EFFECTIVENESS OF DIFFERENT COMPUTER CODES TO ASSIST THE ACOUSTIC CORRECTION OF A LARGE MULTIPURPOSE HALL

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INTRODUCTION

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.

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) .

First of all, binaural measurements were performed in the hall, using a loudspeaker located at the centre of the stage area, a dummy head located at different seats and a special instrumental set up for the acquisition and the post-processing of the impulse responses, as elsewhere described [1]. 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.

Such a complex problem cannot be investigated by conventional tools; in fact, the design of the acoustic correction was based on software simulation [2].

Now, the original project has been revisited, updating the experimental data and using two commercially available programs: *Odeon* vr. 2.0 (an hybrid model) and *Ramsete* vr. 1.0 (a pyramid tracing model). Thus the opportunity arose to make a detailed comparison of the two computer codes, as described in the following of this paper.

MAKING THE HALL MODEL

The creation of the geometrical model of the hall has been the most time-consuming step of the work. In order to have exactly the same model for both programs, the room was drawn with a suitable CAD program and then exported in file formats accepted by the two codes.

Our basic version of *Odeon* required an ASCII file containing the co-ordinates of all corners occurring in the room and of all surfaces formed connecting the relevant corners together [3]. The file was generated from a manual search into the CAD drawing. This tedious task can now be improved with an add-on module which makes an “assisted” conversion. On the other hand, the geometry checking routines of *Odeon* are very helpful in avoiding mistakes otherwise difficult to see (for example, the “watertightness” of the model was first tested in *Odeon*).

Ramsete, which runs in a *Windows* environment, has a simple internal CAD and also accepts files in the DXF format [4]. On the other hand, it requires that the original drawing be exclusively made of few 3D *AutoCAD* entities, and it is very sensitive to mistakes (sometimes the import routine stops and hangs).

All curved surfaces were modelled with several planes. It was found that the proper modelling of the opening between the main nave and the lateral ones has the greatest importance; in particular, the thickness of the walls and of the columns cannot be neglected. On the other hand, the seating areas were modelled with few sound absorbing planes, because a realistic detail in the seat drawing should cause an unacceptable slowing of the program.

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, either in *Odeon* either in *Ramsete*.

With an auxiliary *Odeon* procedure a volume $V = 45900\ \text{m}^3$ and a total surface $S = 12500\ \text{m}^2$ 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 *Odeon* generate 10000 rays to be followed till the 200th reflection. *Ramsete* generated 8000 pyramids (this number must be a multiple of $8 \cdot 2^n$, n integer), followed until the time limit or their energetic extinction; so it was possible to model a clearly non Sabinian environment.

Odeon also required a diffusion coefficient, set to 1 as suggested in [3], and a transition order, set to 5. *Ramsete* always requires to set in advance the time resolution for the impulse response computation: it was set to 10 ms.

VALIDATION OF THE MODELS

In order to evaluate the accuracy of the two models, 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 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 *Odeon* and *Ramsete*: *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 *Odeon* 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 computed C_{80} values 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.

Plaster sound absorption coefficient for 1/1 octave bands						
	125	250	500	1000	2000	4000
ODEON 1	0,03	0,03	0,03	0,02	0,03	0,02
ODEON 2	0,05	0,03	0,01	0,02	0,02	0,02
ODEON 6	0,05	0,03	0,018	0,018	0,018	0,02

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

Plaster sound absorption coefficient for 1/1 octave bands						
	125	250	500	1000	2000	4000
RAMSETE 3	0,04	0,035	0,03	0,02	0,03	0,04
RAMSETE 4	0,045	0,04	0,02	0,02	0,03	0,05
RAMSETE 5	0,045	0,035	0,02	0,02	0,03	0,06

Tab. 2. Plaster sound absorption coefficient in three validation runs of the *Ramsete* model. Values for 1/1 octave bands.

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 *Odeon*. Table 2 reports the initial, intermediate and final values used in *Ramsete*.

