ACOUSTIC CONTROL IN OCTAGONAL GEOMETRY: CASE STUDY OF THE "TORRI DELL'ACQUA" AUDITORIUM

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1 INTRODUCTION

In 2008 the municipality of Budrio, a town near Bologna, proposed to the University of Bologna to cooperate in the acoustical design of a new auditorium. The auditorium is one hall inside of an old hydraulic plant of building. The structural characteristics of the hall, which cannot be changed due to legal constraints, provided an inadequate acoustics. A multipurpose auditorium with 150 seats was required by the designer.
The authors of this work coordinated the acoustic design of this new auditorium.

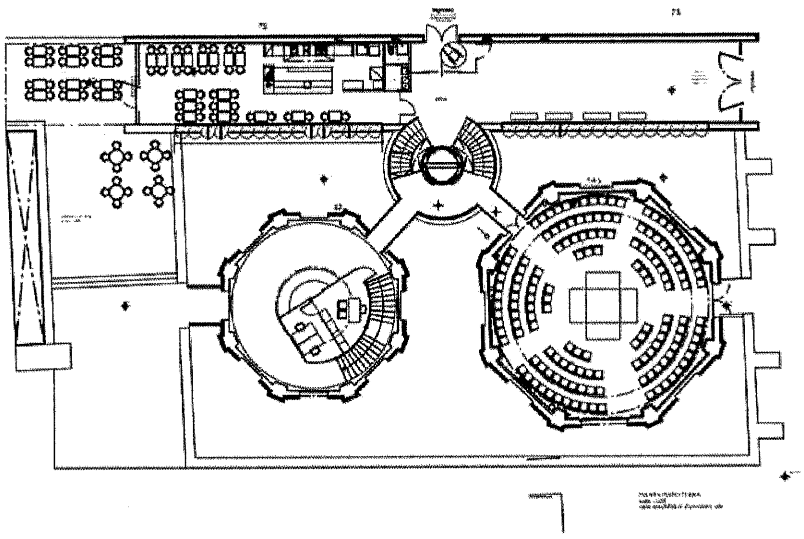


Figure 1: Plan of the complex of buildings, the auditorium is the main octagonal hall.

2 DESIGN CRITERIA

The first measurements (January 2009) confirmed the inadequate acoustics of the hall. Without seats and floor, very high values of reverberation time and early decay time and very low values of clarity were measured. An hybrid ray-tracing model of the hall (fig. 2) has been developed, using the measured values of *EDT*[1] and C_{80} as reference values to calibrate the model. The materials of the seats and the performer's platform have been chosen with the help of simulations. The concrete walls and ceiling couldn't be modified, due to the constraints of law on the preservation of ancient buildings.
The measurements revealed manifest modal frequencies due to the hall geometry. Off course a ray tracing program doesn't permit an adequate simulation of this characteristic of the sound field and

the analysis has been completed with some analytical considerations. Assuming the octagonal geometry as a cylindrical-like one, it's well know that the modes may be expressed in cylindrical coordinates. The longitudinal modes (directed long the *z* axis) have a sinusoidal shop, the azimuthal modes may be neglected due to the symmetry of the hall, the radial modes are proportional to Bessel functions, having the zero values on the symmetry axis of the hall. In shoes-box hall the devices for modal control are located at the edges. In the present case a device for cylindrical modal control should be located near the central axis of the room for maximizing the results. Moreover, in shoes-box hall alls the modes have their maxima in the corners, in a cylindrical hall only the first radial mode has its maximum on the central axis: higher modes have their maxima around the axis of symmetry. This fact allows the definition of a modal control region near the central axis in which the device should be located. A system of asymmetrical suspended reflectors allows the modal control and its position has been chosen to optimize the early reflections (see figure 2). The design has been optimized within the hybrid capabilities of Odeon© software[2].

