3dof representation of the acoustic measurements inside the Comunale-Pavarotti Theatre of Modena

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***Abstract*—The investigation of the acoustics inside the Italian Opera theatres has been undertaken by scholars in order to deepening their scientific studies on the architectural and cultural heritage. This paper deals with alternative ways of how to represent acoustic data, in particular by adding a 3dof representation of the impulse response (IR) besides the graphs related to the main acoustic parameters in line with the standard requirements. The 3dof screen shots have been undertaken by an overlay elaboration, showing the particular architectural components of the theatre that contribute to the early and late sound reflections. A brief introduction of the historical background related to the Comunale-Pavarotti theatre of Modena has been given to understand the architectural characteristics of the entire structure.**

Keywords*—*acoustic parameters, architectural acoustics, spherical array microphone, Italian Opera theatre, 3dof.

I. Introduction

This paper deals with the acoustic behavior of the Comunale-Pavarotti theatre of Modena. Alternative data representations have been introduced by the authors as well as the construction phases succeeded during the history that brought to the erection of one of the most beautiful Opera theatres located in Northern Italy. An acoustic survey has been undertaken by using spherical arrays of microphone and loudspeaker. The multi-channel equipment allowed the rendering of an acoustic video that shows the sound waves interacting with the architectural features of the main hall.

II. Historical Background

In 1838 the marquis Ippolito Livizzani, as a mayor of Modena, assembled a meeting with the conservatories of the city to establish the construction of a new theatre in place of the old music hall located along Via Emilia, which was in bad structural conditions since it was built in 1643 [1]. As such, the pool of politicians decided to commit the project to the architect Francesco Vandelli, who was in service at the court of the Duke Francesco IV d'Austria-Este [1]. Vandelli accepted the design of the theatre, which was realized and opened in 1841 with the name of "The theatre of the most illustrious Community" [2].

The theatre of Modena, built in the core of the city upon an area of 2300 m^2, was realized after the demolition of the existing residences with the financial contribution given by the Duke and the economical earnings obtained by the selling of the stalls to private aristocrats [2]. The rest of the funding was given by the community council. The first artistical performance was Adelaide of Borgogna at the Canossa castle, a new melodrama composed of three acts by Alessandro Gandini, who was the conductor of the chamber music [1].

The florid artistical production continued until the arrival of the World War I, which forced the theatre to suspend the activity between 1915 and 1923 [2]. Although the difficulties persisted also during the World War II, the renaissance of the theatre occurred during the 60's when the management of the activities was held by city council of Modena, which promoted concerts, ballets and dramas. The management of all the theatrical activities has been leading by the Foundation Cassa di Risparmio of Modena since 2002 [1].

III. Geometrical and Architectural Organization

The architect of the theatre of Modena was F. Vandelli, who designed the plan layout having an elliptical shape, where 116 stalls are opened to the hall by being organized onto 4 orders of balconies [2].

Fig. 1. View of the sitting areas from the stage. Comunale-Pavarotti theatre of Modena.

At the center of the second order there is the ducal balcony, coronated at the top of the frame by an eagle, which is the symbol of the ducal family d'Austria-Este [1]. The 5th order is occupied by a *loggione*, where actually there are two cabins for light and sound control during the performances. Fig. 1 shows the interior design of the main hall and the organization of the different orders of boxes.

The entire construction is given by the combination of two main volumes: the elliptical hall, which is the core of the whole building designed in neoclassic style and is related to where the audience stands, and the scenic tower, where different teams of technicians operate in function of the artists [2]. The capacity in the stalls is about of 350 seats, nowadays extremely reduced in line with the Covid-19 guidance.

The influence of the *La Scala* theatre of Milan, designed by Piermarini, is evident into the organization of the stairwells and the vaulted corridors, other than having similarities regarding the arched entrance, as it is visible from the front elevation. In relation to the elliptical shape, it was a common use at that time to be inspired by a pamphlet written by Pierre Patte, who strongly recommended the ellipse as the main expedient in solving the problems related to the direction of reflecting rays, in order to achieve an optimum sound quality at all positions inside the theatre [3]. The pamphlet, called *Essai sur l'architecture théâtrale ou de l'Ordonnance la plus advantageuse à une Salle de spectacle relativement aux principes de l'Optique et de l'Acoustique*, considered the ellipse as the only geometry suitable to combine the acoustical and the optical principles with the purity of the neoclassicism in order to obtain an ideal performing arts space [4].

