards the rear part of the main nave, where the direct wave arrives attenuated by the grazing incidence over the long seating area.

Figure 11 shows the modelled geometry of the church with the proposed acoustic treatment, which actually is already partially executed.

A. Choice Of The Calculation Parameters

In this case an accurate calibration of the computation parameters α and β (that take an important role in the tail correction, as explained in [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, the “optimal” values of α and β were found, which are the values capable of minimising the difference between the two sound decays.

This way it was found that α is almost exactly 2, which means that the field has a perfectly Sabinian character in this room, as the number of reflections increase with the square of the time. β resulted instead 0.076, a value significantly lower than what is expected for a perfectly diffuse room (0.3): this means that the mean free path is lower than $4 \cdot V/S$, and this is due to the shape of this room that is very narrow compared to its length, and 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 mantained for all the reflections: in this sense the adjustment of β make it possible to compensate for this bias error, removing one of the limits of the actual implementation of Pyramid Tracing.

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

B. Validation Of The Model

After the proper choice of α and β, many computations were performed, changing the absorption coefficient of the plaster, in such a way to obtain computed values of the reverberation time T20 close as much as possible to the experimental values. This was possible as the computation time was only 4 minutes on a i486 DX2-66 PC, launching 256 pyramids for each simulation. The advantage of using a reduced number of pyramids, among 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].

Fig. 12 shows the results of the validation process: the computed T20 values are perfectly corresponding to the experimental values. At the lower frequencies the reverberation is very high, but it must be noted that the room was considered empty, and 1200 peoples will add considerable absorption particularly in the low frequency zone.

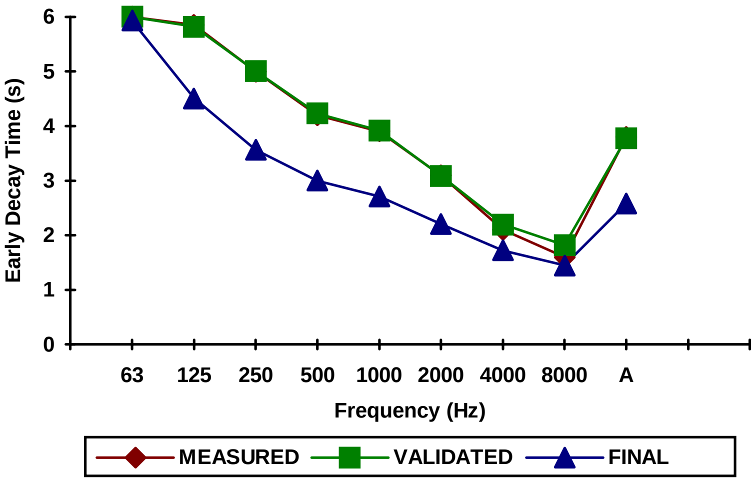

Fig. 12 - comparison of experimental EDT with computed values before and after the treatment

C. 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 laterals walls and realisation of an acoustic reflector over the orchestra pit. All these modifications are shown in fig. 11. 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 vibrating panels on the back wall, to control the low end of the spectrum. This can be shown in fig. 12: the reduction of the reverberation time is noticeable at medium and high frequencies, but it is little at low frequency.

Fig. 13 shows the comparison between the RASTI maps computed in the actual state and after the proposed treatment: there is a relevant improvement of the speech intelligibility, that will probably be beneficial also for music reproduction. The effect on music was anyway evaluated by listening to convoluted music samples, obtained using the convolution software Aurora [5,6] and anechoic samples coming from the DENON PG-6006 CD. Three convolutions were obtained for each sample, the first with experimental impulse responses, the second with the simulation in the original state (which resulted almost identical to the first) and the third after the treatment; the latter exhibit a better clarity, lower reverberation and wider spatial impression. A subjective validation of the auralisation system was conducted including the comparison of the first two samples, as reported in [6]; although the simulated sample resulted 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 signifacntly different.

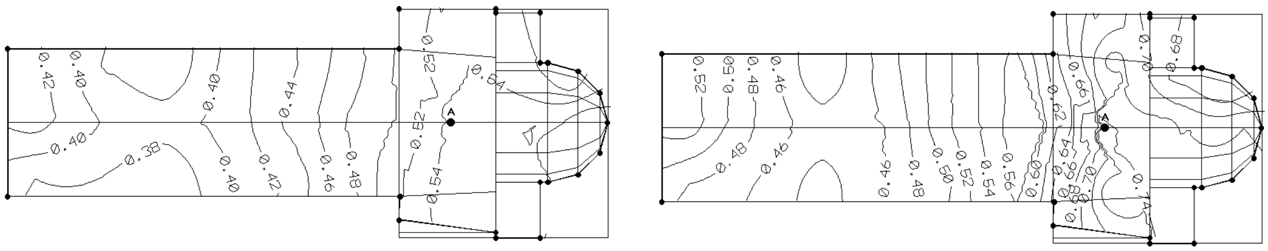

Fig. 13 - Comparison between computed RASTI before (L) and after (R) the proposed treatment

VII. ACKNOWLEDGEMENTS

Work partially supported by the Ministry of University, Scientific & Technologic Research (MURST 40%).

The authors wish to thank Massimo Garai and Giovanni Farolfi for their precious collaboration.

VIII. REFERENCES

1 A. Farina -"RAMSETE - a new Pyramid Tracer for medium and large scale acoustic problems", Proc. of "Euro-Noise 95", Lyon, France 21-23 march 1995.

2 B.I. Dalenback - "The importance of diffuse reflection in computerized room acoustic prediction and auralization", Proc. of "Opera and Concert Hall Acoustics Conference", IOA, pp.27-34, London Gatwick, February 1995.

3 G.Naylor, "Odeon Room Acoustics Program - Version 2.0 User Manual", The Acoustics Laboratory, Lyngby, Denmark (1992).

4 Y.W. Lam "*On the modelling of auditorium acoustics, part II: the validation of an hybrid computer model*", submitted for publication in JASA, December 1993.

5 A. Farina - "An example of adding spatial impression to recorded music: signal convolution with binaural impulse responses" - Proc. of "Acoustics and Recovery of Spaces for Music", Ferrara (Italy) 27-28 ottobre 1993.

6 A. Farina - "Auralization software for the evaluation of the results obtained by a Pyramid Tracing code: results of subjective listening tests" - Proc. of "ICA95", Trondheim, Norway, 26-30 June 1995.