EVOLUTION OF SOME MICROPHONE ARRAYS IN SOUND FIELD REPRODUCTION. APPLICATIONS INSIDE TWO HISTORICAL THEATRES

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Résumé

Les termes « espaces de performances artistiques » caractérisent un type bien spécifique de bâtiments, régulièrement soumis à des tests acoustiques depuis des décennies, et ce, à partir de différentes techniques et équipements. La portée de cet article réside dans l'application et la comparaison successive de certains réseaux de microphones, selon leurs caractéristiques acoustiques, capables de collecter des informations utiles afin à la fois pour déterminer les paramètres acoustiques d'une pièce puis pour reconstruire les champs sonores 3D. L'exécution des mesures acoustiques avec différents équipements a été réalisée dans deux théâtres italiens, dans le cadre du patrimoine culturel du XVIIIe siècle. Le microphone Soundfield, utilisé pour le Teatro 1763 de Bologne, est une technologie limitée par rapport à une nouvelle génération de microphone armé de plusieurs canaux contrôlés individuellement, comme utilisé dans Teatro Sociale de Gualtieri. Ces technologies ont été considérées comme une manière coplanaire d'étudier l'acoustique d'un bâtiment historique. Les auteurs de cet article illustrent les résultats des principaux paramètres acoustiques des deux théâtres sélectionnés, autres qu'une comparaison d'une qualité différente d'analyse graphique dans le rendu de la directivité des rayons sonores en fonction des différents équipements employés.

Mots clefs: Acoustique des salles; Auralisation; Théâtres italiens; Réponse impulsionnelle; Antenne de microphones.

Abstract

Performing arts spaces characterise a specific group of buildings, always subject to be tested under the acoustical point of view with different techniques and equipment through the decades. Scope of this paper is the application and consecutive comparison of some microphone arrays, based on their acoustical characteristics, capable to gather useful information in order to both determine the acoustical parameters of a room and reconstruction of the 3D sound fields. The execution of the acoustical measurements with different equipment setup has been taken in two Italian theatres, as part of the cultural heritage of the 18th century. The Soundfield microphone, employed for the Teatro 1763 of Bologna, is a limited technology if compared with a new generation of microphone armed with multiple channels individually controlled, as utilised in Teatro Sociale of Gualtieri. These technologies have been considered as a coplanar way of how to study the acoustics of a historical building. The authors of this paper illustrate the results of the main acoustical parameters of the two selected theatres, other than a comparison of a different quality of graphical analysis in rendering the directivity of the sound rays based on different equipment employed.

Keywords: Room acoustics; Auralization; Italian theatres; Impulse response; Microphone array.

1 Introduction

Many theatres in Italy are considered quite important for their unique acoustical characteristics. Especially those built between the 17th and 19th century are considered as the referent symbols for the theatrical acoustics across Europe that need to be faithfully reproduced in order to be preserved to the next generations in case of damage.

The collection of acoustical behaviour of historical theatres and opera houses, initially proposed by Gerzon [1], became extremely important after the fire of two Italian theatres: Teatro Petruzzelli of Bari and Gran Teatro La Fenice of Venice [2].

After these sorrowful events, many challenges were achieved to standardise the measurement procedures for theatres and auditoria, considering their importance as an intangible cultural heritage.

Room conditions and specific suggestions for the selection of equipment have been considered in order to entirely recreate the acoustics of such historical buildings. Furthermore, this paper highlights the capabilities of different instrumentations that can be used to accomplish the scope of recreating a particular sound field.

The application of the acoustical measuring techniques, with the acoustical maps overlapped to a 360º view obtained after data processing, have been executed inside Teatro 1763 of Bologna [3] and Teatro Sociale of Gualtieri, similar for volume size.

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In order to obtain a reasonable room impulse response (RIR), these specifications became quite important whenever the auralization is intended to be performed.

2 Equipment and Methodologies

2.1 General considerations on equipment selection

The characteristics of the microphone represent an important matter for both measurements and auralization reconstruction.

