BOXES AND SOUND QUALITY IN AN ITALIAN OPERA HOUSE

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The "Teatro Comunale" (City Theatre) in Bologna is an Italian opera house of the 18th century, designed by the famous architect Antonio Galli Bibiena. Largely built in masonry, it has been only partially restored and altered several times, but never destroyed and rebuilt. The study of its acoustics, while interesting for itself, offers the opportunity to investigate the role of the boxes, which constitute the most evident characteristic of Italian opera houses. The study was carried on at first by measurements, acquiring binaural impulse responses in the stalls and in the boxes, and then by computer simulation, modelling also some changes which cannot be done in the real hall. The measurements revealed clear differences between the listening quality in the boxes and in the stalls, especially regarding *ITDG*, clarity and *IACC*. Computer simulations show how the sound field in the historical theatre could be if the sound absorption of the boxes were changed, adding some velvet curtains, as was done in ancient times, and clarify the effects of the cavities which constitutes the boxes.

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1. INTRODUCTION

The "Teatro Comunale" in Bologna was built in six years in a controversial atmosphere that surely did not bring at the best result both from the architectural and acoustical point of view: Bibiena was obliged to change many details, but he remained steady as a rock in the choice of the shape (a bell) and materials (masonry). The acoustical characteristics (and the problems) that can be found now are quite the same as those of the original hall: fire, the first enemy of the theatres (in the last years the "Petruzzelli" in Bari and the "La Fenice" in Venice were completely destroyed by fire) could not injure this very important cultural heritage even when the wooden stage fired; this result has been possible due to the fundamental choice of the Architect, to whom the cultural community in the world is grateful.

2. THE THEATRE

The "Teatro Comunale" (City Theatre) in Bologna is the masterpiece of the architect Antonio Galli Bibiena, prominent member of a famous family of
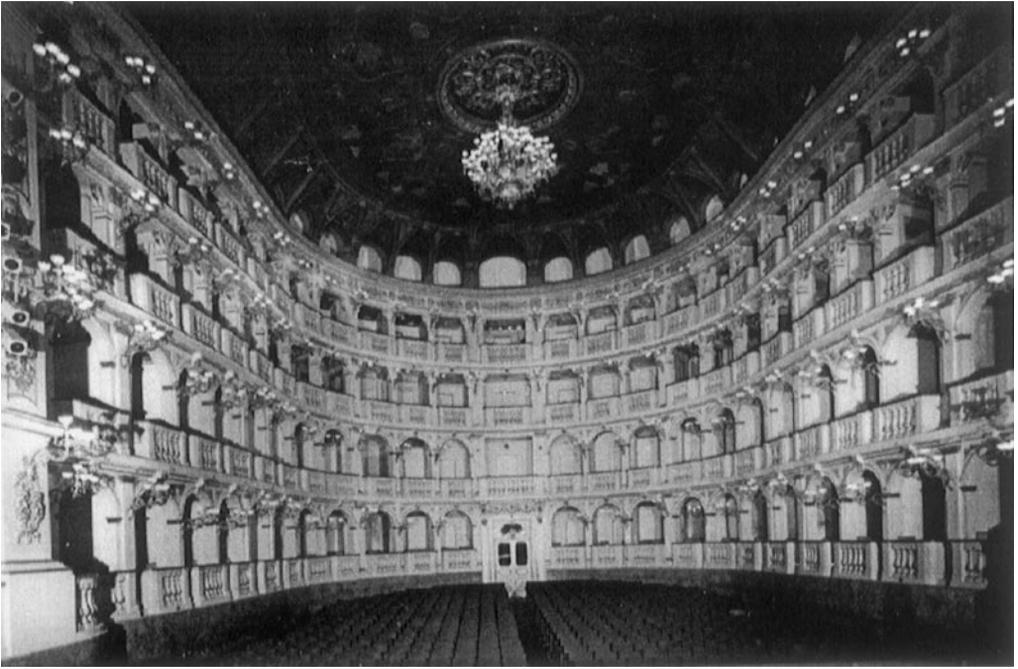
Figure 1. The Teatro Comunale in Bologna.

theatrical architects and set designers in Europe. The theatre is a typical Italian opera house of the 18th century (see Figure 1), and one of the oldest to have survived until present time without being completely destroyed by fire or by war. It was inagurated on 14 May 1763 with the first representation of Gluck's *Il trionfo di Clelia*. The theatre has a "bell" shape in plan, four tiers of boxes plus a gallery on the walls and a vaulted ceiling with a big chandelier suspended in the centre. The Teatro Comunale was largely built in masonry, probably for fire safety reasons, but some wood was also used; for example, the wooden beams supporting the box floors remained in place until the years 1980–81, when an infestation of woodworms made it necessary to replace many of them. In the years 1818–20 the stalls were raised with a wooden parquet; it covers a cavity where a mechanism still exists, though no longer working, that allowed the parquet to be further raised to the level of the stage for balls. The original design by Antonio Galli Bibiena was modified and adapted several times, from construction time through subsequent restorations until present days, simplifying the varied appearance of the original design in the sober and organized present appearance. During the subsequent restorations which occurred in the theatre, the velvet curtains of the boxes were almost completely removed. Most internal surfaces are now plaster-covered; recent restorations discovered frescoes under the plaster of several boxes, privately owned in the past. At the present, there are 540 upholstered seats on the wooden floor of the stalls and 466 in the boxes and in the gallery.
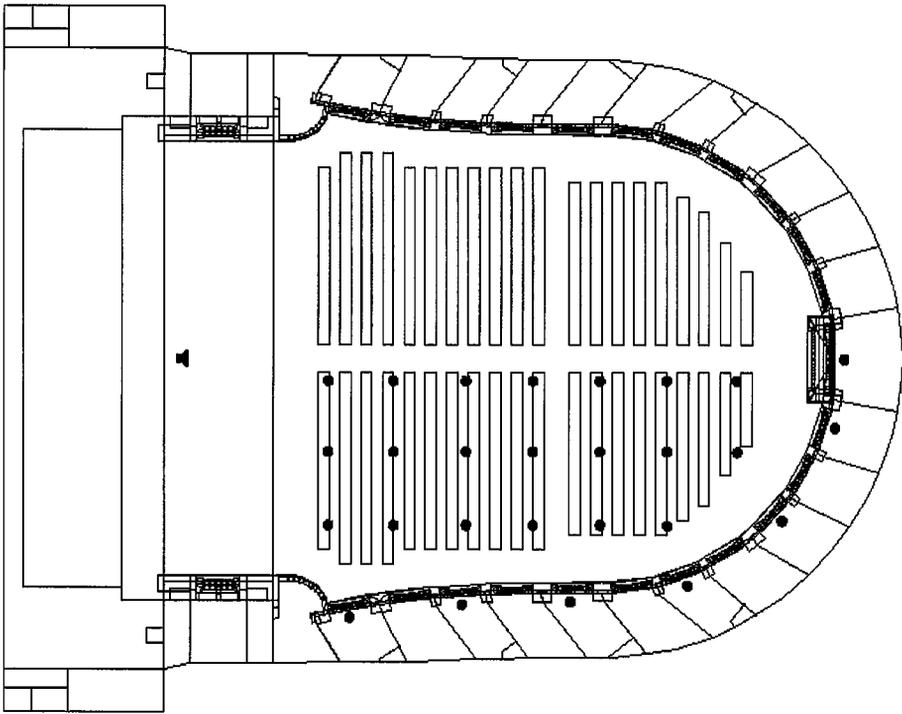
Figure 2. Location of the measurement points: plan view. Sound source at centre stage.