Fig. 2. Elliptical roof of the main hall. Comunale-Pavarotti theatre of Modena.

Fig. 2 indicates the geometry designed by Francesco Vandelli for the theatre of Modena.

The proscenium arch is 13.5m large, while the stage has dimensions of 18.5 × 22 m [L × W] with a wooden floor having an inclination of 6%, slightly more than the floor of the stalls which has a 2% slope [1]. TABLE I. summarizes the architectural features found inside the theatre.

TABLE I. ARCHITECTURAL CHARACTERISTICS OF THE COMUNALE-PAVAROTTI THEATRE OF MODENA

Description	Features
Type of plan layout	Ellipse
Total capacity (n. seats)	350 +
Inclination of stalls area (%)	2
Volume of main hall (m^3)	3800
Inclination of stage (%)	7
Stage dimension (m) [L×W]	18.5 × 22
Volume (m^3)	4900
Total volume (m^3)	8700

IV. MEASUREMENTS

The acoustic characterization of the theatre was carried out by utilizing two different measurement techniques: the first is more traditional and is intended to measure the monaural and binaural parameters in line with the ISO 3382-1 [5], while the second, more innovative, intended to capture all the effects necessary for an acoustic rendering suitable for virtual reality applications.

A. *Measurements of monoaural and binaural parameters*

[3]The acoustic survey was carried out with the following equipment:

- Equalised omnidirectional sound source (Look Line 103);
- 32-channel spherical array microphone (Mh Acoustic em32 Eigenmike®) [9];
- Audio Firewire Interface (EMIB);
- Audio Interface (Orion32).

The sets of measurements were organized by placing the sound source in the central position (C) on the stage, as indicated in Fig. 3, while the microphone was placed in three specific positions across the stalls [6].

The excitation signal emitted by the sound source was the Exponential Sine Sweep (ESS) [7][7][6] having a duration of 10 s in a uniform sound pressure level for the range between 40 Hz and 20 kHz. The acoustic measurements were performed without the presence of audience (in unoccupied conditions) and with the acoustic chamber mounted on the stage, whose ceiling is approximately 8 m high.

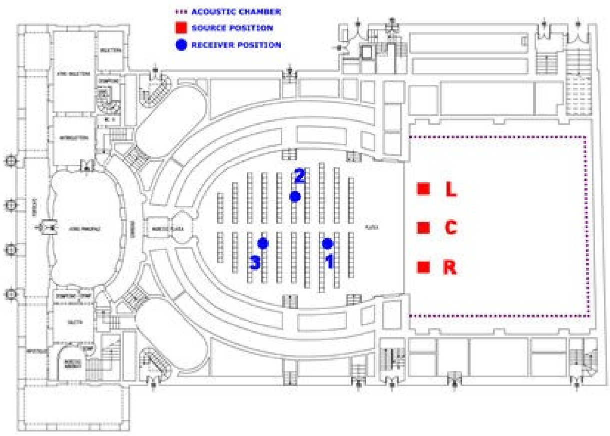

Fig. 3. Source and receiver positions during the acoustic survey.

B. *MIMO measurements*

During the same survey, also MIMO measurements were undertaken, by using the following equipment:

- 32-channel spherical array speaker (UNIPR) [8];
- 32-channel spherical array microphone (Mh Acoustic em32 Eigenmike®) [9];

- Audio Firewire Interface (EMIB);
- Audio Interface (Orion32);
- Amplifier (32 channels, class D);
- 360° camera (Ricoh Theta V);
- Personal Computer.

The sound source and the microphone were both connected via MADI interface to the ORION 32, which in turn was connected to the laptop via USB interface. The test signal, the same as in the previous measurements, was played singularly by each of the 32 transducers of the sound source. Measurements were repeated for each source-receiver combination [10].

The acquisition of the signals by the spherical microphone array and their subsequent processing allowed the definition of nine HOA MIMO IR matrix to be used for the auralization.

V. Results

A. Traditional acoustic parameters

The recorded RIRs signals have been processed and analyzed by using Aurora, a plugin appropriate for Audition CC [11]. From this type of data processing, the main acoustic parameters (monaural and binaural) have been obtained as defined by the ISO 3382-1 [12]. These data are the results of the averaged values of the all measurement positions, as summarized in TABLE II. .

TABLE II. Measured acoustic parameters.