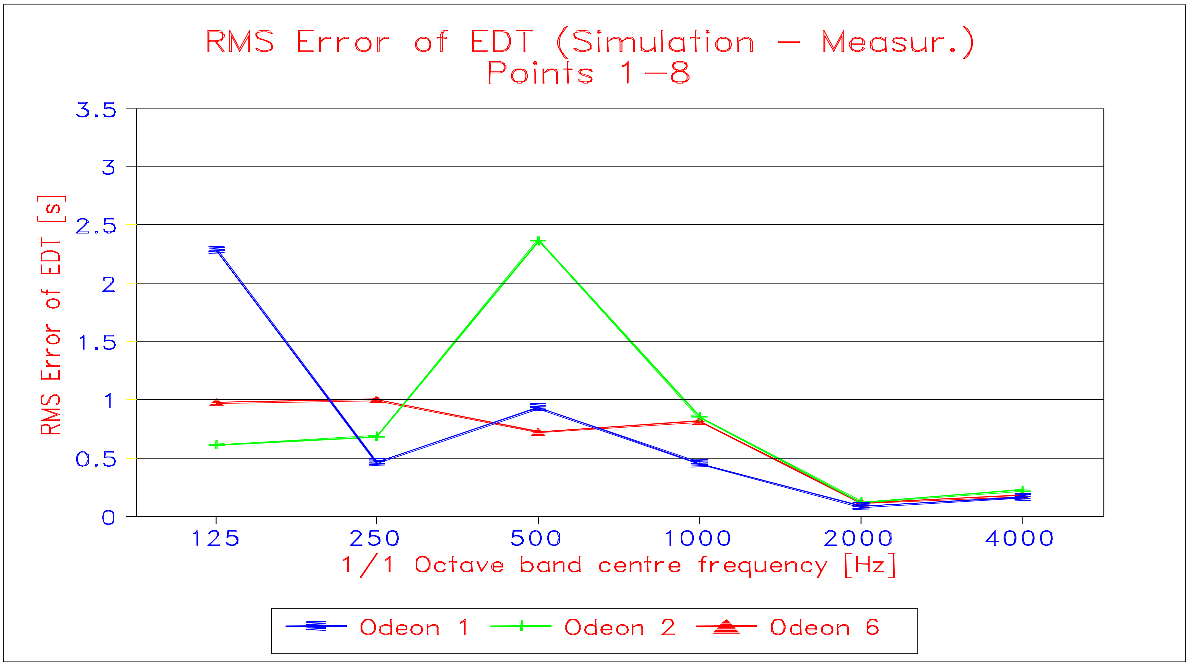

Fig. 1. RMS error of the *EDT* prediction as a function of frequency in different *Odeon* runs; same geometric model, different sound absorption values of the plaster (see tab. 1).

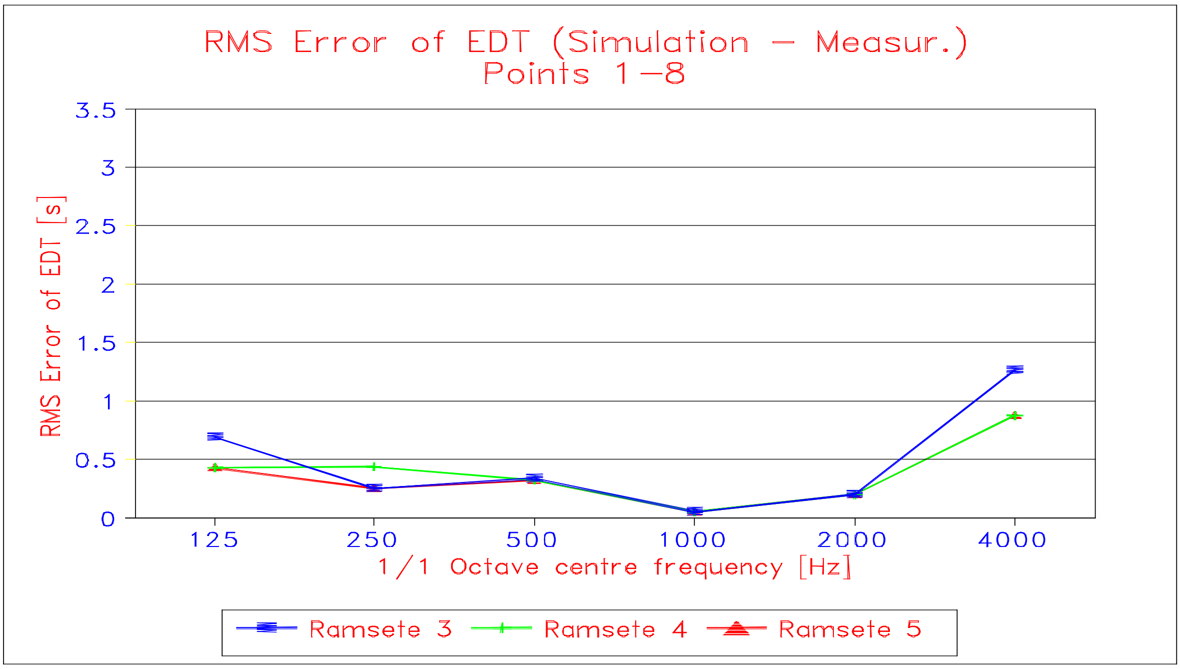

Fig. 2. RMS error of the *EDT* prediction as a function of frequency in different *Ramsete* runs; same geometric model, different sound absorption values of the plaster (see tab. 2).