3. MEASUREMENTS

In a measurement campaign conducted some time ago [1], binaural impulse responses were acquired in the stalls and in the boxes: by post-processing these responses it has been possible to get the most important acoustic criteria. The theatre was in the so-called "symphonic configuration"; as usual in many opera houses; in this arrangement the stage is prolonged, covering the orchestra pit, a room-shaped orchestra shell is mounted on the stage and the symphonic orchestra is arranged inside it.

Impulse responses were acquired by placing in several positions in the stalls and in the boxes a dummy head equipped with two microphones in the outer ear (see Figures 2 and 3). In the boxes, the dummy head was always placed in the first row of chairs. The sound source was a dodecahedral loudspeaker placed on the stage and fed with an MLS signal generated with an A2D-160 board placed inside a PC [2]. The microphone signal was transmitted to the PC by a VHF transmitter/receiver couple. Figure 4 shows a sketch of the measurement set-up; Figure 5 shows two typical impulse responses. After post-processing, mainly by using proprietary software, it was possible to obtain the information detailed in the following. The objective acoustical criteria mentioned in text are defined in the Appendix A.

The measurements clearly revealed a noticeable difference between the listening quality in the boxes and in the stalls, especially regarding $ITDG$, clarity and $IACC$.
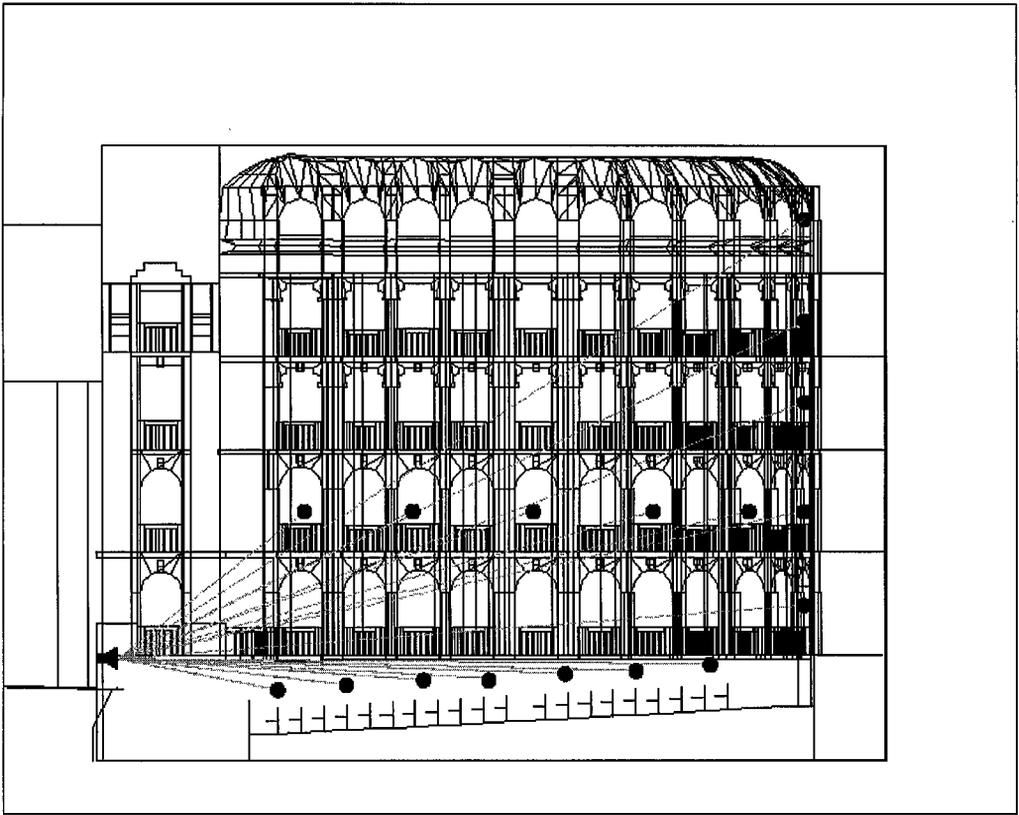
Figure 3. Location of the measurement points: sectional view. Sound source at centre stage. Light gray lines from source to receivers are intended to help in the individuation of the measurements points.
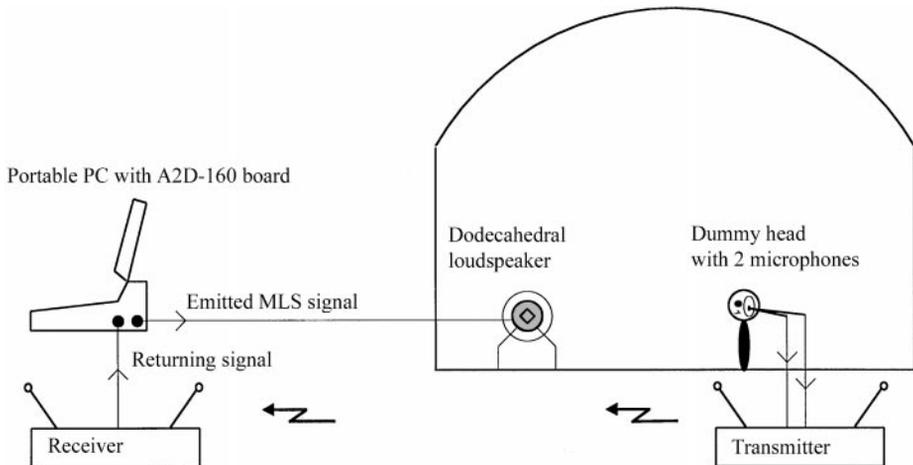
Figure 4. Sketch of the impulse response measurement technique.
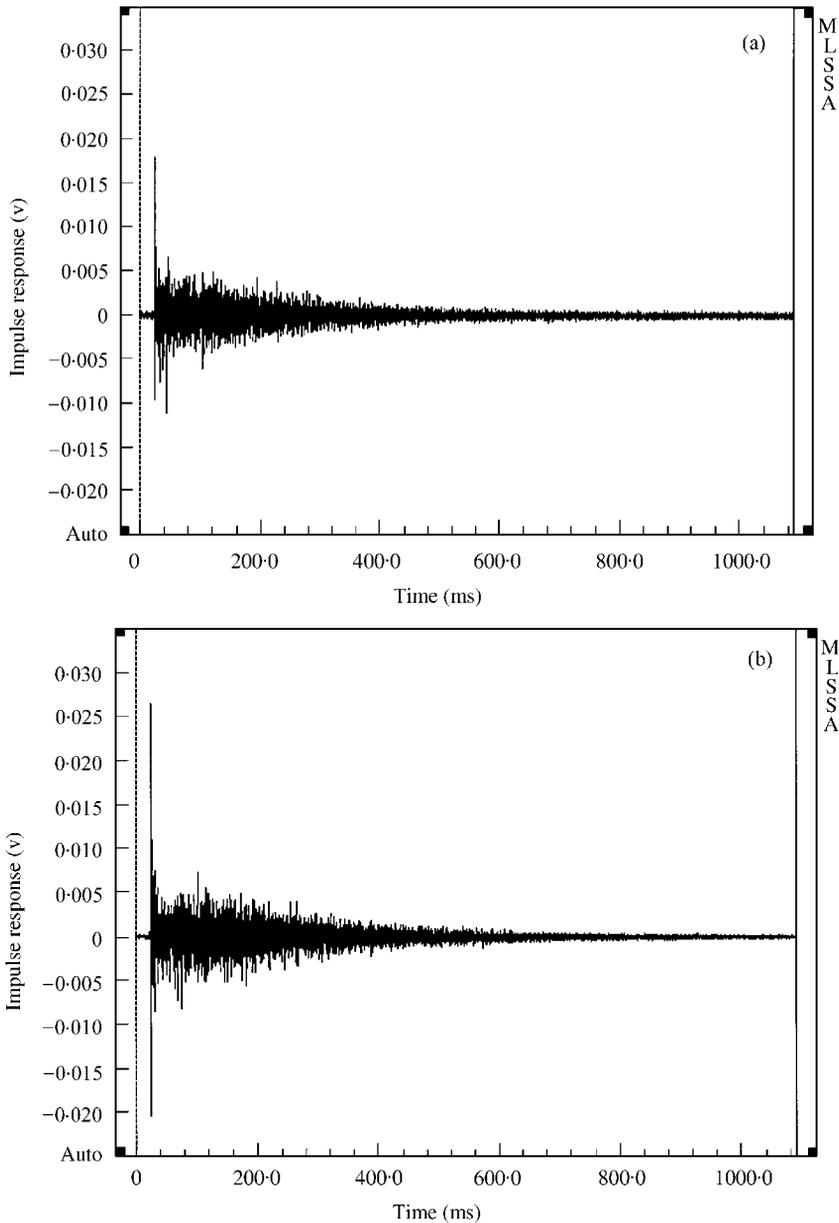
Figure 5. Impulse response for the left ear (a) and the right ear (b) at seat A22 in the stalls.