The necessity of the stereophonic audio has been always appreciated by the listeners because of the potentiality of the sound source localization, which creates a more involvement effect. The progress undertaken by the electronics industry directed its development towards an ever-increasing number of microphones' channels, in order to make the stereophony more detailed, in line with the need of localising the sound source in the space and of faithfully post-reproducing any musical event.

As such, shapes of microphone arrays, realised by organising the capsules of the microphone in a specific way, have the scope of gathering much more information about the soundscape than what is suitable with only one transducer. With this technique, the stereophony can be acquired by a combination of signals coming from different capsules elaborated by a decoding system. The most popular decoding system is Ambisonic, which is capable of decomposing the 3D sound field in spherical harmonics determined at a certain order [4].

Although a common omnidirectional microphone armed with one transducer is good enough to report the acoustical characteristics of a room, representing the scope for many building acoustics activities, it is quite tough with this kind of equipment reproducing the effective directivity pattern of any real source.

However, some of the microphones' outfits are even not capable to reproduce a virtual microphone, which is considered as a sound signal equivalent to what would have been registered a microphone-equipped with arbitrary orientation and with a maximum order of directivity.

The measurement technique employed in Teatro 1763 of Bologna was realised by using a tetrahedral microphone array (i.e. Soundfield), composed of 4 cardioid capsules organised on the faces of a regular tetrahedron. This B-format setting is capable of rebuilding a 3D sound field at a specific point of the space [5].

The evolution of the tetrahedral array is the spherical array, which allows a spherical disposition of the capsules having the equal sensibility to the arrival of the sound waves coming from every direction. The more the number of capsules composing the array, the better is the reconstruction of the 3D sound field and the synthesis of directivities [6].

When the goal of the measurements is to determine the effective directivity patterns existing in the real world (e.g. musical instruments or human voice), a microphone system having individual control of singular transducers is required. This is the technique employed during the acoustical survey undertaken in Teatro Sociale of Gualtieri, by using a 32-channel microphone (i.e. em32 Eigenmike®) equipped with 32 capsules uniformly distributed on a spherical surface, able to be controlled individually.

2.2 Traditional measurement technique of a 3D sound distribution inside Teatro 1763 of Bologna

The aim of the measurement technique employed for Teatro 1763 of Bologna is to capture mono-aural, binaural and impulse response data. By employing this technique, already been described in [7], it is possible to obtain the spatial information of any performing arts space.

During the measurement campaign executed in Teatro 1763, a set of RIRs has been measured at each angular position by using three different types of microphones (i.e. B-format, a binaural dummy head and two cardioids in ORTF configuration) [8]. The ORTF configuration has been used to recording stereo signals obtained by two cardioid microphones spaced 170 mm and diverging each other by 110°. The B-format microphone, which was introduced by M. Gerzon [1], is able to capture 4 signals: one omnidirectional (pressure) and three with polar patterns, called figure-of-eight, oriented along the three axes X, Y, Z. These three capsules allow to obtain a signal proportional to the three components of the particle velocity vector. A combination of the results obtained by applying this measurement technique is able to derive all the multi-channel formats (i.e. 5.1, 7.1, 10.2, etc.).

2.3 MIMO method for RIRs employed in Teatro Sociale of Gualtieri

With the continuous innovation of technology, the methodology discussed in Section 2.2 is considered very slow, not only for the microphone setup being much tedious for a correct installation but also for the combination of the information coming from the three microphone systems. As such, an easier and more powerful measurement system has been developed.

The innovative equipment is composed of a multi-channel microphone (i.e. em32 Eigenmike®), that is based on a spherical microphone array which contains 32 capsules mounted on a spherical surface having an 80mm diameter. It also contains preamplifiers, analogue to digital (A/D) converters, and an audio-over-ethernet chipset. In this way, it becomes simpler to get measurements of multi-channel IRs, considering also a better spatial resolution. Although the producer (i.e. MH Acoustics) developed already a new generation of spherical microphone array equipped with 64 capsules (i.e. em64 Eigenmike®) it was not possible to test this latest kit because not available on the market at the time of measurements; herein is the impossibility to compare its functionalities with the existing applications.

The multi-channel microphone system has been initially developed for real-time recording and broadcasting applications, in order to extract any arbitrary directivity of virtual microphones from real microphone arrays [9], but now it is well known in the acoustics research.