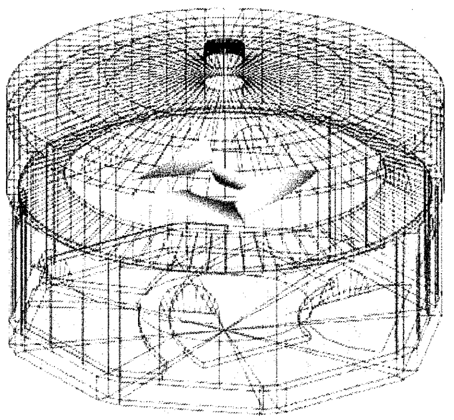
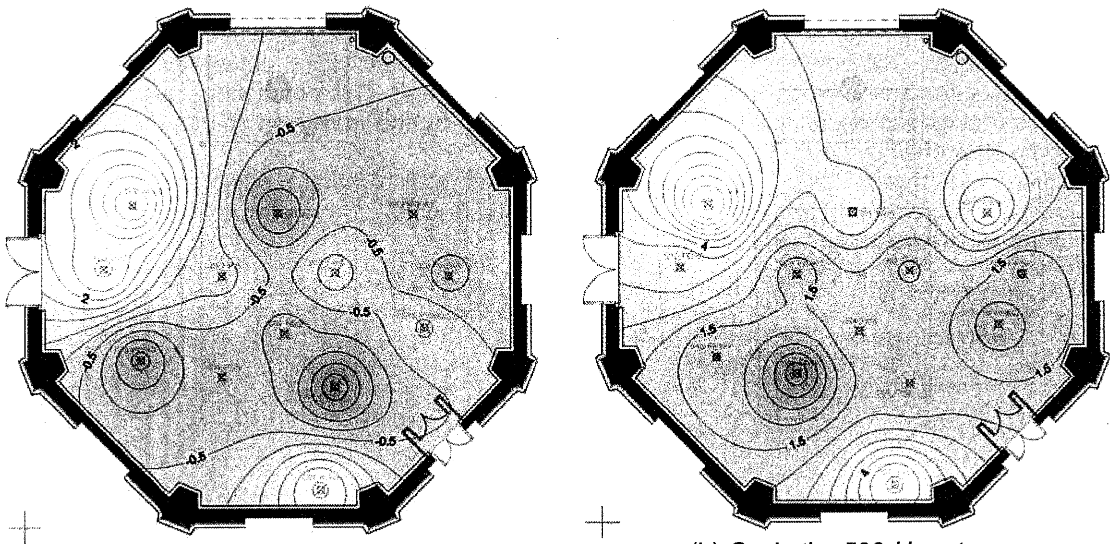


Figure 2: Ray tracing model of the auditorium

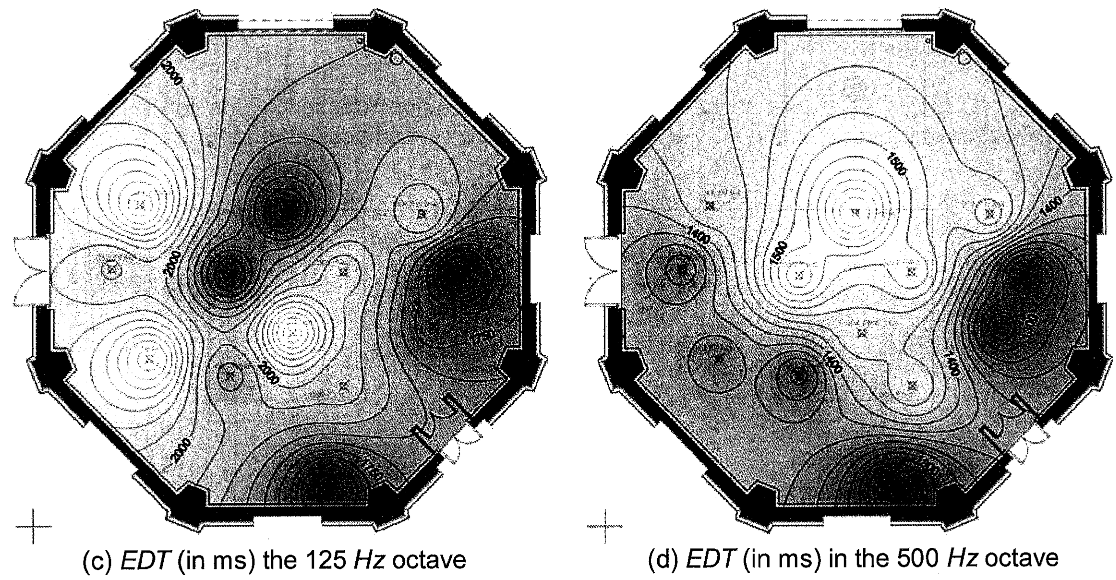
The hall opened on 2009 September 26 and is in service as auditorium, as concert hall for chamber music and jazz music, and as cinema.
According to this multi-purpose usage, some curtains made in absorbing materials have been installed. The different acoustics provided by opening and closing of these curtains will be briefly shown in the section 4.
In order to improve sound diffusion some lateral diffusers have been proposed (see figure 2). At the time of writing (March 2011) these reflectors are not yet installed in the hall. This is due to several reasons: money, safety and also the good spatial performance of the hall as it is now.

