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On the Use of 3D Auralisation to Evaluate Room Acoustic Enhancement in Auditorium Restoration

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Abstract

The acoustic quality in auditorium and concert halls is normally evaluated by the measurements of Impulse responses (monaural, binaural or even MIMO). The subjective evaluation is often obtained by convolving anechoic music with the measured IRs. The psycho-acoustical experiment is achieved using a virtual sound field representation. At the University of Bologna, the listening room Arlecchino includes Ambisonics and stereo dipole techniques for playback. In this paper, two different Italian opera houses and two Japanese concert halls were analysed. They were the Teatro Nuovo in Spoleto (Italy), the Teatro Alighieri in Ravenna (Italy), the Kirishima International Musical Hall in Kagoshima (Japan), and the Tsuyama Musical Cultural Hall in Okayama (Japan). The similarity between real and virtual sound fields, obtained with stereo dipole technique, was evaluated by comparing different acoustic parameters calculated by real and virtual sound fields, in the four halls in different designed configurations. Finally, the stereo dipole technique was added to the ambisonic methodology to reproduce the sound fields for the psycho-acoustical experiment. The dual stereo-dipole technique using two kinds of cross-talk cancelling filters can be one of the solutions for improving the acoustical quality of home theatre.

1. Introduction

Refurbishing theatres, like other historical buildings, can be challenging environments for several reasons (Fabbri et al., 2014; Fabbri and Tronchin, 2015; Tronchin and Knight, 2016; Tronchin et al., 2018), even though the main use of theatre is for acoustic performances. In this process, virtual sound fields can firstly help in the design process in order to reach the intended standards and secondly make it possible to test technological solutions. Two theatres are studied here with two concert halls.

1.1 Teatro Nuovo in Spoleto

The Teatro Nuovo in Spoleto opened in 1864 in spite of some discussion; the plan of the stalls is horseshoe shaped in the style of the classical Italian opera house, and the frontage of the four box rows or orders faces the stalls (Farina and Tronchin, 2005 and 2013; Tronchin, 2013). A loggia or a balcony crowned the last box order, and the ceiling is connected to it by a kind of coupling called "Vanvitelli" style or "Umbrella", typical in that period. Stalls, boxes and loggia can contain a maximum of 800 people. Changes to the Teatro Nuovo have been carried out on different occasions; the most striking change was the reduction of the stage, which enlarged the orchestra place, in 1914. Such a modification has most likely damaged the good balance between the singer on the stage and the orchestra in the pit: Furthermore, some musical instruments, recently studied (Farina et al., 1998; Farina and Tronchin, 2000; Tronchin, 2012; Tronchin and Coli, 2015; Tronchin et al., 2020) now play under a flat reflecting surface, which means that some sound reaches the stalls more than 0.5 seconds later than the direct sound. In addition to these modifications, some other changes have been carried out. In 1933 all the original floors were renewed because of the new building safety regulations and consequently, the stage was dismantled to change its structure almost completely by substituting steel for wood. In 1950, work started on the orchestra pit in order to extend its proper space in depth under the stage. More recently, the Regional Authorities have approved further restoration work in order to make some acoustical improvements in the theatre.

Fig. 1 – View of Teatro Nuovo in Spoleto, Italy

1.2 Teatro Alighieri in Ravenna

In 1838 the Municipality of Ravenna decided to build a new opera house, in order to replace the Teatro Comunitativo. The young Venetian architects Tomaso e Giovan Battista Meduna were commissioned to design the new opera house. They proposed a theatre not very different from the Venetian Teatro la Fenice, well known for its acoustics (Tronchin and Farina, 1997), which had opened just a couple of years earlier, after the burning of the first theatre designed by Selva (1795). However, the original design slightly changed a few years later, and in 1852 the Teatro Alighieri opened. The main hall contains many paintings of Venetian artists and golden stuccos. In 1929 the gallery replaced the balcony in the fourth order, and the stage was also remodelled, enlarging the stalls. The chandelier was added in 1960. One of the most relevant factors of the theatre is the cavity located below the orchestra pit. It is one of the few cavities not dismantled in other Italian styled opera houses during the 20th Century, and it was recognized as being responsible of some modification in strength and reverberation time during recent acoustic measurements in this theatre, which also involved other aspects (Caniato et al., 2015 and 2016; Tronchin, 2013).