The microphone em32 is capable of capturing any real-time variable directivity in order to follow actors/musicians during the performance. The real-time variable directivity is possible by using a mouse/joystick, able to change the sharpness of the patterns by zooming in/out. The pattern is determined by using cardioid microphones of various orders, according to equation (1).

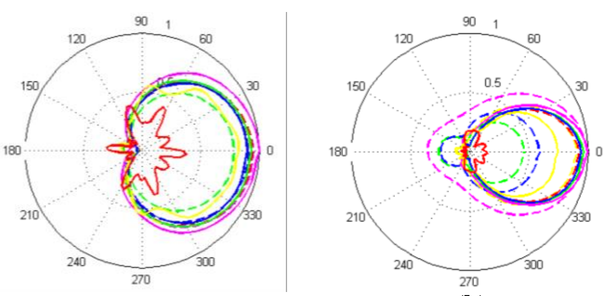
$$Q_n(\vartheta,\varphi) = |0.5 + 0.5 \cdot \cos(\vartheta) \cdot \cos(\varphi)|^n \qquad (1)$$

where *n* represents the directivity order of the microphone.

The signals recorded by the em32, analysed in a post-processing phase by using Matlab application, can generate 32 virtual microphones [10, 11], which could be subjectively perceived [12, 13] having any directivity patterns by combining the directions of the 32 capsules located on the spherical surface [14-16], eventually adding nonlinear effects [17].

In this way, the 3D sound environment can be spatially sampled with an almost constant angular amplitude [18]. The spatial sampling resulting from the measurements can therefore be considered as a PCM sampling, whereas the traditional spherical harmonics sampling by using a high order Ambisonic (HOA) system can be ordered as a spatial Fourier sampling [19, 20].

Figure 1 shows two polar patterns related to virtual cardioid microphones of 1st and 4th order Ambisonics, obtained by applying the FIR filters into the analysis process [20].



(**a**) (**b**)

Figure 1: Directivity patterns of a virtual microphone : (a) 1st order, (b) 4th order Ambisonic.

3 Two cases of historical theatres

3.1 Teatro 1763, Bologna, Italy

Historical Background

The Teatro 1763 in Bologna is a small theatre inside the historical Villa Aldrovandi Mazzacorati and it was inaugurated on 24th September 1763. It was built as a private theatre of Aldrovandi family. The interior decoration of the theatre was entirely organized by Count Gian Francesco Aldrovandi. The paintings were commissioned to Filippo Balugani while the backdrop on stage was assigned to Antonio Basoli in 1810 [21]. The audience area has a rectangular shape and is characterized by the presence of twenty-four plaster telamones and caryatids, which support two continuous "U"-shaped balconies. The main spaces characterising the Teatro 1763 are the following: backstage, raised stage, tooling room, foyer with double access from outside and another entrance connecting the theatre with the internal halls. It has a capacity of 80 seats, but originally chairs and balconies could accommodate till 200 attendees. With the extinction of Aldrovandi dynasty, the ownership of the Villa passed to Giuseppe Mazzacorati in 1828 first and other families until the property in 1928 was ceded to fascist soldiers who made of it a summer camp for children [21].

Figure 2: View of the main hall of Teatro 1763.

Although the entire building fell into disuse for many years, the theatre itself was not damaged even during the Second World War, keeping preserved its original shape. Moreover, it still retains some original elements including canvas backdrop, ten sceneries on stage and many chairs [22]. Figure 2 gives a good view of how the theatre has been preserved with the original features and furniture [22].

Table 1 summarises the architectural features of the Teatro 1763.

Table 1: Architectural characteristic of Teatro 1763.

Description	Data
Shape of the main hall	Shoe-box
Levels of balconies	Two
Type of roof	Wood and Flat
Initial capacity (n. seats)	200
Actual capacity (n. seats)	80
Volume of the main hall (m^3)	Approx. 1150

Acoustical measurements

The acoustical measurements were undertaken with the following equipment:

- Sound source: equalized dodecahedron;
- Microphones:
  - Dummy head (Sennheiser);
  - B-Format microphone (Soundfield MK-v);
- Personal Computer connected to a loudspeaker and to receivers.

