Acoustics and Spatial Sound Distribution in the Theatre Comunale in Bologna, Italy

Massimiliano Manfren – University of Southampton, United Kingdom – m.manfren@soton.ac.uk
Benedetto Nastasi – Delft University of Technology, The Netherlands – benedetto.nastasi@outlook.com
Francesca Merli – University of Bologna, Italy – francesca.merli8@unibo.it
Vincenzo Vodola – University of Bologna, Italy – vincenzo.vodola2@unibo.it

Abstract

The acoustic quality of concert halls is extremely relevant for the modeling and simulation of the global music experience and for improving the acoustic design of music spaces. Furthermore, the acoustic characteristics of historical opera houses are considered to be one of the most important intangible elements of the cultural heritage of Italian history. An important Italian opera house is the theatre "Comunale" in Bologna (designed in the 18th Century by Galli Bibiena), and has a particular characteristic: the shape of the balconies and the materials with which they were constructed are different from those of a classical Italian opera house. This special feature of the balconies affects the listening conditions related to the position of sound sources on the stage and in the orchestra pit. This study investigates the acoustic properties of this important theatre in order to reproduce the sound properties by means of a 3D auralization. For describing the spatial sound characteristics of the hall, an experimental campaign was carried out. An omnidirectional, pre-equalized sound source was installed in the orchestra pit and on stage, and a dummy head was put in several listening positions on the balconies and in the stalls, accomplished with a B-format (soundfield) microphone. Moreover, the special features of the ACF (autocorrelation function) and the IACC (InterAural Cross Correlation) and other acoustic parameters were measured experimentally in order to reproduce them in the listening room "Arlecchino" at the laboratory of University of Bologna, by means of the Stereo Dipole and Ambisonics technique. The main results from the experiments are reported in this paper.

1. Introduction

It is well known that the acoustic properties of opera houses and concert halls are extremely important for determining the global sensation that is experimented by listeners and musicians. Since the 1970s, with the work of Gerzon (1975) and subsequent research (Farina and Tronchin, 2005 and 2013; Tronchin, 2013; Tronchin and Coli, 2015), the sound properties of the special opera house have been considered to be of equal importance to ancient musical instruments (Tronchin et al., 2020). Therefore, cultural heritage is compoased by their acoustical properties too apart from the architectural features. The theatre "Comunale" in Bologna is an important Italian opera house and has a particular characteristic: the shape of the balconies and the materials with which they were constructed are different from those of a classical Italian opera house. This special feature of the balconies affects the listening conditions related to the position of sound sources in the stage and in the orchestra pit. The aim of this paper is to investigate the acoustic properties of this important theatre with the purpose of reproducing its characteristics by means of a 3D auralization.

2. Materials and Methods

1.1 Historic Background of the Theatre

The Teatro *Comunale* in Bologna was designed by the architect Antonio Galli Bibiena, one of the most active architects for music venues in the 18th Century, and inaugurated in 1763. From the beginning

Part of
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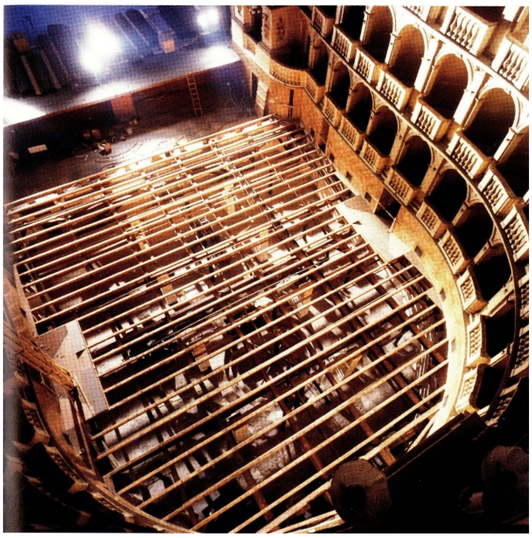
of the design process, Galli Bibiena considered a different shape of theatre to that of the typical horseshoe shape, namely a bell shape. Thus, the *Comunale* of Bologna was the first example of a special "*phonic*" shape conceived by Galli Bibiena, and was followed by the Teatro Scientifico in Mantova and the Four Horsemen Theatre in Pavia. At that time, however, this idea was not supported by other physicists and acousticians.



(a)

(b)

Fig. 1 – (a) The device below the floor of the stalls and (b) the hall

The *Comunale* also had other specific characteristics: the brick structure of the main hall was one of the most important innovations and was used instead of a wooden structure, in order to reduce the risk of the theatre being damaged or destroyed in a fire. The theatre also had two major innovations in balconies and stalls. The balconies were designed to allow the owners to customize the walls, colour the walls, change the interiors, etc. The floor of the stalls was equipped with a special device: it could be lifted to the height of the stage by a special mechanism. There would have been a large cavity, with musicians and singers on the same level; Bibiena believed that the movement of the floor would enhance the intelligibility of the singers. This mechanism was active until 1820.