1.3 Kirishima International Musical Hall

The Kirishima International Musical Hall was opened in 1994 in Kagoshima (Japan). The shape of stalls is based on the shoe-box style. However, the arrangements of the lateral walls are uneven like a natural leaf. The reflections which are returned from these lateral walls maintain the same angle of incidence when they arrive at listeners. This makes the value of the IACC (Inter Aural Cross Correlation) low. The audience area is covered by the ceiling: the shape of this ceiling is not unlike the inverted hull of a ship.

Fig. 2 – View of Teatro Alighieri in Ravenna, Italy

The enclosures realize the well-diffused sound field. There are 518 seats in the stalls and 252 seats in the gallery. The reverberation time is from 1.6 to 1.8 s.

Fig. 3 – View of Kirishima International Musical Hall, Japan

1.4 Tsuyama Musical Cultural Hall

Tsuyama Musical Cultural Hall was opened in Okayama (Japan) in 1999. Following the concept of the "acoustics of the forest", a large number of pillars are arranged in rows in front of the lateral walls. The diffused sounds would be similar to those which could be found in the forest. In the ceiling, the floating reflective boards are hung by wire ropes. There are 600 seats. The reverberation time is around 1.6 s.

Fig. 4 – View of Tsuyama Musical Cultural Hall, Japan

2. Materials and Methods

Acoustical measurements were taken by arranging source and receivers and the procedure of stereo-dipole was applied in 3 steps.

2.1 General Measurement Conditions

To obtain binaural and b-format impulse responses, a logarithmically sine-swept FM chirp was generated by a PC. The sine signal with exponential varied frequency was defined by a starting frequency 40 Hz, an ending frequency 20k Hz and a total duration ranging from 20 to 30 s, as normally measured in several acoustic applications (Caniato et al., 2016; Tronchin, 2013).
The sound source and the receiver were employed by an omnidirectional, pre-equalized loudspeaker (Look Line) and a dummy head (Neumann KU100). The waveforms were acquired by means of a multi-channel soundboard and stored at 96 kHz and 32 bits. The height of the source was 1.4 m when placed on the stage, and 1.2 m when placed in the orchestra pit. It was located 2 m from the edge of the stage , whereas in the pit, it was 3.6 m from the pit fence. The height of the microphones was 1.1 m from the floor to ear. In the box, the microphones were brought near to the opening and chairs were moved close to the door. The direction the dummy head was facing was adjusted to the source position in each measurement.

2.2 The Layout of the Sources and Receivers

The measured impulse responses analysed in this paper are four for Teatro Nuovo, three for Teatro Alighieri, one for Kirishima musical hall, and one for Tsuyama musical hall. The arrangements of the sources and receivers and the names referred to in the following sections are shown in Table 1.

Table 1 – Kinds of measured impulse responses

Auditorium	Source	Receiver	Name
Teatro Nuovo di Spoleto	stage	stalls	SPO_ss
	pit	stalls	SPO_ps
	stage	box	SPO_sb
	pit	box	SPO_pb
Teatro Alighieri di Ravenna	stage	stalls	RAV_ss
	stage	box1	RAV_sb1
	stage	box2	RAV_sb2
Kirishima musical hall	stage	stalls	KIR_ss
Tsuyama musical hall	stage	stalls	TSU_ss

2.3 Stereo-Dipole 1: Measurement in Arlecchino Listening Room

The single and dual stereo-dipole representations were carried out in an Arlecchino listening room in Bologna (Italy), which has been developed to recreate other indoor environmental conditions (Caniato et al., 2019; Tronchin and Fabbri, 2017). The property of the swept-sine is shown in Table 2.

Table 2 – Properties of swept sine signal

Variable	**Value**
Start freq. [Hz]	50
End freq. [Hz]	18000
Duration [s]	30
Amplitude	8192
Sampling [Hz]	44100
Scale	32-bit

Two loudspeakers (Montarbo W400A) are located in front of a dummy head (Neumann) and the other two loudspeakers (Montarbo W400A) are located to the rear of it as shown in Fig.s 5 and 6.