3 MEASUREMENTS

Monaural measurements done in June 2010 confirm the simulation results and the modal considerations. The measured values of C_{80} and *EDT* are shown in figure 3. The Schroeder's frequency of the hall is located in the octave band of 125 Hz and so the *EDT* values shown in figure 3(a) confirm the effectiveness of the modal control. The same values measured ante operam were in range 2.8÷3 *s*.



(a) C_{80} in the 125 *Hz* octave (b) C_{80} in the 500 *Hz* octave



(c) *EDT* (in ms) the 125 *Hz* octave (d) *EDT* (in ms) in the 500 *Hz* octave

Figure 3: Maps of measured post-operam values.

Binaural impulse response measurements have been done in 2011 March. MLS sequences of 256K have been used to evaluate about 5 *s* of sound decay. The binaural impulse responses have been acquired using a binaural microphone (Sennheiser MKE 2001). The measured impulse responses may be quite different to the ones measured using a dummy head (*e.g.* Neumann KU100). It has been verified that *IACC* values may be quite lower that the ones measured using a dummy head.
From these impulse responses monaural and binaural room descriptors have been extracted (T_{15}, *ITDG*, *EDT*, C_{80}).
The values of T_{15} are extracted from monaural impulse responses using the Schroeder's backward integration in the range −5 ÷ −20 dB. High values of Pearson coefficient r^2 > 0.98 are obtained.
The values of *ITDG* are extracted from the impulse response with an algorithm based on the iterated sharpening. The absolute value of the impulse response is preprocessed with an iterated sharpening, returning the local maxima. The sharpening permits to identify the local maxima of the impulse response and the delay time of each reflection. A short-time integration is then performed

on the squared impulse response returning an energy curve. The second local maxima of this curve identify the region of the expected first reflection. The maximum value of the local maxima calculated by sharpening and located in the region were the first reflection expected is assumed as the first reflection. The time delay between the instant of the direct sound arrival and the instant of the first reflection arrival so calculated is the *ITDG* (see figure 4). This approach is quite different to that which takes into account the reflection characterized by the maximum of the amplitude. The method is described by De Cesaris et Al.[3].
In addition others room descriptors have been extracted from binaural measurement, in order to evaluate the subjective preference functions proposed by Ando[4].
The *A* values are calculated in form:

$$A = \sqrt{\frac{\int_{5ms}^{\infty} p^2(t)dt}{\int_{0}^{5ms} p^2(t)dt}}$$

where p(t) is the monaural impulse response, and t = 0 is the arrival time of the direct sound.
The values of the *LL* are calculated from binaural impulse responses as:

$$LL = 10\log_{10}\sqrt{\Phi_{LL}(0)\Phi_{RR}(0)} - LL_{pos=1}$$

Where $\Phi_{LL}(\tau)$ and $\Phi_{RR}(\tau)$ are, respectively, the autocorrelation function of the left and the right impulse responses; $LL_{pos=1}$ is the *LL* value measured in the central position near to the stage.