The excitation signal to measure the RIR was an exponential sine sweep (ESS), having a frequency range set between 40 Hz and 20 kHz. The sound source has been located on the stage while all microphones were moved to different positions throughout the stalls and the first gallery, in order to better represent all the audience areas, as indicated in Figure 3.

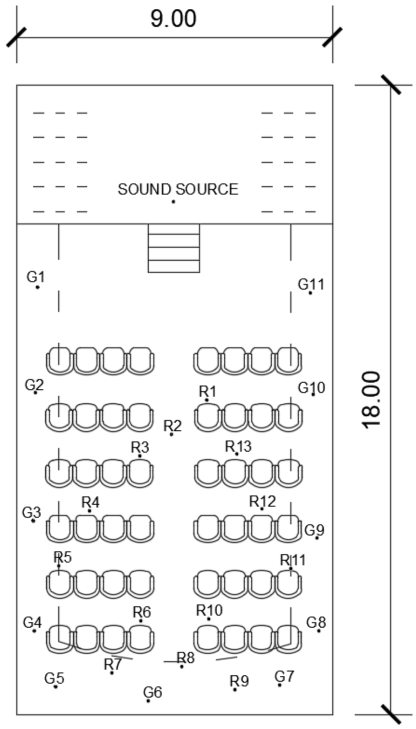


Figure 3: Source and receiver positions (R1-R13: receivers in the stalls; G1-G11: receivers in the first gallery) in Teatro 1763 of Bologna. The main dimensions of the theatre are 18 x 9x h7 meter.

Results of measurements undertaken inside Teatro 1763 of Bologna

The recorded ESS signals have been processed by using the plugin Aurora suitable for Audition. The results of the data analysis represent the main acoustical parameters, presented in the octave bands between 125 Hz and 8 kHz, as shown in the following figures. The values are to be considered as the average results of all the measurement positions.

Figure 4 indicates that the parameters EDT and T_{20} are very comparable. The results give an average value of approximately 1.2s for low-mid frequency bands, with a small shortfall (till 0.9s) for 2 kHz and 4 kHz. The graph indicates a good time response for both speech and music, with a uniform balance across all the spectrum.

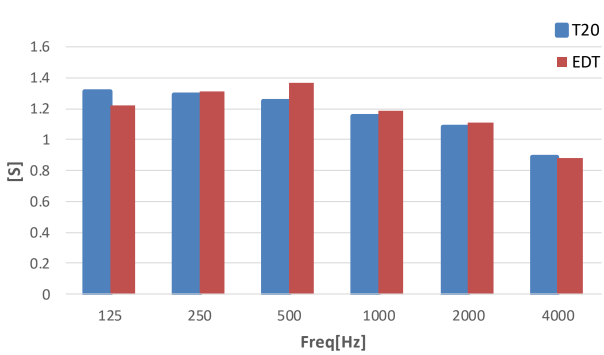


Figure 4: Measured results of Reverberation Time.

Figure 5 and 6 show respectively the averaged values of C_{50} and C_{80} of all the receivers as a function of frequency.

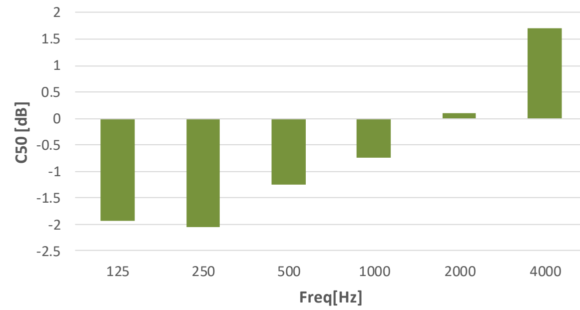


Figure 5: Measured results of Clarity Index (C_{50}).