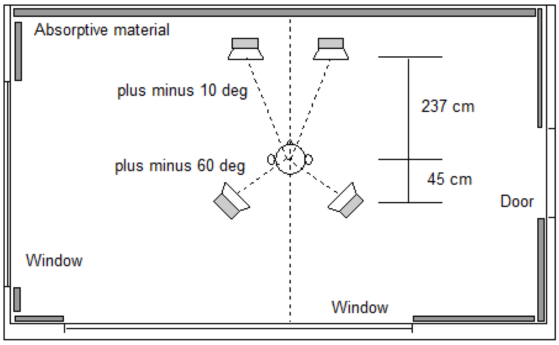

Fig. 5 – Plan of Arlecchino listening room

To obtain the BIR in the listening room, a log swept-sine signal is generated by Adobe Audition and is presented by the four loudspeakers alternately. After de-convolution of the signals recorded by the dummy head, the impulse response of the listening room can be obtained respectively for the front and rear loudspeakers. The envelopes of impulse responses are smoothed in order to cancel extra reflections and only the direct sound remains.

2.4 Stereo-Dipole 2: Generation of Cross-Talk Cancelling Filter

The smoothed impulse response is converted into cross-talk cancelling filter by using the plug-in of "Invert Kirkeby" in Adobe Audition. In this examination, the two kinds of cancelling filters are generated for the frontal loudspeakers and for the rear loudspeakers (Shimokura et al., 2011). Table 3 shows each calculation condition of the Invert Kirkeby plug-in.

Table 3 – Properties of Invert Kirkeby plug-in for Frontal and Rear cancelling filters

Variable	**Value**
Filter length [sample]	2048
Lower cut freq. [Hz]	80
IN-band parameter	1
High cut freq. [Hz]	16000
OUT-band parameter	10
Width	0.33

Fig. 7 shows the spectral characteristics of the two cancelling filters.

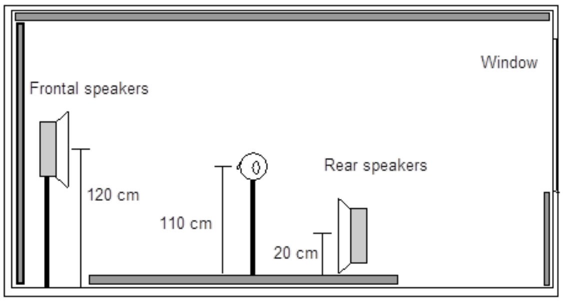

Fig. 6 – Section of Arlecchino listening room

Since the Arlecchino listening room is not a perfectly anechoic room, it is difficult to generate the cross-talk cancelling filters with linear spectral characteristics from the impulse responses in it. The two cancelling filters are calculated to lower the spectral gaps, as shown in Fig. 7.

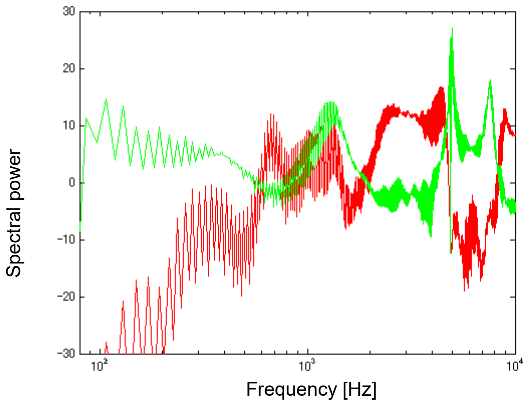

Fig. 7 – Spectral powers of front cancelling filter (red) and rear cancelling filter (green)

2.5 Stereo-Dipole 3: Presentation

The anechoic swept-sine signal was convoluted with the impulse responses of the theatres. The echoic swept-sine signals were convoluted again by the cancelling filters for the frontal and rear loudspeakers. The resulted signals were presented by the frontal and rear loudspeakers at the same time, and the sounds were recorded by the dummy head under similar conditions to those in the Arlecchino listening room when the impulse response was measured. Finally, by de-convoluting the recorded signal, an impulse response is generated. In this study, it is called “virtual IR” in order to distinguish the “real IR” that was measured in the theatres. A similar procedure was also applied for the Ambisonic playback system, but the results are not presented in this paper.