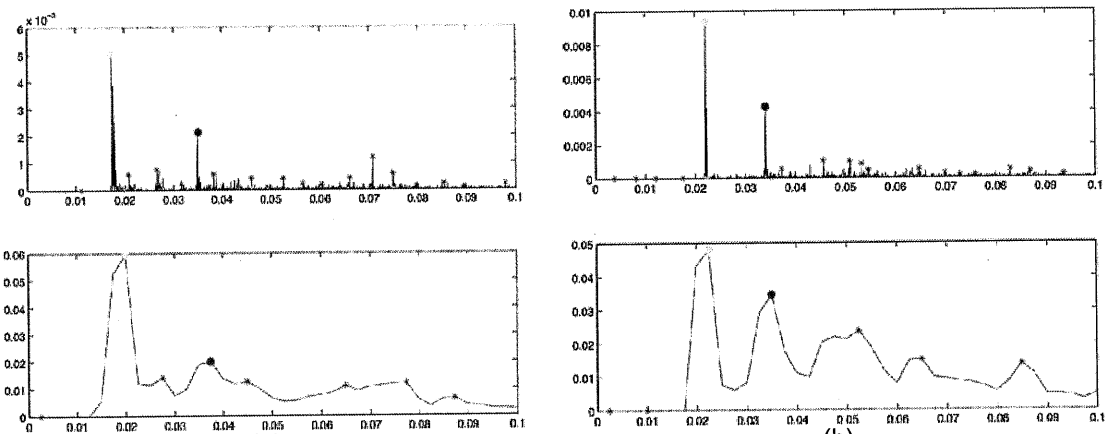
Pos	ITDG [ms]	T_{15} [s]	IACC	LL [dB]	A
01	14	1.74	0.47	0	12.1
02	22	1.87	0.37	-1.6	14.5
03	20	1.84	0.11	-2.8	21.3
04	20	1.69	0.19	-2.4	14.1
05	20	1.94	0.16	-1.8	14.4
06	16	1.76	0.28	-0.3	13.1
07	27	1.66	0.10	-3.5	12.2
08	17	1.72	0.11	-3.0	20.9
09	14	1.81	0.15	-2.9	23.5
10	18	1.56	0.11	-3.2	9,1
11	17	1.74	0.14	-3.0	22.3
12	16	1.70	0.18	-3.0	34.0

Table 1: Values of monoaural and binaural room descriptors at different listener's seats.

Alternative values of the binaural factors are measured with closed curtains. The measurement values and the variations are shown in table 2. The differences confirm the performer indications: when the curtains are opened the sound field is more diffuse and the sound pressure is higher and more constant in the listener places. This configuration results preferable in case of chamber music performances. The configuration with closed curtains results preferable when the auditorium is used as cinema or as conference hall.