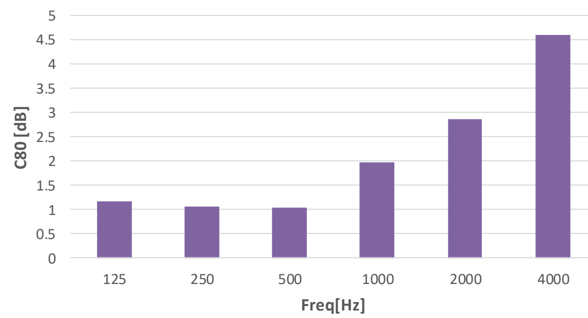


Figure 6: Measured results of Clarity Index (C_{80}).

The clarity of speech (C_{50}) resulted to be between -2 dB and+2 dB, which is a very good range. The clarity of music (C_{80}) resulted slightly high (i.e. 4.5 dB) only at 4 kHz, while for the other frequency bands the range is between 1 dB and 3 dB, which are also good values.

The averaged value of definition (D_{50}), as shown in Figure 7, resulted between 40% and 50% for low-mid frequencies, which is considered the minimum acceptable percentage for both good listening and speech comprehension. Values more than 50% were found at high frequencies, which is quite common for rooms of similar volume dimension.

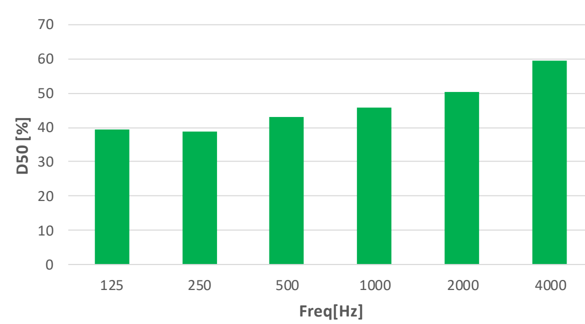


Figure 7: Measured results of Definition

Beside the acoustical parameters, which could be obtained even with a common mono-aural microphone, the utilisation of the B-format microphone (i.e. Soundfield) can be considered one of the first approach used to gather the detection-of-arrival of the sound reflections after hitting the boundaries of the room. The acoustical maps obtained after data processing are rendered with a panoramic view of the ambient combined with the overlapped sound rays, represented in the function of relative sound intensity.

Figure 8 shows an alternative arrangement of how the acoustic study of a room can be implemented by representing a visual map of the sound rays. In particular, the moving circle on the top right corner of Fig. 8, indicates the direction of arrival of the sound ray, which is also represented on the panoramic view on the left window, that shows which construction element has been hit by the sound wave. Furthermore, the variable diameter of the green circle is directly proportional to the sound energy on the room's surface, while its position follows the movement of the sound signal inside the theatre.

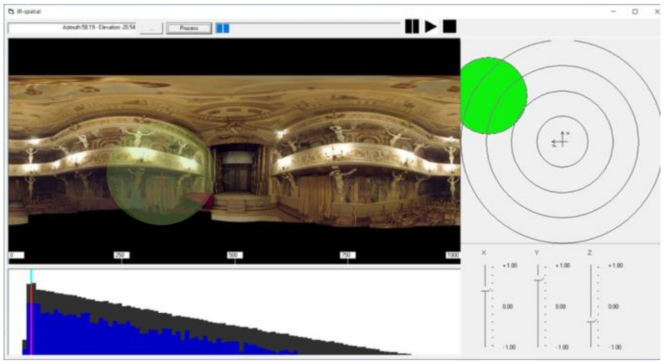


Figure 8: Directional map representing the reflections bounced on the boundaries of the theatre. Note that the x-axis is oriented towards the stage.

3.2 Teatro Sociale, Gualtieri, Italy

Historical Background

Teatro Sociale of Gualtieri was realized inside the Bentivoglio palace, a building-fortress built during the 16th century and promoted by Duke Alfonso II d'Este [23]. During the 17th century, the palace was disfigured and partially destroyed, especially when it became a military barrack during the civil wars. In 1750 the palace was bought by the city hall of Gualtieri and it became a municipal property [23]. Among the civil activities (e.g. slaughtering, wheat storing) hosted inside the palace, the population promoted also the development of performing arts and the realization of a small theatre, that was designed by the architect G. B. Fattori [23].