1.2 The Acoustic Measurements

A measurement campaign was undertaken in order to properly describe the spatial sound characteristics of the hall, with a special focus on the stage and orchestra pit and the relationship between the perception of the sound of the musical instruments and their characteristics in the stalls and balconies (Farina et al., 1998; Farina and Tronchin, 2000; Shimokura et al., 2011; Tronchin, 2012; Tronchin and Coli, 2015). Then, in a further step, the ACF (autocorrelation function) and IACC (InterAural Cross Correlation) and other acoustic parameters were calculated from the impulse responses thanks to the Stereo Dipole and Ambisonics techniques, in order to reproduce them in the listening room "Arlecchino" at the laboratory of University of Bologna.

The instruments used are::

- on the stage and in orchestra pit, an omnidirectional, frequency-equalized sound source (namely LookLine);
- at the receiver's positions (Neumann KU-100) to measure binaural impulse responses and parameters, a dummy head;
- in the theatre, similarly to the dummy head, a Soundfield microphone (MK V) probe. For calculating the monoaural and 3-dimensional parameters, a four-channel output was adopted.

An exponential, 30-second-long sine sweep (chirp) was played by the omnidirectional sound source and, to store the signals from the microphones, a 20-bit 96 kHz 8-channel sound board was utilized. The measurements were taken in 25 different positions, from stalls to balconies, as shown in Fig. 2.

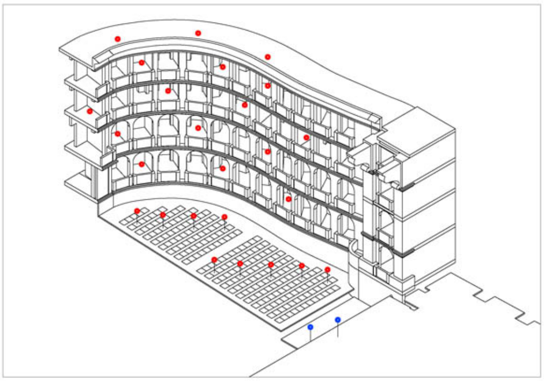


Fig. 2 – The points for measurements in red dots in the *Comunale*

Then, the authors used a numerical simulation model. On the stage the sound source was put and the measurements were repeatedly moved to the orchestra pit. To calculate the strength spatial maps at 1 m a reference position was added. Some additional measurements were carried out with the sound source to evaluate the different impulse responses during the 3D auralization process (Binaural and B-formats) including floor effects for sound insulation (Caniato et al., 2016 and 2018).

The mono-aural parameters, such as reverberation time, center time and clarity, were calculated considering the W channel from the Soundfield microphone, as well as spatial parameters, such as LE and LF and the B-format Impulse Response. The measurement of binaural parameters was taken by the dummy head, such as the IACC (Farina et al., 2013). In addition, the discovery of virtual acoustics in the theatre (Tronchin, 2013) was made possible by the B-format impulses obtained through the Soundfield and the bi-induction responses by the dummy head, crucial for retrofitting (Caniato et al., 2015 and 2019; Fabbri et al., 2014; Fabbri and Tronchin, 2015; Tronchin and Fabbri, 2017; Tronchin and Knight, 2016; Tronchin et al., 2014 and 2016).

3. Results

The results from the measurements are briefly reported in the following paragraphs. Various acoustic parameters were calculated from the measurements. Table 1 reports the average values of the acoustic parameters measured in the theatre. The results show that the position of the sound source from the stage and the orchestra pit modifies the parameters. As mentioned above, a sound source with a directivity pattern was also used during the measurements. For further analysing the influence of both the position of the sound source and its directional patterns, the results for a specific position in the stalls are shown in the graphs.

Table 1 – Values obtained in the Teatro Comunale of Bologna with reference to the positions of the sound source on the Stage

Frequency	C50 [dB]	C80 [dB]	D50 [%]	Ts [ms]	EDT [s]	T20 [s]	LF
63	-5.2	-1.7	26.2	179.9	2.1	2.3	0.94
125	-5.3	-1.5	25.0	154.2	1.8	2.0	0.81
250	-2.6	0.6	36.5	117.8	1.6	1.8	0.81
500	-2.4	0.6	37.6	111.3	1.6	1.7	0.78
1k	-2.8	0.2	35.3	114.7	1.6	1.6	0.78
2k	-3.1	0.2	34.1	113.1	1.6	1.6	0.68
4k	-2.4	1.2	37.4	94.9	1.3	1.3	0.58
8k	1.1	4.6	55.8	58.5	0.9	1.0	0.48