3.1. INITIAL-TIME-DELAY GAP (*ITDG*)

The distribution of the wide band *ITDG* values in the stalls is shown in Figure 6. The influence of the reflecting strip of smooth plaster located on the two sides of the audience is evident.

For the boxes the situation requires a careful interpretation of the definition of *ITDG*. In fact, it is defined by Beranek, who first recognized its importance, as "the
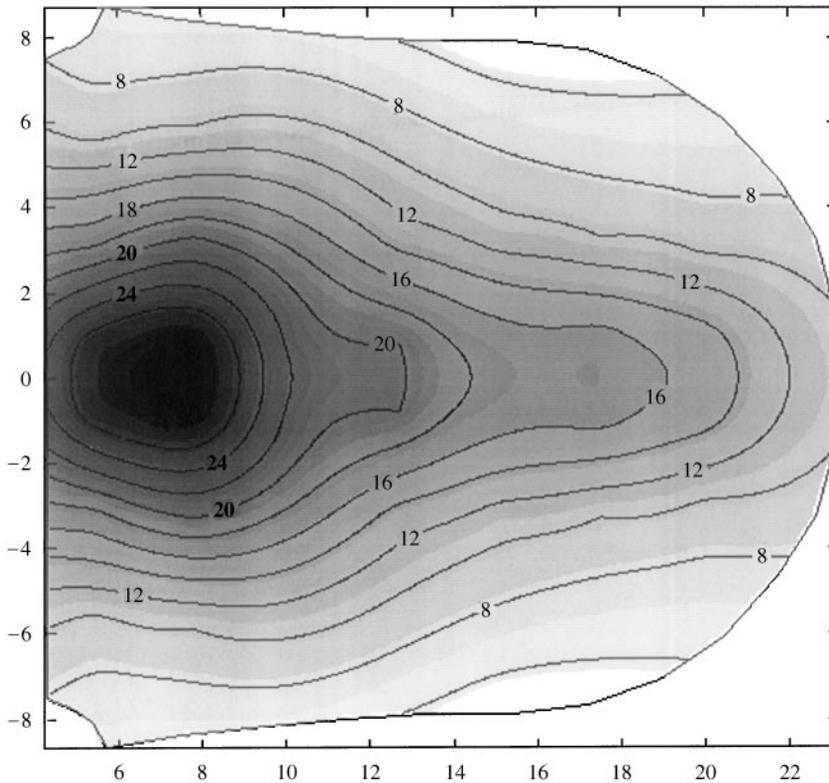
Figure 6. Measured distribution of *ITDG* values (in ms) in the stalls. Sound source at centre stage.

time interval in milliseconds between the arrival at a seat in the hall of the direct sound from a source on the stage to the arrival of the first reflection" [3]. In the stalls the first reflection is also the strongest one, as it has the smallest geometrical spreading, and the preceding definition applies. For listeners in the boxes, the first reflection comes from the reflective inside-box walls, but the strongest and most meaningful reflection arrives later from the hall. Thus, the choice of the reflection to be used determines the result: the wide band *ITDG* values along a vertical section through the stall and the boxes are shown in Figure 7(a); the wide band *ITDG* values along a horizontal section through the boxes of the second tier are shown in Figure 7(b). It seems that for opera houses the above definition of *ITDG* should be clarified specifying that Beranek means the "strongest" reflection, that often—but not always—is the "first".

3.2. REVERBERATION TIME

Figure 8 shows the reverberation times T_{15} and EDT, computed in octave bands by using the Schröder technique and averaged in the stalls and in the boxes. In the octave bands from 63 to 500 Hz the EDT values are considerably smaller than those of T_{15}. In general, the measured values are slightly high for a typical opera house [3–5].
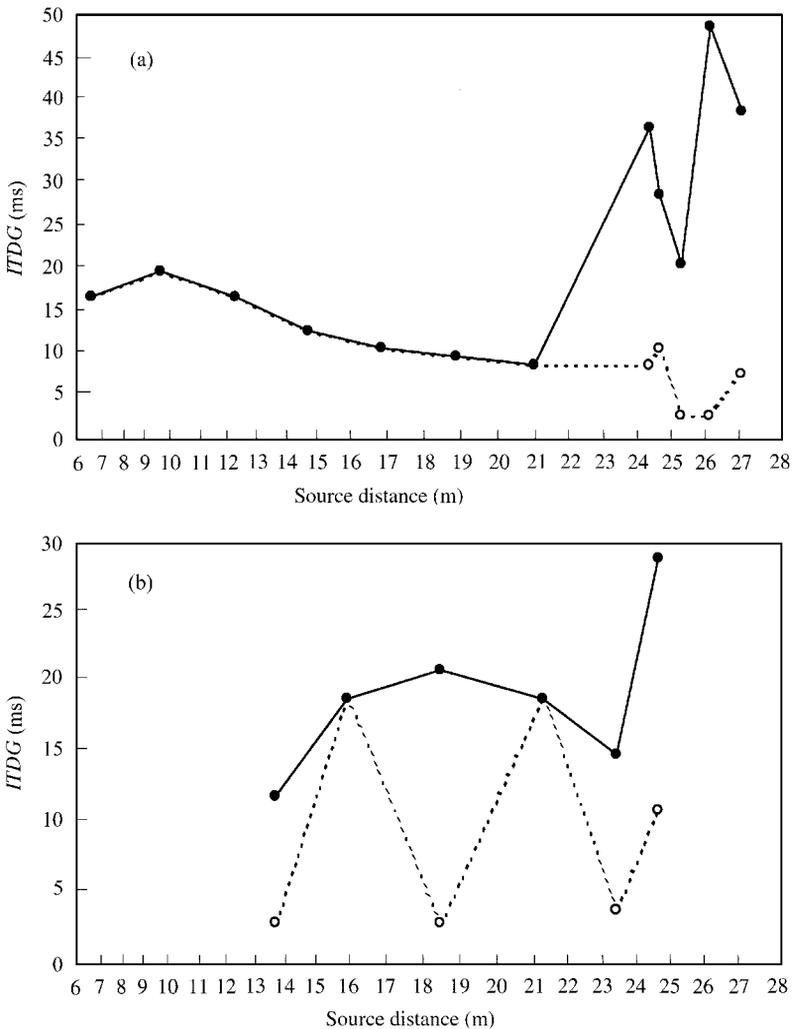
Figure 7. Value of the $ITDG$ along (a) a vertical section traced through the stall and the boxes; (b) a horizontal section through the boxes of the second tier. Stage on the left: (———) using the strongest (second) reflection; (- - -) using the first reflection.