3. Results

To confirm the accuracy of the sound field representation by the stereo-dipole technique, in this paper the real IR and virtual IR were compared in terms of these acoustical parameters: SPL (Sound Pressure Level), EDT (Early Decay Time).

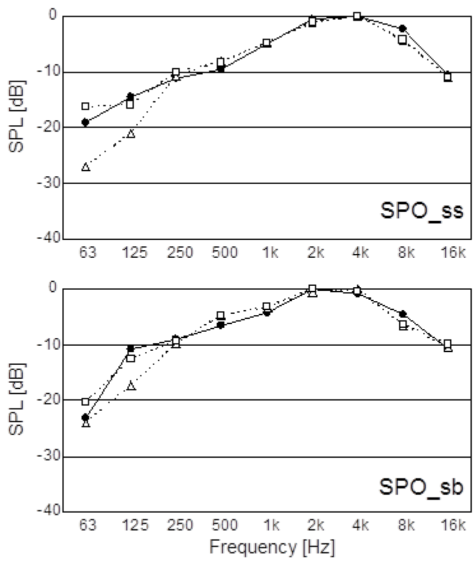

Fig. 8 – SPL: real IR (●), virtual IR by single stereo-dipole (Δ), virtual IR by dual stereo-dipole (□): Spoleto 1/2

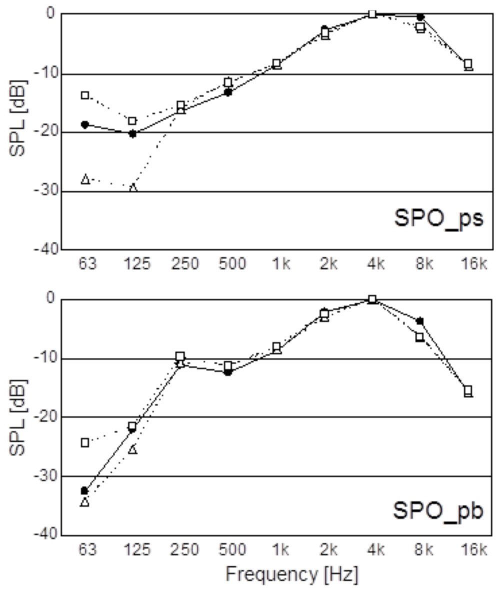

Fig. 9 – SPL as a function of band frequency: Spoleto 2/2

The values are the averaged SPL and EDT calculated from the left and right impulse responses. Only in the case of KIR_ss, is the data of the virtual IR by dual stereo-dipole a shortage. Fig.s 8 to 13 show the SPLs calculated from the real IR and the virtual IR by single and dual stereo-dipoles. The virtual IR by single stereo-dipole is obtained by using only the frontal loudspeakers.