The theatre was planned to have a layout in horseshoe shape with three orders of balconies in baroque style. The initial dimensions were restrained if considered that the volume of the main hall was 11×8×6 meters (L×W×H), and the stage was extracted by a stairwell. As such, the theatre had been living always with the problem of craving more space to facilitate the arrangement of seats more comfortably [24].

During the first decade of the 21st century, the necessity of restoration works brought to the idea of rotating the original functions of the room in order to do not destroy the authenticity of the historical decorations [24]. Therefore, the seats have been planned to be organized into the space of the old stage, while the actors would be standing onto the area previously dedicated to the audience, as shown in Figure 9.

Figure 9: View of the Teatro Sociale of Gualtieri.

Table 2 summarises the architectural features of the Teatro Sociale of Gualtieri

Table 2: Architectural characteristic of Teatro Sociale of Gualtieri.

Description	Data
Shape of the main hall	Horseshoe
Levels of balconies	Three
Type of roof	Bricks and Arched
Initial capacity (n. seats)	120
Actual capacity (n. seats)	300
Volume of the main hall (m^3)	Approx. 1050

Acoustical measurements

The acoustical measurements were undertaken with the following equipment:

- Sound source: spherical array of loudspeaker (i.e. prototype realized by University of Parma) [6];
- Microphone: spherical array multichannel (i.e. em32 Eigenmike®);
- Personal Computer connected to the loudspeaker and the receiver.

The excitation signal to measure the RIR was an exponential sine sweep (ESS), having a frequency range set between 40 Hz and 20 kHz. Figure 10 shows that the sound source has been located in three positions while the microphone has been moved to six positions throughout the audience area.

Results of measurements undertaken inside Teatro Sociali of Gualtieri – Standard representation

The results shown in the following figures are to be considered as the average results of all the measurement positions, that are presented in the octave bands between 125 Hz and 8 kHz.

The averaged result of T_{20} across all the spectrum, as shown in Figure 11, is approximately 1.2s which is a good value for both speech understanding and listening to music. The EDT curve has a downwards trend, which is 1.8s at 125 Hz and having values similar to the T_{20} for high frequencies. This effect is mainly

Figure 10: Source and receiver position inside Teatro Sociale of Gualtieri.

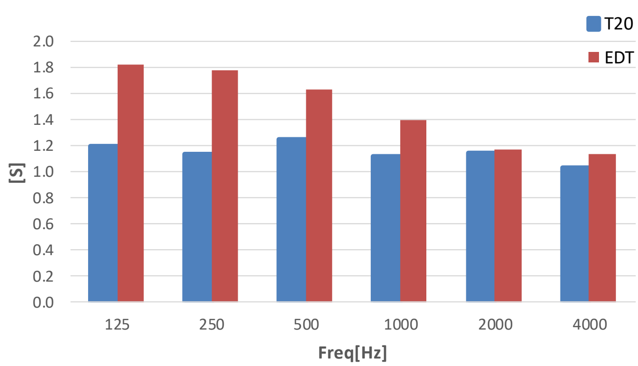


Figure 11: Measured results of Reverberation Time

due to the reversing position of stage and audience areas because nowadays the sitting area is in place of the previous scenic tower, where the vertical surfaces, important for early reflections, are more distant than what it would be in the horseshoe hall.

Figure 12 and 13 show, respectively, the averaged values of C_{50} and C_{80} of all the receivers as a function of frequency.

The clarity of speech (C_{50}) resulted to be between -2 dB and +2 dB across all the spectrum, which is a very good range, except for 125 Hz, showing a value of 4.5 dB, which is slightly high but not disrupting for a speech understanding.

Overall, the values related to the clarity of music (C_{80}) have a good range between 0 dB and 5 dB, although the curve is dissimilar across all the spectrum. The C_{80} shows values around 0 dB for 250 Hz and 500 Hz, and around 5 dB for 125 Hz and 2 kHz.

The peak at 125 Hz, resulted for both C_{50} and C_{80}, is mainly due to the booming effect provoked by the volume of the scenic tower, whereas the audience stands for this particular theatre. While the peak at 2 kHz is owed to the hard material on floor and walls (i.e. bricks and stone), reflecting the most directive sound waves at this specific frequency band.