3.3. CLARITY

Figure 9 shows the distribution of the wide band values of the clarity C_{80}, in decibels, in the stalls. The clarity values are better near the stage (for the listeners but not necessarily for the conductor) and in the rear of the stalls. Figure 10 shows the values of C_{80} and C_{50} in one-third octave bands averaged in the stalls. The trend is similar for both criteria except in the 125 Hz one-third octave band.

Figure 11(a) shows the wide band values of C_{80} and C_{50} along a vertical section traced through the stalls and the boxes. The trend is similar for both criteria, with lower values for C_{50} due to its smaller upper integration limit (50 instead of 80 ms):
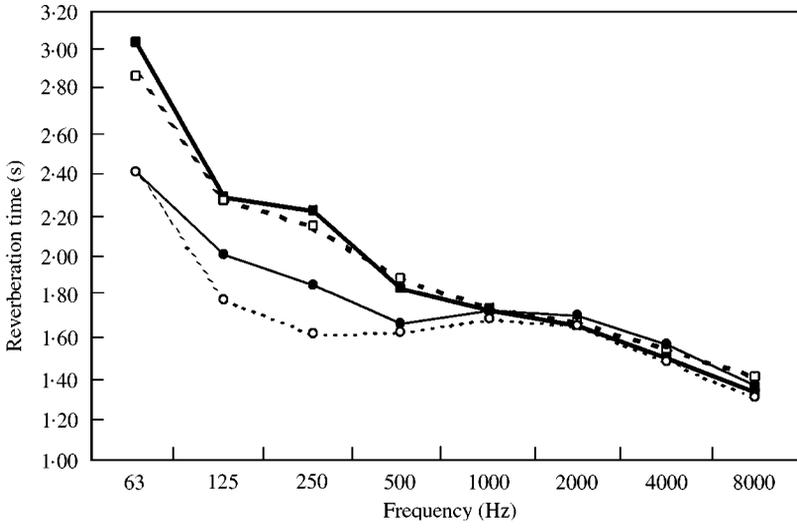
Figure 8. Averaged reverberation times: (——) T_{15}, averaged in the stall; (- - - -), T_{15}, averaged in the boxes; (——), *EDT*, averaged in the stalls; (- - - - -), *EDT*, averaged in the boxes.
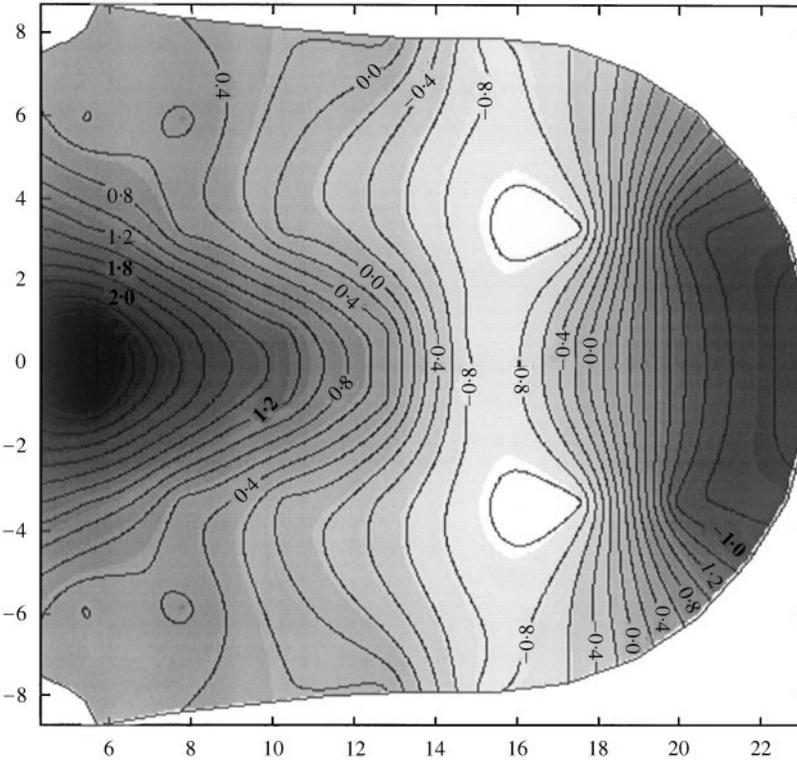
Figure 9. Measured distribution of clarity C_{80} values (in dB), in the stall. Sound source at centre stage.
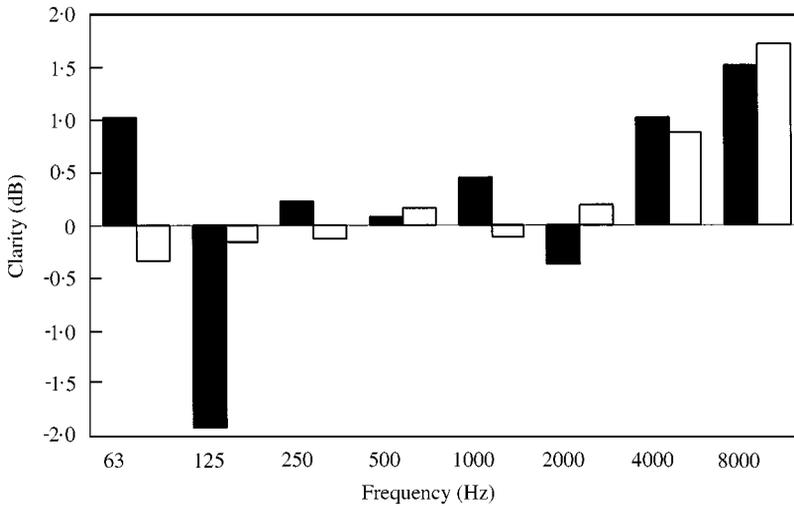
Figure 10. Averaged clarity values in the stalls: ■, C_{80}; □, C_{50}.

in the stalls the values decrease moving away from the stage and raises again in the rear stalls; then, in the boxes, they increase with the height of the boxes until the third tier; the sudden decrease measured at second tier is due to the fact that the box in which the measurements where taken is adjacent to the central box, which in the second tier is greater than in the other ones and has a bigger projecting balustrade; since ancient times it has been reserved for the authorities ("royal box"). In the central boxes of the fourth tier and the gallery the clarity values decrease again: this is due to a late arrival of sound energy, related to a second order reflection on the flat, reflecting, rear wall of the orchestra shell and the ceiling; the late reflection can be seen in Figure 12, reporting the impulse response measured in the fourth tier box adjacent to the central box.

Figure 11(b) shows the wide band values of C_{80} and C_{50} along a horizontal section through the boxes of the second tier. Again, the trend is similar for both criteria, with a better clarity in the boxes closer to the stage. The clarity distribution found experimentally in the opera house under study is in agreement with the Mozart's famous statement, written in October 1791 to his wife [6]: "by the way, you have no idea how charming the music sounds when you hear it from a box close to the orchestra—it sounds much better than from the gallery".