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. 1 shows the RMS errors obtained for the same *Odeon* runs of table 1. Fig. 2 shows the RMS errors obtained for the same *Ramsete* runs of table 2.

As can be seen, with *Odeon* a reasonable accuracy can be obtained, but in the 125 Hz octave band (perhaps a different diffusion coefficient should be selected at low frequency). On average, *Ramsete* achieves a better accuracy than *Odeon*, with the exception of the 4000 Hz octave band, where probably a bias error occurs in *Ramsete* in the computation of the sound absorption in air.

DESIGN OF THE ACOUSTIC CORRECTION

The visual analysis of the ray paths, possible in *Odeon*, 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 simulated 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. 3); 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. Both the *Odeon* and *Ramsete* runs showed that to be effective the panels should span over almost all the width of the main nave.

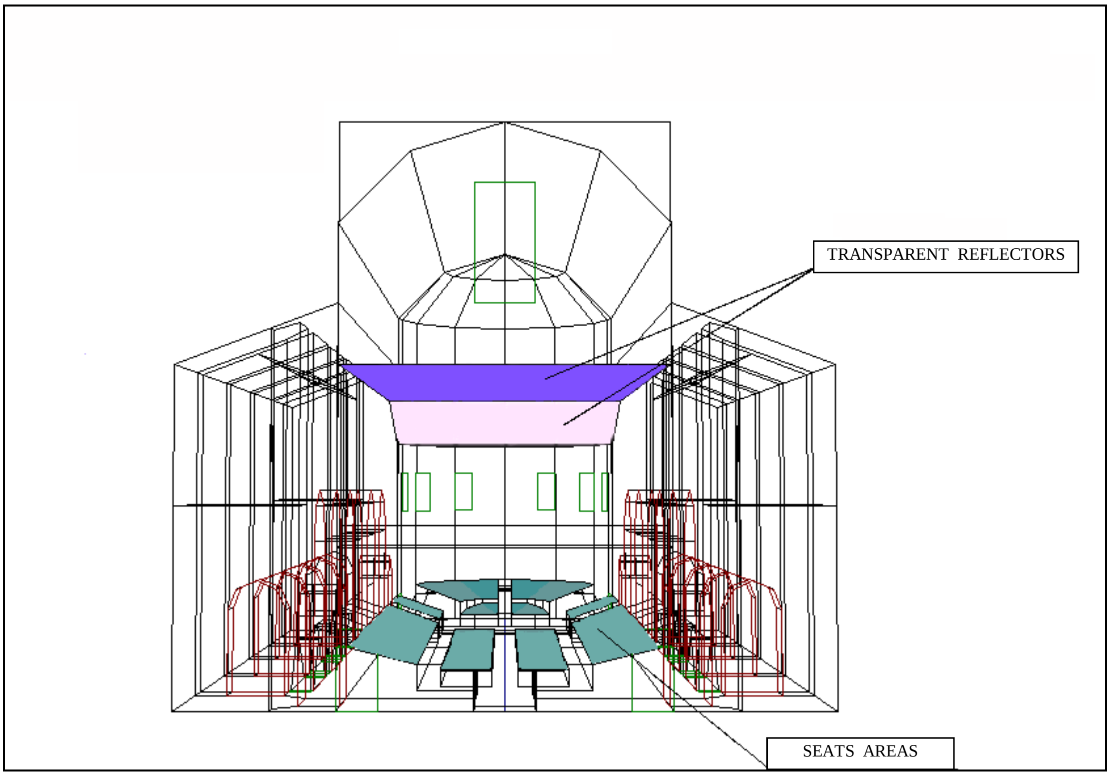

Fig. 3. CAD model of the hall with the proposed acoustic corrections as resulted from the *Ramsete* simulation.

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.

Fig. 3 shows the final appearance of the room with the proposed acoustic reflectors as modelled in *Ramsete*.

CONCLUSIONS

In Italy many dismissed churches exist, which could become fascinating concert halls, so it is very interesting to have a tool for the design of their acoustic correction; afterwards, the architectural team could give to the technical proposal the best look. Computer simulation offers a very effective way to accomplish this task. While on the aesthetic side one could think to less intrusive solutions, the acoustic engineer carries the responsibility of assuring accurate results.

This paper shows that in practice the accuracy of the simulation strongly depends on a suitable validation procedure, rather than on the usage of a particular computer code. It is possible, with an iterative procedure, to modify the geometry of the hall and the sound absorbing coefficient of the surfaces until the computed values of the proper acoustical criteria become close to the measured ones. The choice of the reference acoustic parameter(s) for the validation procedure is also critical: the clarity, e.g., is not yet a reliable criterion, because of the geometrical simplifications and of the physical approximations implicit in the present computer models.

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