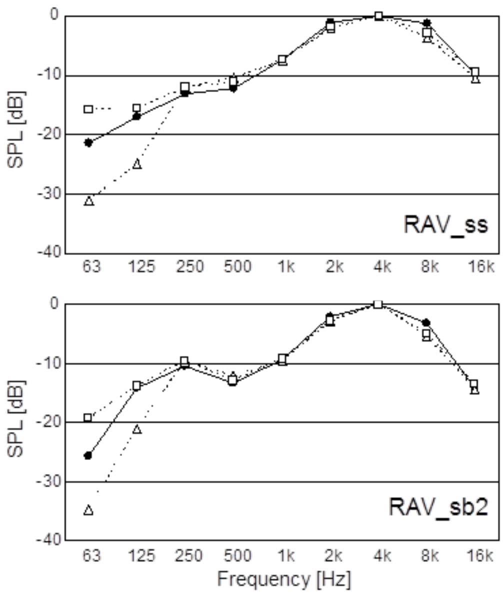

Fig. 10 – SPL as a function of band frequency: Ravenna 1/2

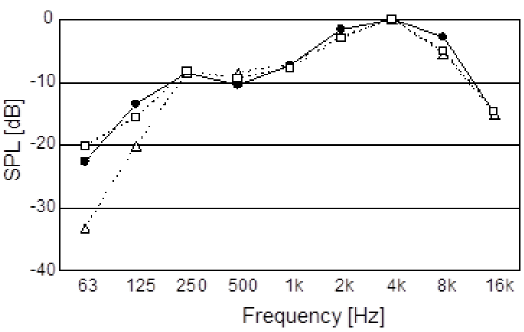

Fig. 11 – SPL as a function of band frequency: Ravenna 2/2

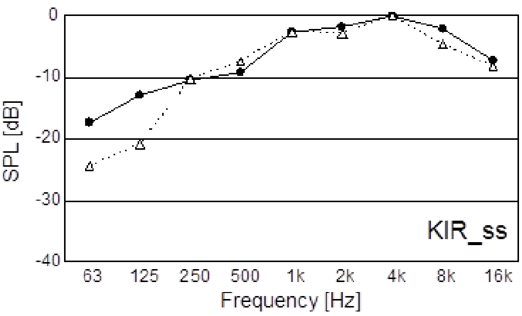

Fig. 12 – SPL as a function of band frequency: Kagoshima

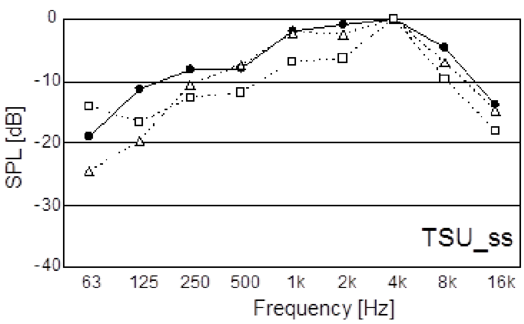

Fig. 13 – SPL as a function of band frequency: Okayama

In all cases, the SPL of the virtual IR is close to the SPL of the real IR. However, in the low-frequency range, the SPL of the virtual IR by single stereo-dipole tends to be lower than the SPL of real IR. The gap of SPL is improved by carrying out the dual stereo-dipole. For the concert hall, the single stereo-dipole shows better performances than the dual stereo-dipole. Fig.s 14 to 19 show the results of EDT. From these results, it can be seen that the stereo-dipole technique in the Arlecchino listening room works for the sound field representation with a high correlation. However, like the results of SPL, EDT of the real IR in the low-frequency range is difficult to be expressed by the single stereo-dipole.

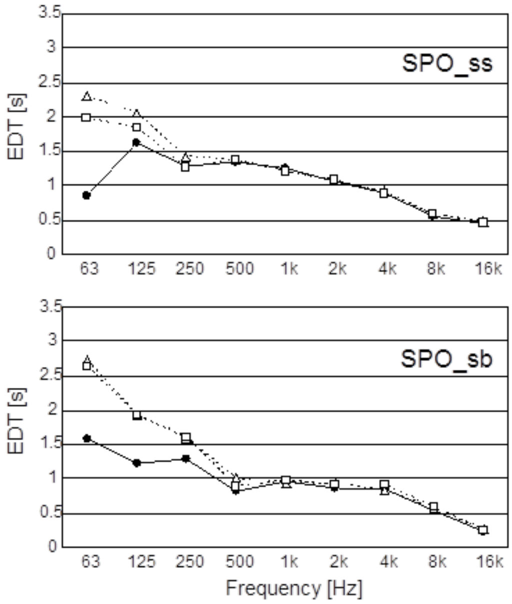

Fig. 14 – EDT: real IR (●), virtual IR by single stereo-dipole (Δ), and virtual IR by dual stereo-dipole (□): Spoleto 1/2

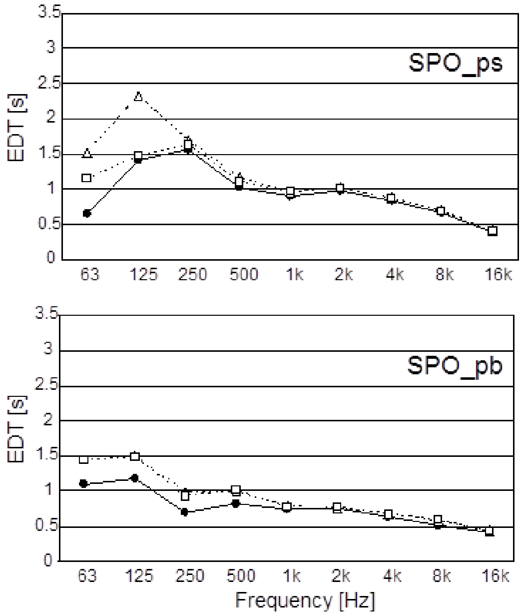

Fig. 15 – EDT as function of band frequency: Spoleto 2/2

The dual stereo-dipole contributes to covering the gap of EDT.