3.4. CENTRE TIME

Figure 13(a) shows the wide band values of the centre time T_s along a vertical section traced through the stalls and the boxes. Figure 13(b) shows the wide band values of the centre time T_s along a horizontal section through the second level boxes. As can be seen, the trend for T_s is the reciprocal of the trend for clarity, confirming the well-known correlation between the two criteria.
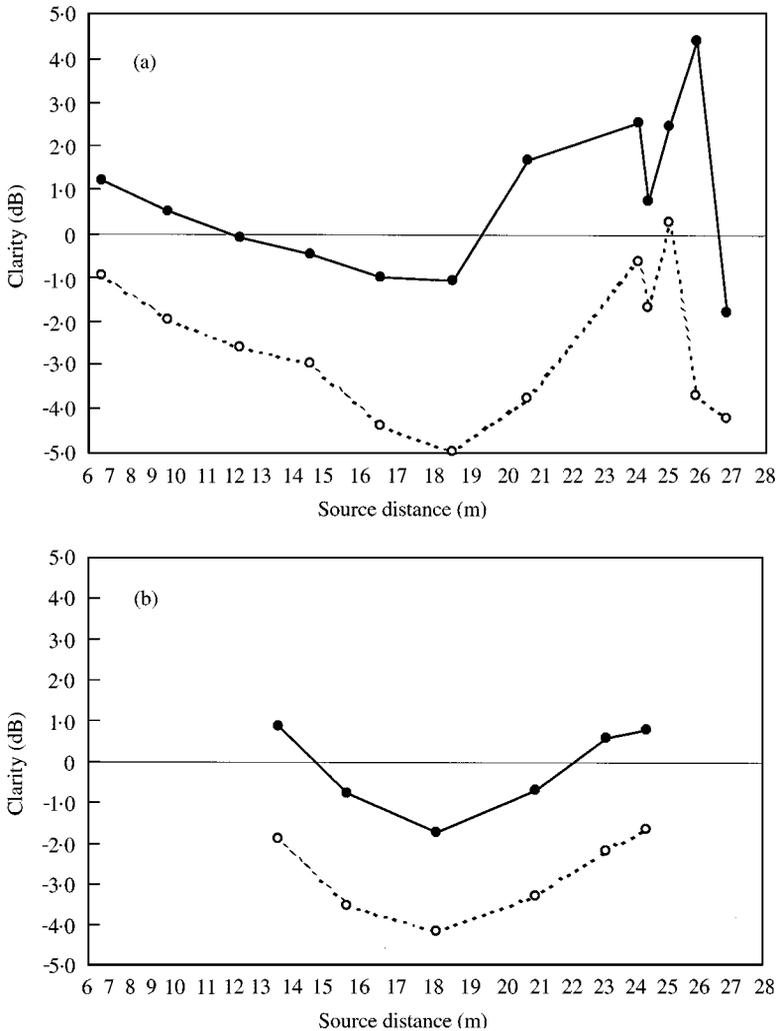
Figure 11. Clarity values along (a) a vertical section traced through the stall and the boxes; (b) a horizontal section through the boxes of the second tier. Stage on the left: (——), C_{80}; (- - -), C_{50}.

3.5. INTER-AURAL CROSS-CORRELATION

Figure 14(a) shows the wide band values of the inter-aural cross-correlation coefficient $IACC_{50}$ along a vertical section traced through the stalls and the boxes. In the boxes directly facing the stage, the $IACC_{50}$ values are higher—and then worse [7]—than those obtained in the stalls; only in the fourth tier and in the gallery the $IACC_{50}$ returns to values close to those in the stall. The second tier box is an exception because it is adjacent to the royal box and thus is influenced by an asymmetric reflection on the projecting balustrade. Figure 4(b) shows the wide band values of the inter-aural cross-correlation coefficient $IACC_{50}$ along a horizontal section through the boxes of the second tier: the best values are found in the lateral ones.
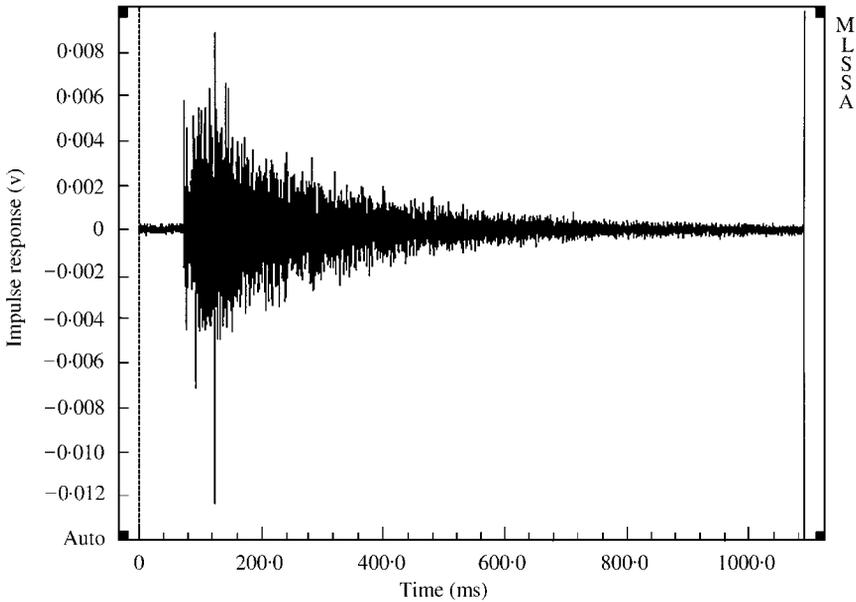
Figure 12. Impulse response in the fourth tier box adjacent to the central box.

3.6. ANDO'S RATING SYSTEM

Figures 15 and 16 show the results obtained by applying Ando's theory for two different kinds of music to the data measured in the Teatro Comunale in Bologna. In this context, music motifs are classified from their effective duration of the autocorrelation function τ_e [7], as shown in Table 2.

The main criticism about the theatre under study, already raised against the first proposal by Antonio Galli Bibiena and reported even in modern literature [4], is that the hall is not acoustically good, chiefly for operas. The distributions of the total scale values of preference show that the acoustical response in the stalls really changes when listening to "slow" or "fast" music, but also that fast music, with a shorter τ_e, can better withstand the hardness of the masonry. In this respect, criticism of the work of Antonio Galli Bibiena should be attenuated. It is interesting that with the Mozart motif (see Figure 15) better preference values are found close to the orchestra in lateral positions in the stalls, corresponding to which Mozart himself referred regarding the boxes in his above-mentioned letter. Anyway, the scale value distribution is not uniform and another zone for better listening to fast music is found in the rear stalls.