The *Teatro Comunale* gives an overall impression of the sound of typical Italian opera houses. The reverberation time at mid frequencies was approximately 1.4 s. The acoustics of the orchestra pit, however, differ significantly from the stage. These differences are particularly significant in the stalls rather than on the balconies. Variations in acoustic parameters could be seen specifically in the initial part of the impulse responses (less than 100 ms), as depicted in the graphics reporting the values of the acoustic parameters measured in one specific position not far from the orchestra pit. The energetic parameters (i.e. clarity) showed a significant difference from the stage with the orchestra pit whereas the position of the sound source, effected by the fence, induces a diffuse sound field with no direct sound from the source to the receivers (which was clearly perceived by the receiver) and the orchestra pit. Including the reverberation times, the sound source from stage to pit was significantly different. The estimated Early Decay Time was affected more than the RT30, due to its longer decay time. In some cases, the variation of EDT also ranged from 0.5 s at mid-frequencies to 0.2 s in RT30.

Table 2 – Values obtained in the Teatro Comunale of Bologna with reference to the positions of the sound source on the Pit

Frequency	C50 [dB]	C80 [dB]	D50 [%]	Ts [ms]	EDT [s]	T20 [s]	LF
63	-0.2	3.5	49.1	112.4	1.0	2.1	0.8
125	-8.7	-0.8	17.7	148.5	1.7	2.0	0.7
250	-4.3	2.1	31.2	110.8	1.4	1.7	1.0
500	-4.2	1.3	32.0	108.2	1.4	1.6	1.1
1k	-3.4	0.8	34.5	110.9	1.6	1.6	1.0
2k	-3.0	1.0	35.3	104.1	1.5	1.5	0.8
4k	-1.7	2.2	41.1	86.7	1.2	1.3	0.6
8k	2.1	5.9	59.9	54.0	0.7	0.9	0.5

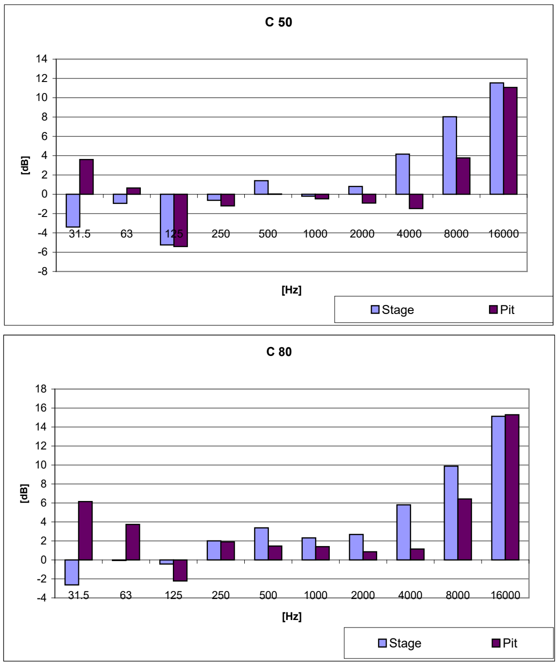


Fig. 3 – Values of Clarity measured in stalls (14F), in the Teatro Comunale of Bologna, Italy

Additional analysis consisted of a variety of sound source positions and directivity patterns. Some acoustic measured parameters in the hall are shown in Fig.s 6 to 8. There were remarkable variations in these parameters.

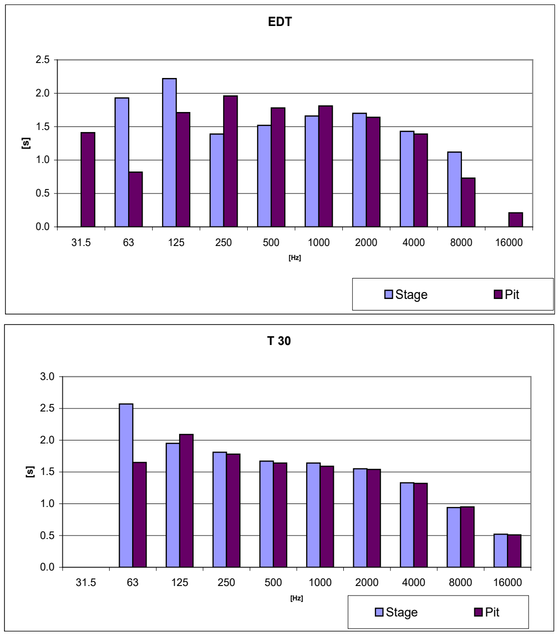


Fig. 4 – Values of Early Decay Time and Reverberation Time measured in stalls (14F), in the Teatro Comunale of Bologna, Italy