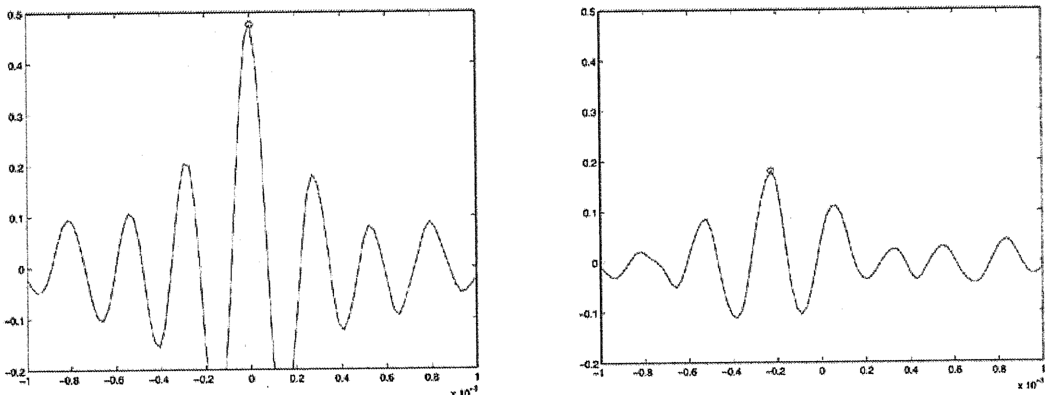
Pos	IACC	$IACC_{closed}$	ΔIACC	LL [dB]	LL_{closed} [dB]	ΔLL [dB]
01	0.47	0.54	+0.07	0	0	0
02	0.37	0.36	-0.01	-1.9	-2.3	-0.6
03	0.11	0.13	+0.03	-2.6	-3.4	-0.4
04	0.19	0.22	+0.03	-2.3	-3.0	-0.5
05	0.16	0.21	+0.05	-1.9	-2.3	-0.6
06	0.28	0.31	+0.03	-0.2	-0.8	-0.6
07	0.10	0.15	+0.05	-3.5	-4.4	-1.1
08	0.11	0.17	+0.06	-2.9	-3.6	-0.6
09	0.15	0.19	+0.04	-2.7	-3.5	-0.8
10	0.11	0.13	+0.02	-3.2	-4	-0.6
11	0.14	0.17	+0.03	-2.9	-3.9	-0.7
12	0.18	0.19	+0.01	-3.1	-3.7	-0.6
MEAN			+0.03			-0.7

Table 2: *IACC* and *LL* values for two different hall configurations.



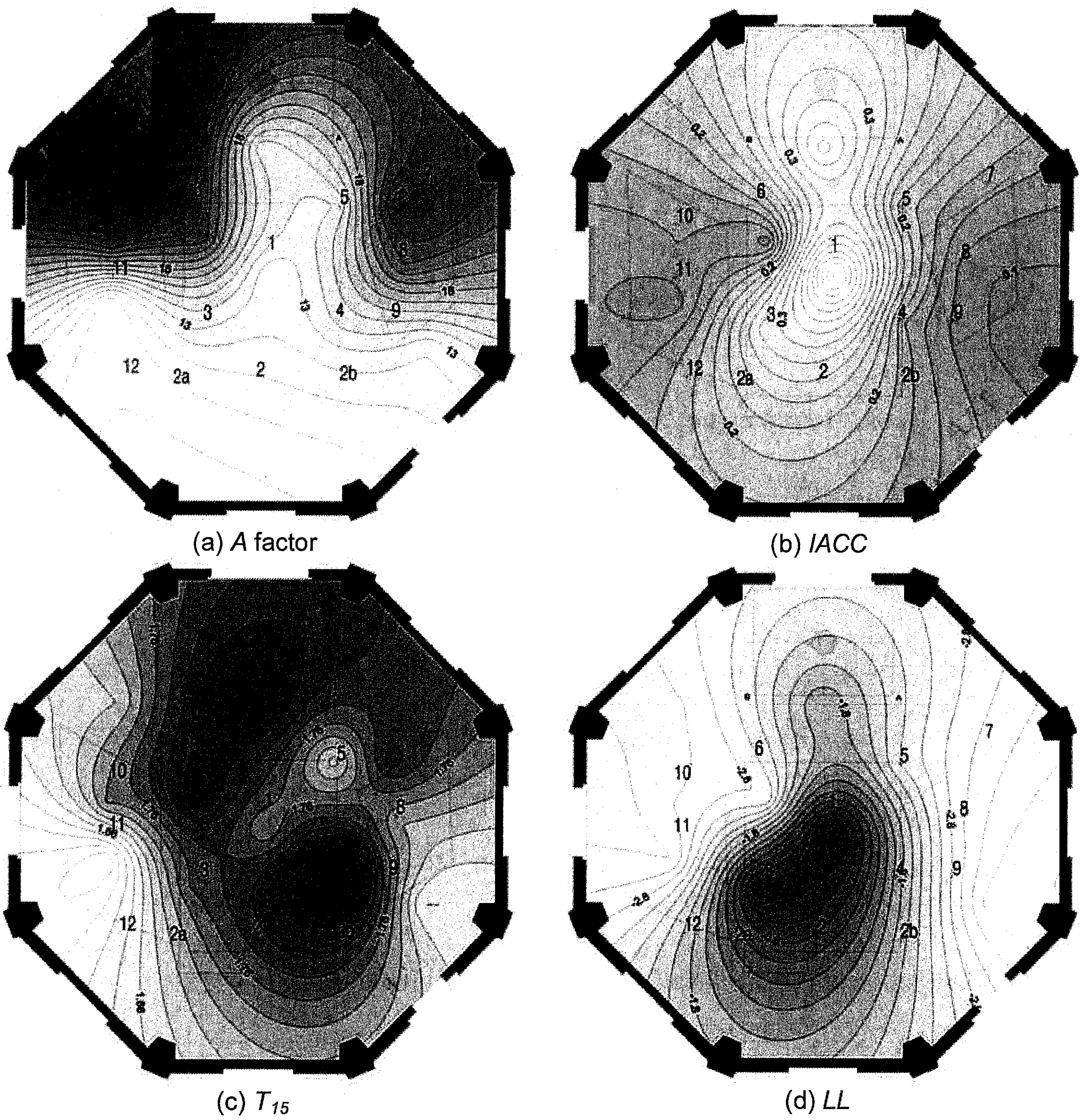
(a) (b)