4. THE BOXES: SOUND ABSORPTION AND EFFECT OF CAVITIES

There are many possible mechanisms by which the boxes influence the sound field in the stalls: the sound absorption of the box internal walls or of curtains in the boxes and the effect of the ensemble of cavities filling the box-covered walls are surely two of them [8]. While it is impossible to alter an ancient theatre to study
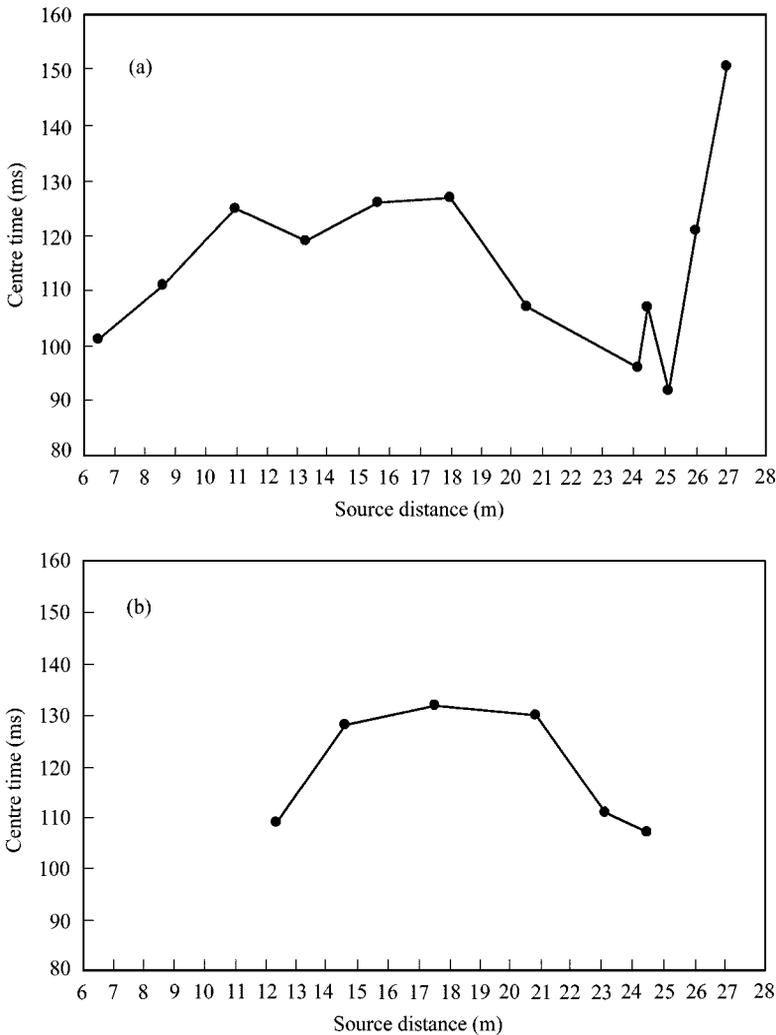
Figure 13. Centre time values along (a) a vertical section traced through the stall and the boxes; (b) a horizontal section through the boxes of the second tier. Stage on the left.

these effects in an experimental way, computer simulation is a viable way to investigate them. During the several restorations which have occurred in the Teatro Comunale in Bologna, the velvet curtains at the opening of the boxes, existing in ancient times, were completely removed and now it is difficult even to guess the acoustic characteristics of the original blend of materials. At present, the theatre has a T_{15} of about 1·6–1·8 s at mid-frequencies in the stalls (see Figure 8) and is claimed to be more "live" than similar Italian opera houses (following Beranek [3], "liveness" is related primarily to the reverberation times at middle and high frequencies, those above about 350 Hz). In order to restore the original sound absorption of the box-covered walls, modern fire-proof fabric curtains could be added in the boxes; computer simulation can help in understanding how and how
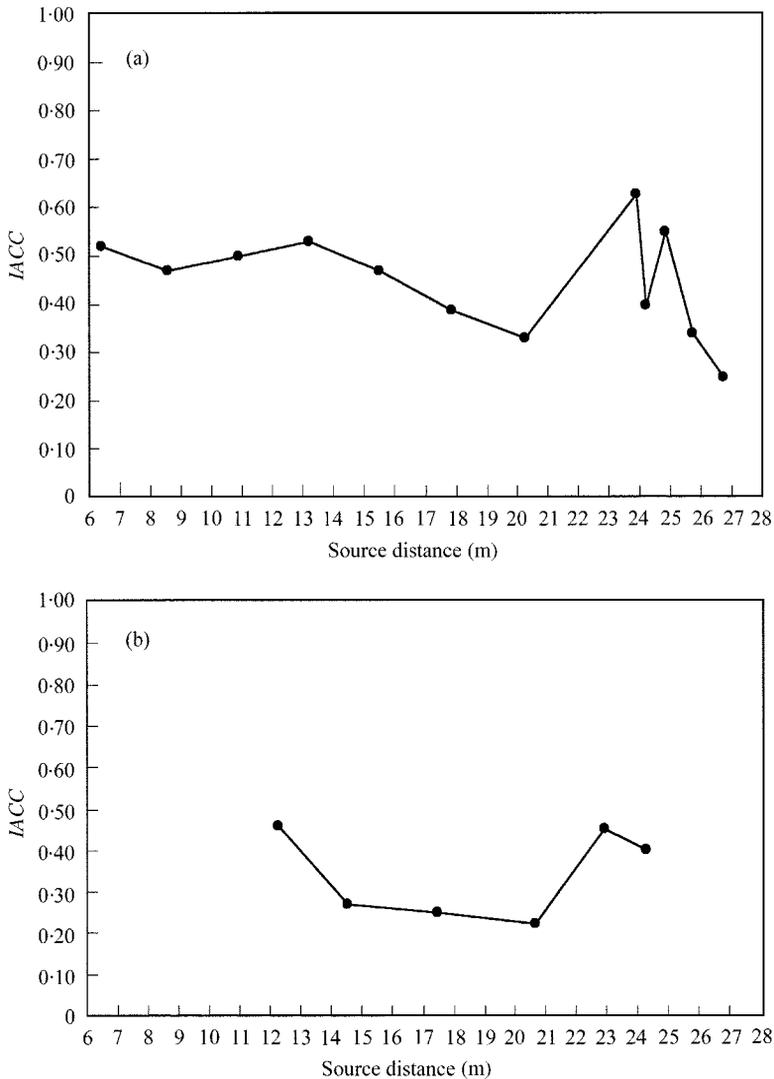
Figure 14. Inter-aural cross-correlation values along (a) a vertical section traced through the stalls and the boxes; (b) a horizontal section through the boxes of the second tier. Stage on the left.

much the introduction of these curtains could change the theatre acoustics. Computer simulation can also help in understanding the role of the cavities which constitute the boxes: for instance, the effects of these cavities can be "cancelled' by inserting a smooth wall closing the opening of each box in the computer model and the resulting situation can be studied.

Figure 17 shows the computer model of the theatre, built to be used with the simulation software *Ramsete* [9]; each curved surface was represented with several plane facets. The accuracy of the model was validated by using an iterative procedure, elsewhere detailed [10], to adjust the model geometry, the sound power level of the source and the sound absorption of the surfaces until the values of the
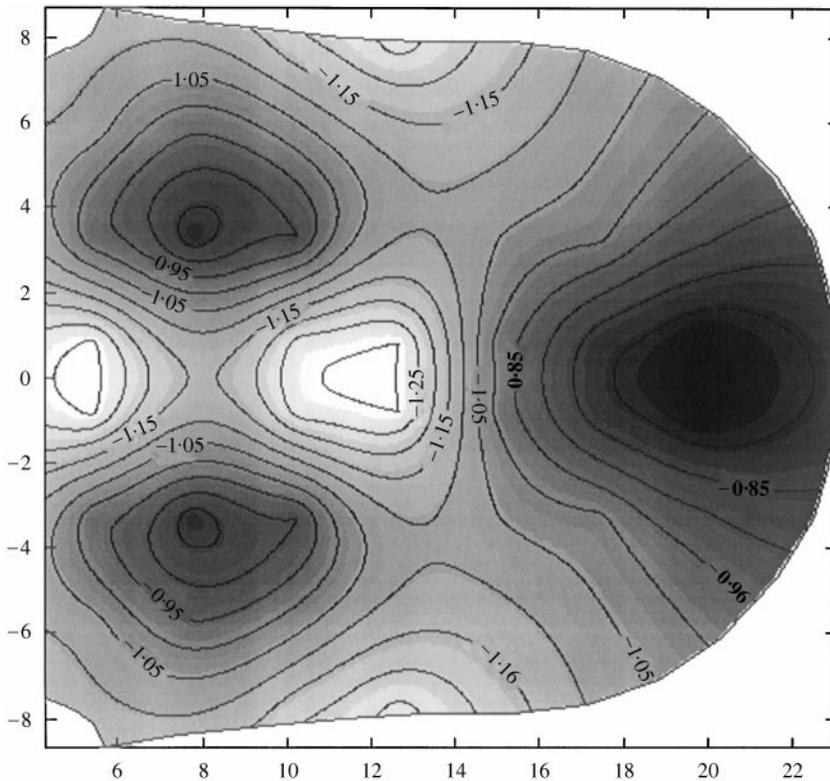
Figure 15. Distribution of Ando's total scale values of preference, in the stalls, calculate with a "fast" music (Mozart's symphony KV 551 *Jupiter*, fourth movement, $\tau_e = 38$ ms). Sound source at centre stage.