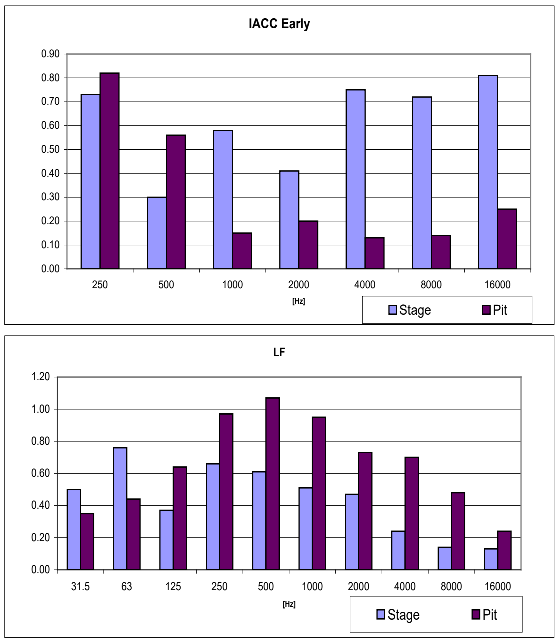


Fig. 5 – Values of InterAural Cross-Correlation and Lateral Fraction measured in stalls (14F), in the Teatro Comunale of Bologna, Italy

Even the *clarity* of the sound source changed considerably. Only the reverberation time with sound sources remained relatively stable. However, the analysis of the variation of the IACC led to the identification of differences of between 0.15 and 0.075 at the frequency of 2 kHz, depending on the sound source.

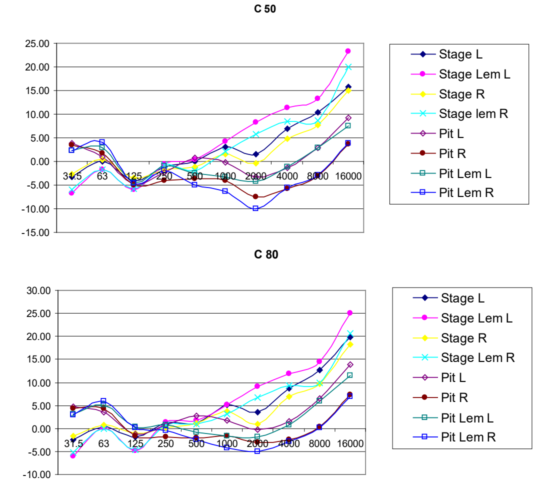


Fig. 6 – Values of Clarity measured in stalls (14F) with different sound sources and positions in the Teatro Comunale of Bologna

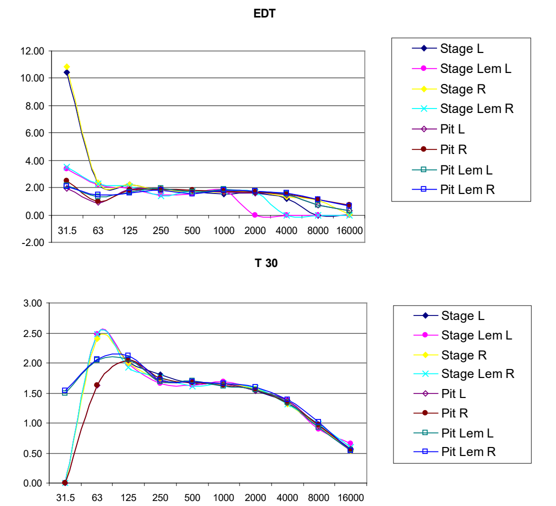


Fig. 7 – Values of Reverberation Time measured in stalls (14F) with different sound sources and positions in the Teatro Comunale of Bologna

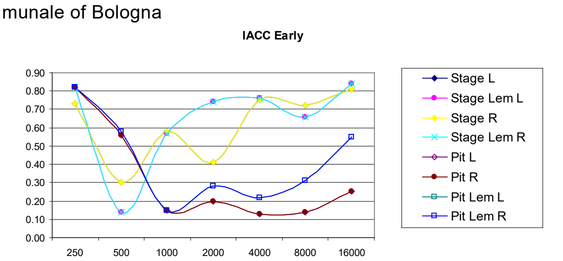


Fig. 8 – Values of IACC measured in stalls (14F) with different sound sources and positions in the Teatro Comunale of Bologna

This was not a surprise because the first 80 ms of the impulse response (IACC) were considered in the calculation, i.e. the component of the binaural impulse responses that was heavily dependent on the different characteristics of the sound sources and their positions.

4. Conclusion

In conclusion, based on the results discussed in this paper, it is possible to state that the Teatro *Comunale* presents the typical sound characteristics of Italian-style opera houses. Yet, the acoustics of the stage and the orchestra pit were found very different. This fact makes unique this opera house.

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