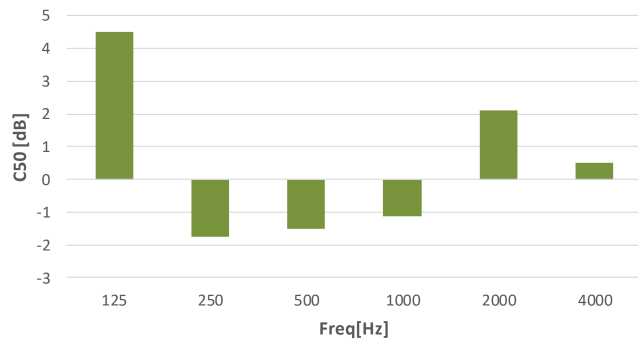


Figure 12: Measured results of Clarity Index (C_{50}).

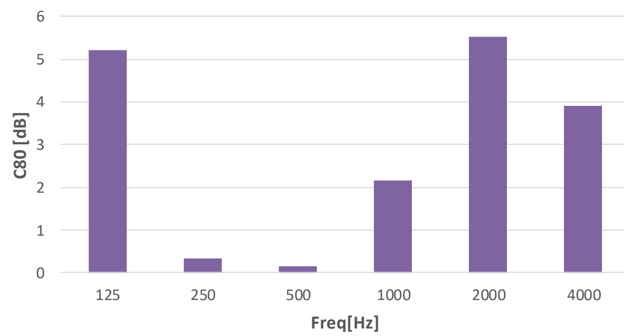


Figure 13: Measured results of Clarity Index (C_{80}).

The parameter of definition (D_{50}), as shown in Figure 14m resulted poor at low frequencies (i.e. 125 Hz), nearly acceptable at mid frequencies (i.e. between 250 Hz and 1 kHz) with a small shortfall and acceptable at high frequencies. This subdivision in three different steps reflects the considerations previously discussed. In particular, the low frequencies feel the lack of definition due to the booming effect, which occurs when the reverberant field is predominant than the direct sound, which is what is occurring in an empty scenic tower at whole height, having reflecting materials on walls and floors. If this result can be considered a worth on the musical side, by creating a fusion of musical notes, it is seen uncomfortable for speech understanding.

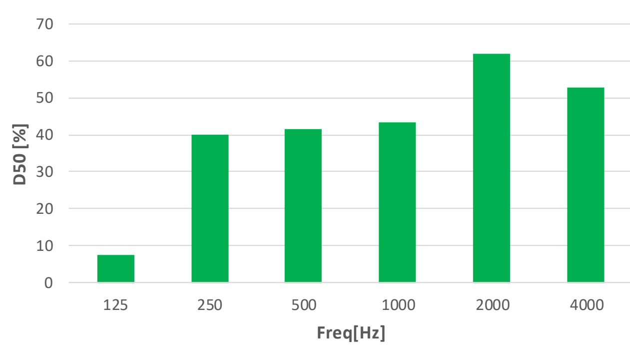


Figure 14: Measured results of Definition

The RIR data gathered by the measurements [5] undertaken inside the Teatro Sociale can be processed in another way, in order to obtain added outcomes in addition to the standard representation of the acoustical parameters. By using a spherical array 32-channel microphone (i.e. em32

Eigenmike®), instead of a 4-channel B-format microphone, the acoustical maps can be developed. In particular, the more innovative graphical analysis is able to show the spatial distribution of the energy emitted by the sound source throughout coloured contour levels in the function of the sound intensity, whereas with the previous technique it was shown by the diameter of a green circle.

The 3D audio playback is obtained by extracting a set of virtual microphones from the IR data. The directivity of each virtual microphone is obtained by solving a matrix of linear and time-invariant FIR filters, (i.e. a process commonly called beamforming) [10].

The overall result is a coloured video which renders a sound map overlapped to a 360° panoramic view. A screenshot of such rendering is shown in Figure 14 below.