reverberation time T_{15} and the sound pressure level match the measured values. The variations of the acoustic criteria with the position in the hall were taken into account by placing into the model a set of receivers corresponding to the measurements positions in the real hall. Table 1 shows the differences between the simulated and measured values of reverberation time and sound pressure level, averaged over the 31 receivers, after completion of the validation procedure.

In order to study the two above-mentioned effects, each orchestra section has been modelled by a sound source with the appropriate sound power spectrum and directivity [11]. Regarding the first effect (sound absorption), velvet curtains were added into the boxes in the computer model and the simulation results were compared to those obtained for the actual all-plaster boxes. For each acoustic criterion, the change from the actual situation was computed and averaged over the stalls. Figures 18 and 19 show that the reductions of *EDT* and T_s have a similar trend, due to the added absorption. The predicted variations are non-uniform over the frequency range, because the sound absorption coefficient of the velvet curtains takes into account an air gap between the curtains and the wall.

Regarding the second effect (role of the cavities of the box-covered walls), the action of such cavities was "cancelled" by inserting in the computer model a smooth

Figure 16. Distribution of Ando's total scale values of preference, in the stalls, calculated with a "slow" music (Gibbon's Royal Pavane, $\tau_e = 127$ ms). Sound source at centre stage.

TABLE 1

Differences between simulated and measured values of reverberation time and sound pressure level, averaged over 31 receivers (measurement positions)

Octave band (Hz)	63	125	250	500	1000	2000	4000	8000
T_{15} (s)	0·00	0·03	− 0·02	− 0·01	− 0·07	− 0·04	− 0·07	− 0·04
SPL (dB)	− 0·01	0·00	0·00	0·00	0·00	0·00	0·00	0·00

TABLE 2

Effective duration of the autocorrelation function of the two music pieces used to calculate Ando's scale value of preference (after reference [7])

Title	Composer	τ_e (ms)
Royal Pavane	Gibbons	127
Symphony in C major KV 551, 4th movement	Mozart	38

Figure 17. Computer model of the Teatro Comunale in Bologna.
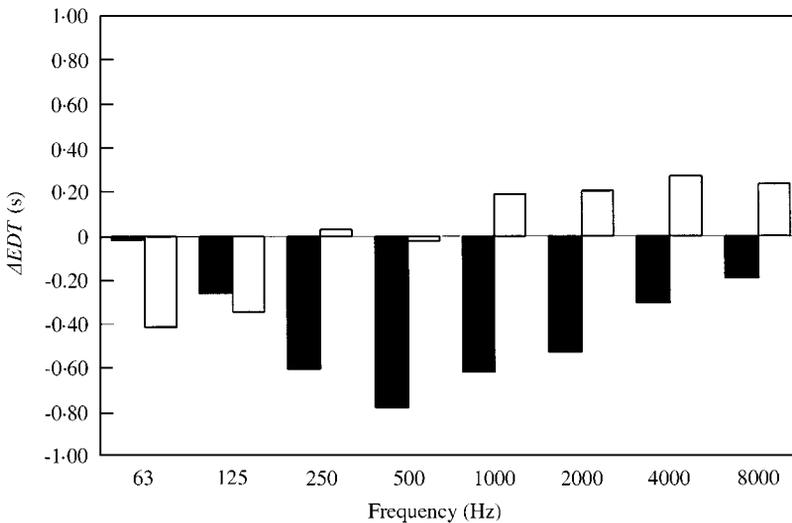
Figure 18. Averaged changes of *EDT* in the stalls: ■, inserting the velvet curtain; □, closing the boxes.

wall closing the opening of each box. Figures 18 and 19 show that, without the box cavities, *EDT* and T_s would be reduced at low frequencies and enhanced at high frequencies. The hypothesis can be made that at low frequencies the boxes act as resonators to sustain the reverberant field, while at high frequencies they are
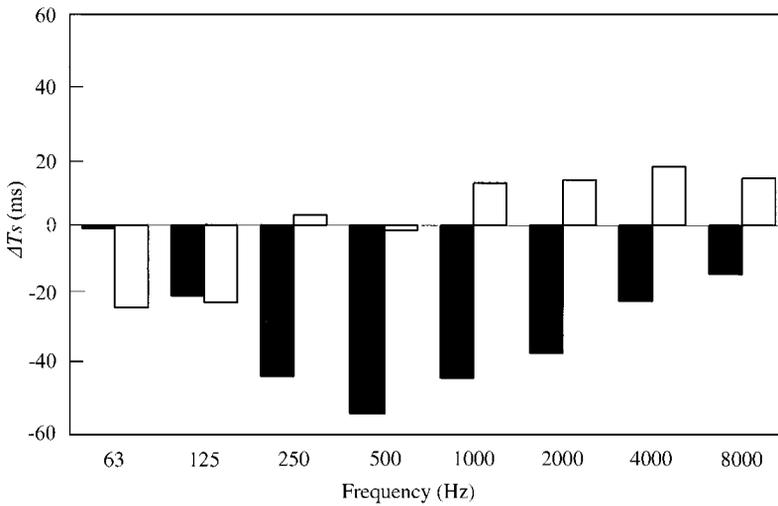
Figure 19. Averaged changes of T_s in the stalls: ■, inserting the velvet curtains; □: closing the boxes.
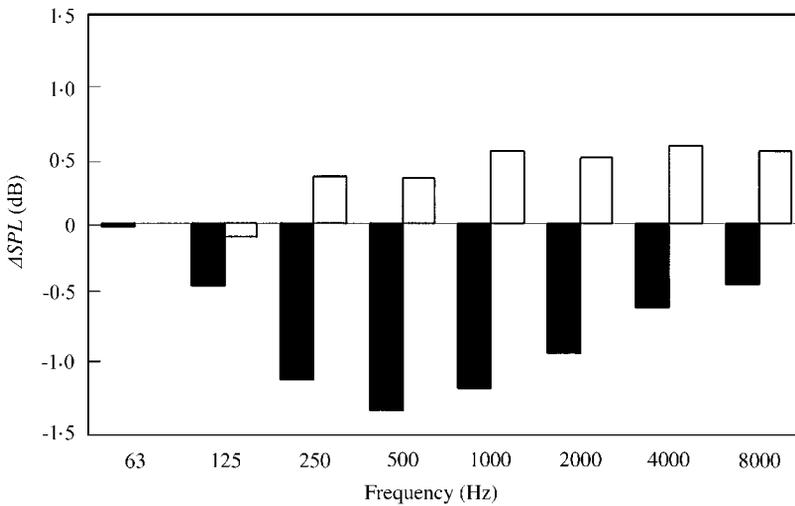
Figure 20. Averaged changes of sound pressure levels in the stalls: ■, inserting the velvet curtains; □: closing the boxes.