Freq. [Hz]	125	250	500	1000	2000	4000	8000
C50 [dB]	-2.9	-3.9	-0.1	-2.1	-0.7	-1.9	2.3
C80 [dB]	1.3	-0.3	1.7	0.7	1.7	1.1	4.9
D50 [%]	35.5	31.0	49.4	38.5	46.0	39.6	61.9
ts [ms]	120.2	125.6	99.8	108.0	96.0	98.1	53.9
EDT [s]	1.5	1.7	1.7	1.6	1.6	1.4	1.0
T20 [s]	1.9	2.0	2.0	1.8	1.7	1.4	1.1
T30 [s]	1.9	2.0	2.0	1.9	1.7	1.4	1.1
Jlf	0.1	0.2	0.1	0.2	0.1	0.2	0.1
Jlfc	0.2	0.2	0.1	0.2	0.2	0.3	0.2
Lj [dB]	6.5	15.9	18.8	19.2	21.5	21.7	17.4

Fig. 4**Error! Reference source not found.** to Fig. 6 show graphically the trends of some of the measured parameters. Fig. 4 shows that T_{20} and T_{30} resulted very similar, approximately around 1.9 s in the frequency bands ranging between 125 Hz and 1 kHz, and decreased up to 1 s at 8 kHz [13].

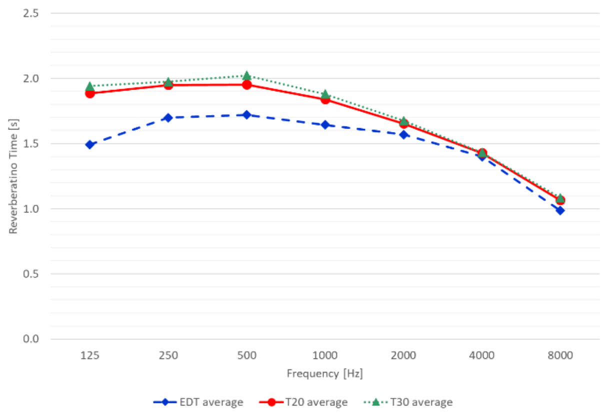

Fig. 4. Measured reverberation times.

Typically, the parameters T_{20}, T_{30} and EDT in a room where the sound field is strongly diffuse should be identical. In this theatre the EDT values are lower than T_{20} and T_{30} and the magnitude of the discrepancy is a good judgement for imperfect local spread [14].

The data analysis of the impulse response (IR) shows that the average of the reverberation time (T_{20}) is approximately 1.9 s across all the frequency bands. These values seem to be in line with what has been suggested by the optimal curves related to different space functions. Fig. 5 shows the optimum values of reverberation time in function of the room volume size [15][16][15]. This result is considered a compromise between music and prose performance, as the Opera houses have been designed for [16].

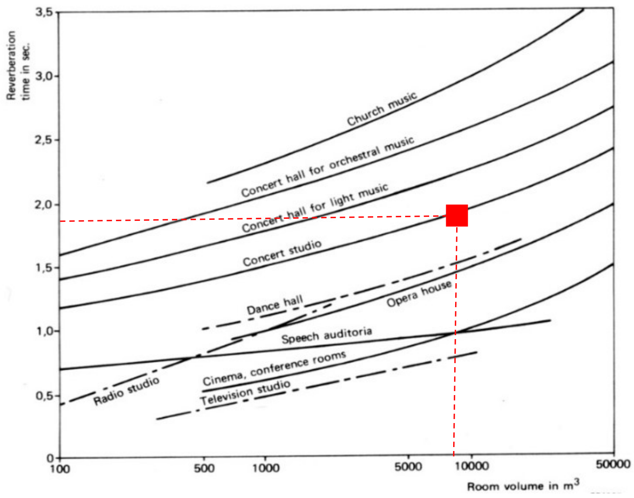

Fig. 5. Optimum reverberation time values in function of room volume.

The results shown in Fig. 6 indicate that the speech clarity index (C_{50}) is slightly lower than the optimal values; this occurred across all the frequency bands and particularly at low frequencies, as the values do not achieve the target set to be > 3 dB. This result could be translated in a light difficulty in speech understanding, especially at low frequencies [16].