Figure 4: Extraction of *ITDG* values on two different positions. After[4].



(a) (b)

Figure 5: Interaural Cross Correlation Functions (*IACF*) measured in central position near to the sound stage (a) and in lateral position far from the sound stage (b).



(a) *A* factor (b) *IACC*

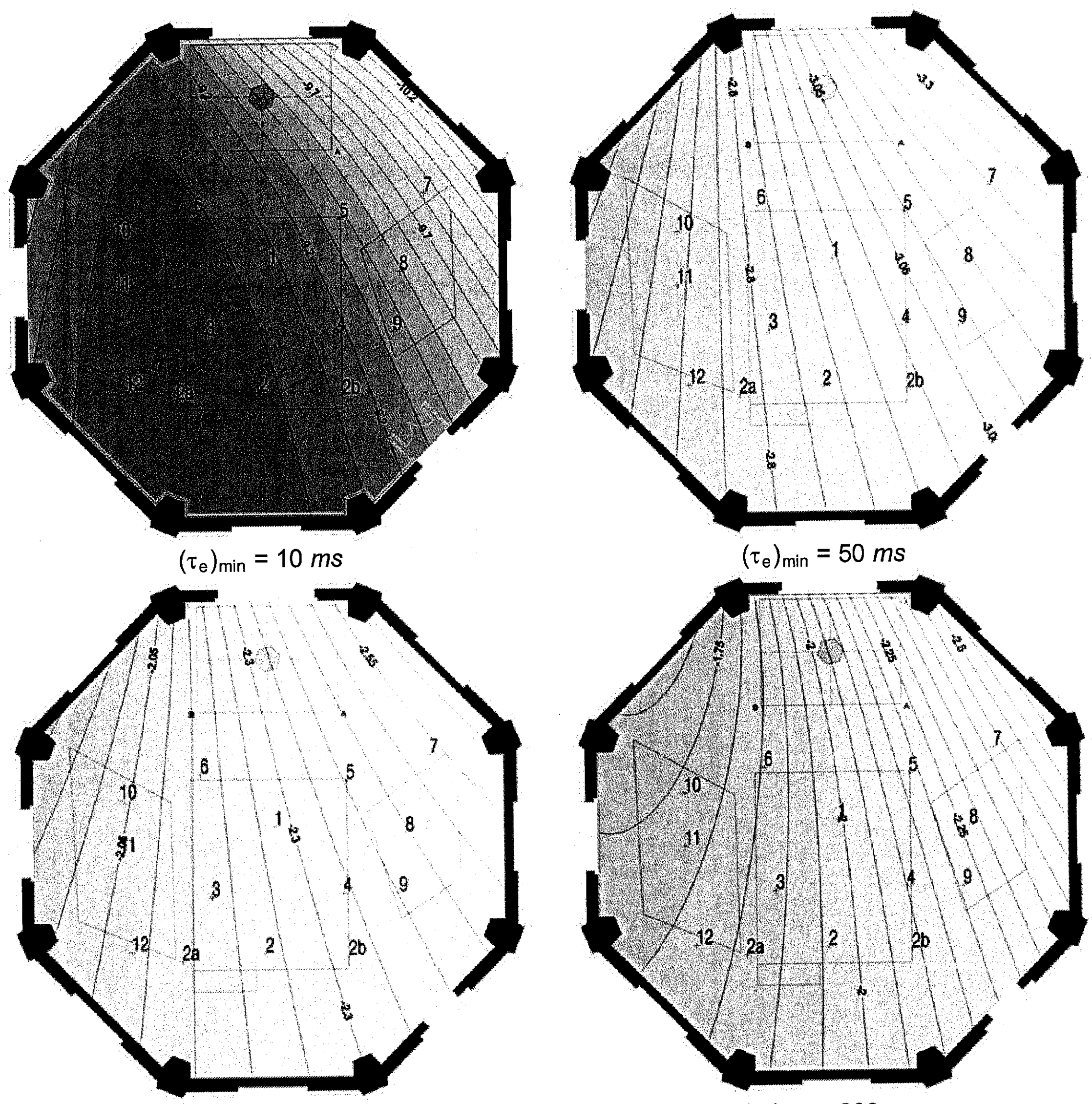
(c) T_{15} (d) *LL*

Figure 6: Maps of measured post-operam values.

4 EVALUATION OF THE SUBJECTIVE PREFERENCE

Following the Ando's theory of subjective preference[4], different functions of the subjective goodness may be calculated for each position. Varying the values of $(\tau_e)_{min}$ from 10 *ms* to 200 *ms*, different map of the total preference functions have been calculated (see figure 6).

The high *A* values measured make low subjective preference values for the first reflection delay time and the subjective preference value for the whole range of $(\tau_e)_{min}$. The subjective preference for the subsequent reverberation time is low for $(\tau_e)_{min} < 100$ *ms*. Moreover, the high *A* values and the low *IACC* mean that the acoustic energy is quite constant in the hall. The subjective preference for the listener level is good and also the one for the *IACC*, as expected. It should be noted that the total value of the subjective preference decreases for $(\tau_e)_{min} > 150$ *ms*.



$(\tau_e)_{min}$ = 10 *ms* $(\tau_e)_{min}$ = 50 *ms*