"sound traps" which recall some energy from the hall. The transition is smooth and located in the 250 and 500 Hz octave bands. This hypothesis would confirm that the "warmth" or Italian opera houses is also due to the box-covered walls (following Beranek [3], "warmth" in music is defined as liveness of the bass, or fullness of the bass tones (between 75 and 350 Hz), relative to that of the mid-frequency tones (350–1400 Hz)). The same simulation shows that the effect on sound pressure level would be small (see Figure 20), as the temporal redistribution of sound energy does not affect its overall value.

From this study by computer simulation the conclusion can be drawn that the introduction of velvet curtains in the boxes would help in controlling the excessive liveness of the hall; computer simulations also confirm that the box-covered walls are important for the acoustical quality of the opera house.

5. CONCLUSIONS

Binaural measurements performed inside the Teatro Comunale in Bologna clearly revealed a lot of difference between the listening quality in the boxes and in the stalls, especially regarding *ITDG* clarity and *IACC*. The distributions of the total scale values of preference show that the acoustical response in the stalls really changes when listening to slow or fast music, and also that fast music is more suitable for this hall. Better clarity values were found in the boxes closer to the stage, in agreement with a Mozart's famous statement. The role of the boxes on the acoustics of the theatre, and of the Italian opera houses in general, has been further clarified by computer simulation, a valuable tool to perform "virtual experiments" on ancient halls which cannot be altered in practice. In particular, in the present work it has been shown how the introduction of curtains in the boxes could improve the theatre acoustics and how computer simulation can help in understanding the role of the cavities that constitute the boxes and contribute to make the typical sound of Italian opera houses.

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APPENDIX A: DEFINITION OF SOME ACOUSTICAL CRITERIA

The objective acoustical criteria mentioned in the text are briefly defined here. More detailed information can be found in references [3, 5, 7, 12].

A.1. INITIAL-TIME-DELAY GAP *ITDG*

The time interval in milliseconds between the arrival at a seat in the hall of the direct sound from a source on the stage to the arrival of the first reflection. Following Beranek [3] the *ITDG* correlates with the subjective impression of "intimacy".

A.2. REVERBERATION TIME T_{15}

Time, expressed in seconds, that would be required for the sound pressure level to decrease by 60 dB, at a rate of decay given by the linear least-squares regression of the measured decay curve from a level 5 dB below the initial level to 20 dB below.

A.3. EARLY DECAY TIME *EDT*

Time, expressed in seconds, that would be required for the sound pressure level to decrease by 60 dB, at a rate of decay given by the linear least-squares regression of the measured decay curve from the initial level to 10 dB below it. *EDT* is considered subjectively more important than T_{15} in relation to perceived reverberation [3, 5, 12], while T_{15} is considered more related to the physical properties of the hall.

A.4. CLARITY

Early-to-late arriving sound energy ratio, calculated for a fixed early time limit t_{lim} and expressed on a logarithmic scale in decibels:

$$C_{t_{\text{lim}}} = 10 \lg \left[\int_0^{t_{\text{lim}}} p^2(t) \, dt \left/ \int_{t_{\text{lim}}}^{\infty} p^2(t) \, dt \right. \right] \quad \text{(dB).} \tag{A1}$$

Here $p(t)$ is the measured impulse response, and t_{lim} is the early time limit of either 50 or 80 ms.

Usually, C_{50} is preferred for speech and C_{80} for music; the situation for typical operas is in between. C_{80} is properly named "clarity", whereas C_{50} is sometimes referred to as "50 ms clarity".

A.5. CENTRE TIME T_s

Time, usually expressed in milliseconds, of the centre of gravity of the squared impulse response:

$$T_s = \int_0^{\infty} t p^2(t) \, dt \left/ \int_0^{\infty} p^2(t) \, dt \right. \quad \text{(ms).} \tag{A2}$$

A.6. INTER-AURAL CROSS-CORRELATION COEFFICIENT $IACC_{50}$

Many studies have shown that binaural measurements with a dummy head having small microphones at the entrance of ear canals correlate well with the subjective quality "spatial impression" [3, 5, 7]. According to reference [12], the normalized inter-aural cross-correlation function for the first 50 ms of the impulse responses for the left and right ear canals, $IACF_{50}$, is defined as

$$IACF_{50}(\tau) = \int_0^{50 \text{ ms}} p_l(t)p_r(t+\tau)\,dt \Bigg/ \left[\int_0^{50 \text{ ms}} p_l^2(t)p_r^2(t+\tau)\,dt\right]^{1/2}, \quad (A3)$$

where $p_l(t)$ is the impulse response measured at the entrance of the left ear canal and $p_r(t)$ is the impulse response measured at the entrance of the right ear canal.

The inter-aural cross-correlation coefficient, for the first 50 ms of the impulse responses for the left and right ear canals, $IACC_{50}$, is given by

$$IACC_{50} = \max|IACF_{50}(\tau)| \quad \text{for } -1 \text{ ms} \leqslant \tau \leqslant 1 \text{ ms}. \quad (A4)$$

A.7. ANDO'S RATING SYSTEM

Ando stated [7] that all acoustic information given by the independent objective criteria extracted from the sound pressure signals at the two ears of a listener can be reduced to four orthogonal factors. These four factors are the listening level, the $ITDG$, the subsequent reverberation time (in practice, T_{15} is used) and the $IACC$. The first three are temporal-monoaural criteria, the latter ($IACC$) is a spatial-binaural criterion. They are first converted into four dimensionless variables x_i by taking the ratio of each criterion with a preferred value, except for $IACC$ that already is dimensionless:

$$x_1 = 10\lg(p^2/p_p^2), \quad x_2 = 10\lg(ITDG/[ITDG]_p) \qquad (A5a, b)$$

$$x_3 = 10\lg(T_{15}/[T_{15}]_p), \quad x_4 = IACC. \qquad (A5c, d)$$

Here $p(t)$ is the impulse response measured at the listener position; the values suffixed with p are the "most preferred" ones [7].

The preferred values for $ITDG$ and T_{15} depend on the music piece to be played in the hall, through the value of the so-called effective duration of the autocorrelation function of the music piece, τ_e [7]. In the present study, two music pieces were used, with the values of τ_e reported in Table 2. Then, the dimensionless values x_i are further converted in four scale values of preference of the form

$$S_i = -\alpha_i|x_i|^{3/2} \quad (i = 1, \dots, 4), \qquad (A6)$$

where the α_i are weights, whose values are detailed in reference [7].

Finally, as they are orthogonal, the S_i can be summed up in a total scale value of preference:

$$S = \sum_{i=1}^4 S_i = -\sum_{i=1}^4 \alpha_i|x_i|^{3/2}. \qquad (A7)$$

The contribution of each factor has a maximum value of zero at its preferred value; above or below this preferred value, the scale takes on negative values.

Even if there is no general agreement that this methodology can substitute a careful judgement based on many acoustic criteria [3, 4, 5, 12], the possibility of condensing into a single rating value the balance among several independent acoustic attributes is attractive, and the results so obtained are not too far from the reality.