Figure 15 shows the implemented representation of what has been explained previously in relation to the Teatro 1763. In particular, with the increase of the number of channels, the sound pressure level, having different ray energy, is represented by an iris colour scale. The scale of values represents the difference in intensity, not the absolute values. The sound waves having more energy are represented with red and warm colours, while the blue-violet colours indicate a poor energy sound wave. Figure 15 shows the reflections hitting the sidewalls of the proscenium arch of the Teatro Sociale of Gualtieri.

Figure 15: Example of a graphical analysis showing strong reflections hitting the sidewalls of the proscenium. The scale of values represents the difference in intensity, not the absolute values.

The impulse response of the multichannel microphone array has been captured by using incident wavefronts from a large number of characterization directions, which are uniformly distributed over a spherical surface by a spatial oversampling owed to a 32-channel microphone [9], as already described in Section 2.3.

4 Discussion

The speedup of progress related to science and technology during the last few decades moved the industry towards the improvement of the digitalization.

Over this background, one of the scopes of Sipario project, a research project funded by the Italian region Emilia Romagna, is the virtual reconstruction of 3D audio and panoramic view of real musical events performed inside historical theatres and concert halls [25]. In order to achieve this purpose, the acoustic RIR measurements can be advanced by using a new generation of equipment, capable of giving back both the results of the acoustical parameters and the information related to the spatial control of the sound propagation.

It should be considered that the improvement of results related to the reconstruction of auralization is mainly related to the usage of equipment typology, which shall satisfy the ever-increasing needs of faithfully representing the reality with the virtual devices.

This paper has shown a few steps of how the technology progression has repercussions on the acoustical results. As the standard equipment composed of an omnidirectional sound source and an omnidirectional microphone are sufficient to describe the acoustical parameters of a room, the implementation by using multi-channel equipment can offer further outcomes to be considered as an added value (and not a substitution) of the traditional representation by graphs.

The passage from a 4-channel to a 32-channel microphone allows obtaining a more detailed and refined rendering in terms of directivity patterns. At the time of measurements, a 64-channel microphone was not yet available on the market, which would have been a good case-study to complete the comparison described in this paper. With the utilisation of the em64 Eigenmike® in the next measurement campaigns, the authors expect that the double number of capsules (i.e. 64, instead of 32) would give more highly directive virtual microphones, having beam width sharper than what obtained with 32 channels.

5 Conclusion and further research

The development of RIR analysis combined with the Multiple Input Multiple Output (MIMO) technique determines the direction where the auralization is addressed nowadays. Although the utilization of multichannel spherical arrays of both microphone and loudspeaker is still experimental, the demand of a faithful reproduction of a 3D audio playback of artistical venues is increased considerably, especially during the lockdown period of Covid-19 pandemic.

Other than reproducing the acoustical features of historical architecture, one of the targets to be achieved by Sipario project is to address people, that never attended live performances, to appreciate performing arts. As such, Sipario is widening the already described acoustical techniques in order to reproduce a 3D soundscape measured into theatres by using inexpensive devices (e.g. a set of head-mounted display HMD plus headphones or Google Cardboard visor, smartphones, etc.) and keeping in the meanwhile the high quality of the recordings [26]. In addition, an immersive listening experience can offer unique feelings when a 360° panoramic video allows to virtually visit such historical buildings, most of them protected by international organizations (e.g. Unesco), in order to preserve them to the future generations.

Further research studies will be focusing on a double number of multichannel source and a multi-channel receiver. A customized construction of a sound source equipped with 64 transducers (always characterized by a spherical array), having the same number of capsules of a new microphone (i.e. em64 Eigenmike®) will be the development of the principles already discussed. The expected results would be a sharper directivity of such virtual microphones and virtual sound sources, capable of rendering more realistically the audio-visual environment.

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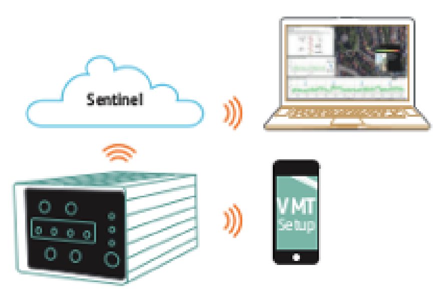

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