$(\tau_e)_{min}$ = 100 *ms* $(\tau_e)_{min}$ = 200 *ms*

Figure 7: Maps of subjective preference values for different values of effective duration of the ACF.

5 CONCLUSIONS

The acoustic design of an octagonal hall is briefly resumed in this work.
Some hypothesis on the modal characteristics of the hall have been proposed, Following these hypotheses, a system of asymmetrical suspended reflectors has been installed to allow the modal control and to optimize the early reflections. The acoustic design of the hall, permitted to get:
- *EDT* and C_{80} values adequate to the intended use of the hall;
- high diffuseness of the sound field;
- quite constant values of the sound energy in the seat areas and high sound pressure levels;
- a certain degree of variable acoustics to agree with the request of performers.

Ando's subjective preference functions have been also calculated for different sound signals, represented by their $(\tau_e)_{min}$ values.

6 REFERENCES

1. M. Barron, 'Interpretation of Early Decay Times in concert auditoria', Acustica, 81, 320-331 (1995).
2. G. M. Naylor, 'ODEON – Another Hybrid Room Acoustical Model', Appl. Acoust. 38, 131-143 (1993).
3. S. De Cesaris, D. D'Orazio, M. Garai, '*ITDG* calculation with a non linear iterative algorithm', Proc. of the I.O.A. 33(2) (2011).
4. Y. Ando. Concert Hall Acoustics, Springer-Verlag, New York (1985).