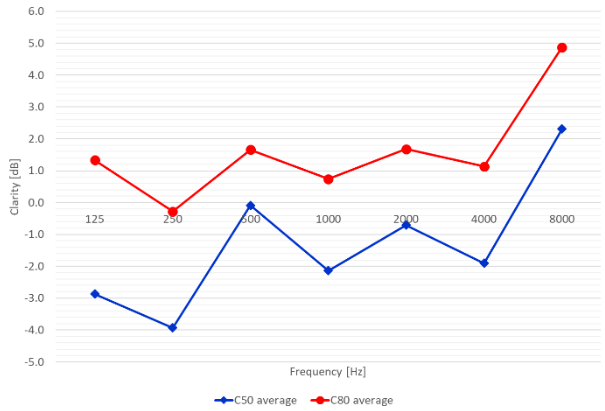

Fig. 6. Measured results of clarity indexes (C_{50} and C_{80}).

In terms of music (C_{80}), the clarity index results within the optimal range limits, with the exception of the value at 8 kHz found to be higher than the upper range limit (i.e. +2 dB).

B. Acoustic analysis of 3D sound maps

The analysis of the MIMO data allowed the authors to elaborate 32 signals extracted by 122 high directivity virtual microphones [18]. The result is a color map overlay composed of a certain number of frames and showing the beamformed multichannel RIR as a combination of one source-receiver position [19].

The color scale of the rendered video has a range comprised between red-warm colors, representing sound waves with a high energy level, and blue-violet colors, representing the sound waves with a low energy level. A panoramic image, realized with a 360° camera, has been overlapped to the IR playback, in order to best visualize the direction of the arrival sound waves.

Examples of such acoustic maps are given in Fig. 7 to Fig. 8, related to the sound source placed in the center of the stage while the receiver is in position 2.

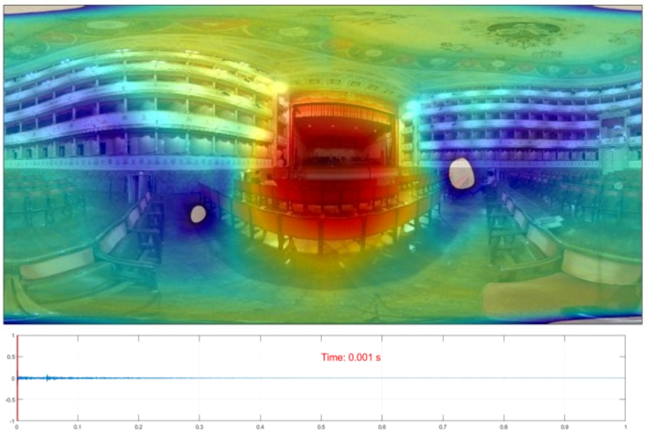

Fig. 7. Acoustical map showing the direct sound arriving to the receiver.

A few captured moments of the RIR inside the Comunale-Pavarotti theatre of Modena visualize the specific architectural elements that contribute to the reflections.

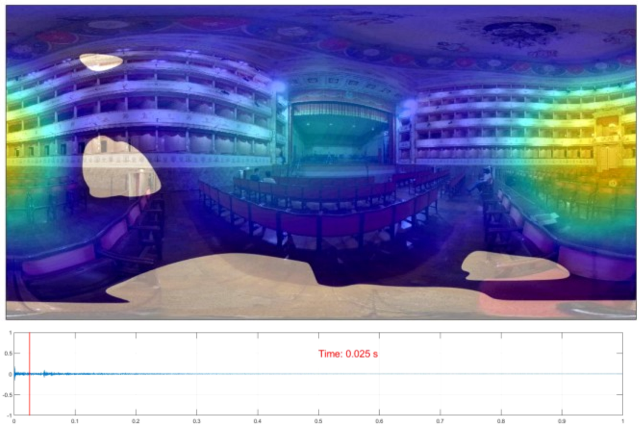

Fig. 8. Acoustical map showing the sound reflections on the back wall.

Fig. 8 shows the reflections hitting the back walls of the main hall.

VI. Conclusions

This paper introduces two types of results' representations in relation to the acoustic measurements undertaken inside the Comunale-Pavarotti theatre of Modena and conducted in unoccupied conditions but with a mounted acoustic chamber. The results show that the acoustical parameters in function of the finish materials and volume size are suitable for both music and prose performance. The acoustic analysis reflects the determination of the acoustic parameters in line with the standard requirements outlined by ISO 3382-1. A further analysis involved a visual study of the directivity and intensity of the sound waves occurred at the side walls of the main hall.

The combination of a 32-channel loudspeaker and a 32-channel microphone is appropriate for tracing the sound rays directivity, although the best response is given for the frequency range comprised between 63 Hz and 4 kHz due to its stable flat response.

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