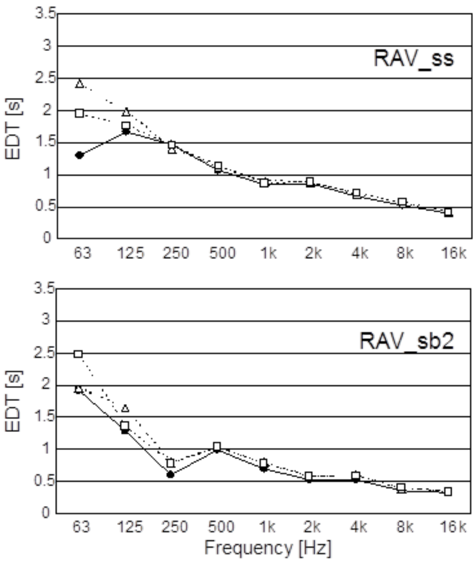

Fig. 16 – EDT as a function of band frequency: Ravenna 1/2

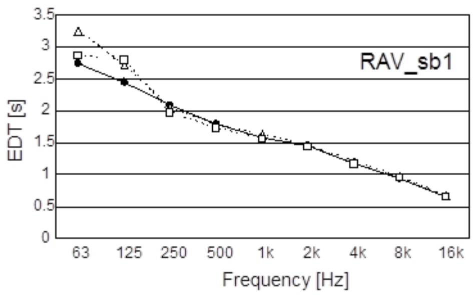

Fig. 17 – EDT as a function of band frequency: Ravenna 2/2

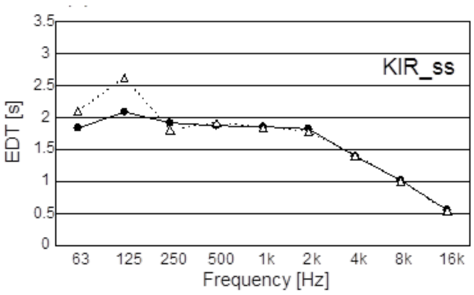

Fig. 18 – EDT as a function of band frequency: Kagoshima

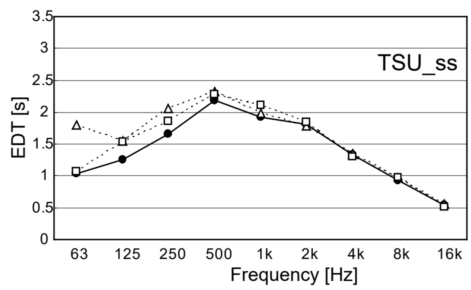

Fig. 19 – EDT as a function of band frequency: Okayama

4. Discussion

The Arlecchino listening room was redecorated by putting the absorptive material on the walls to perform the virtual sound field reproduction and listening tests. As a result, the reverberation in the high-frequency range (>500 Hz) was greatly removed while low-frequency reverberation (<250 Hz) remained again in the range shorter than 1s. In such a semi-anechoic condition, the generation of virtual sound fields by the stereo-dipole technique is not easy to carry out, because the cross-talk cancelling filter based on the impulse response with some reverberation is not flat spectrally. According to the parameters in the invert Kirkeby method, the cancelling filters have spectral peaks and dips as shown in Fig.s 14 to 19. However, the shortage of spectral power can be overcome by using two kinds of cancelling filters, which are presented by the dual-stereo dipole technique. Fig.s 8 to 13 and 14 to 19 show the advantages of dual stereo-dipole in terms of SPL and EDT. In general, the Ambisonic method, for reproducing virtual sound fields, showed a good enhancement at these frequencies. It is therefore likely that this limitation could be circumvented with the Ambisonic method.

5. Conclusion

The stereo-dipole technique has been developed to be applied to "home theatre", which realizes the 3D sound for home use. Unlike the perfectly anechoic listening room in a laboratory, the room in a home has some reverberations unless absorptive materials are introduced in it. The dual stereo-dipole technique using two kinds of cross-talk cancelling filters can be one of the solutions to improve.

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