The Sound Representation of an Opera House's Orchestra Pit: The Stereo Dipole Technique

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Abstract. By using 2 or 4 loudspeakers, the stereo dipole technique is able to realize the virtual sound field of an auditorium in an anechoic listening room. Making use of binaural impulse responses (BIRs) measured in the auditorium and the auralization technique, the virtual BIR can be generated. The accuracy of the sound representation is investigated by comparing the real and virtual BIRs. For a well-diffused sound field like concert halls, this technique enables a highly accurate representation of the sound field. Yet, when the sound source is in the small regularly shaped enclosures like an orchestra pit of an opera house, a peculiar amplification contained in the low-frequency range of the measured BIR is still more emphasized in the virtual BIR disturbing the linear sound representation. This study aims for the solution to this problem.

1. Introduction

Built environment indoor comfort analysis is often focused on temperature and humidity conditions [1] from a modelling & simulation perspective [2], while an in-situ measurement one [3] and in the validation phases of linking them [4]. Whereas, acoustics is mainly analysed only in specific facilities [5] such as theatre, opera or concert hall [6]. Advanced techniques are used to measure performance of cutting-edge energy systems [7] or controlling systems [8] but they require complex architecture [9] and not fully reliable business plan to justify their use [10]. The design for the physical properties of spaces and materials is crucial to make the building suitable for the use and people comfort [11].

In acoustics, many techniques to check performance and model them to simulate the response in case of use are available [12] and they differ from their intended use when more suitable for outdoor [13] or indoor [14].

The stereo-dipole technique can be applied through the use of 2 or 4 loudspeakers (corresponding to single stereo-dipole or dual stereo-dipole) and a listener who is seated centrally to them. To perform this technique, proceed with canceling the sounds in cross pathways so that the presentation of the parallel sound generates the 3D sound field for the listener [15]. Subsequently, employing the invert Kirkeby method, the cross-talk canceling filter is produced in a base of a BIR measured in a listening room [16,17]. The stereo-dipole technique is capable of reproducing highly accurate virtual sound fields of opera houses, well diffused and without any obstacles [18].

The aim of this study is, therefore, to systemized in a listening room the virtual sound fields of a concert hall, the Japanese Kirishima International Musical Hall, and an opera house, the Italian Teatro Nuovo in Spoleto.
The listening room used is called *Arlecchino* and is situated in Bologna (Italy). The room was re-decorated by putting the absorptive material on the walls for a congenial restoration [19, 20].

Unlike the concert hall, the opera house’s sound field is dry and closed, particularly if the sound source is placed in the orchestra pit. By using the stereo-dipole technique, the BIRs measured under these less diffused conditions are reproduced in the virtual sound field. Then, the recorded virtual BIRs and the virtual BIR based from the concert hall are compared in order to check if the restoration of materials was suitable for thermal [21] and acoustic purposes [22, 23] as well.

2. Methodology

2.1. Measurements in the Real Environments

The acoustical measurement conditions in the concert hall and the opera house are common in the almost parts. The sound source was employed by an omnidirectional loudspeaker (Time domain Yoshii 9 or Look Line) and the receiver by a dummy head (Neumann KU100). The waveforms were acquired by means of a multi-channel soundboard and stored at 96 kHz and 32 bits.

In order to obtain the binaural impulse responses, a logarithmic sine-swept FM chirp was generated with the exponential varied frequency defined by a starting frequency of 40 Hz, and an ending frequency of 20kHz. The total duration ranging from 10 to 30s.

In the Concert Hall, the sound source position is centered and close to the edge of the stage while the receivers are located in the stage and in the stalls. Despite the BIRs were recorded in all seats positions, one BIR used in the examination of stereo-dipole is selected as shown in Figure 1. Following, it is defined as “real BIR_css”.

![Figure 1](image.png)

*Figure 1.* Image (left) and plan (right) of Kirishima International Musical Hall (Japan). The points in the plan identify the positions of the sound source and of the receiver.

In the Opera House, the acoustical measurement was carried out in two source positions: the stage and the orchestra pit. The source in the orchestra pit is located under the frontal part of the stage, and the direct sound pathway is obstructed by the pit fence. The receiver was positioned in the middle of the horse-shoe shaped stalls (Figure 2). They are defined respectively “realBIR_oss” and “realBIR_ops”.

2.2. Analysis of the measurements

In a less diffused sound field like an opera house, especially in the orchestra pit of the Teatro Nuovo which is more extensive than other Italian traditional opera houses, it is possible to observe some wavy behavior of sound related to coloration and flutter echo phenomenon like mode and diffraction; some listeners in the stalls perceive the flutter echo in the sound from the pit [24]. In this paper, we carried
out the autocorrelation analysis of BIR in order to detect the repetitive feature in a low particular frequency [25].

![Figure 2](image.png)

**Figure 2.** Image (left) and section (right) of Teatro Nuovo di Spoleto (Italy). The three points indicate the positions of source and receiver.

The BIRs are low pass filtered (< 500 Hz) using the Butterworth filtering algorithm (order = 5), then the normalized autocorrelation functions (ACFs) are calculated. Figure 3 shows the waveforms and ACFs calculated by the 3 impulse responses in left channel. In the concert hall, the BIR does not have any repetitive feature, which means that the sound is structured only by the forward traveling wave. On the other hand, in the opera house, the BIRs include particular repetitions whose temporal intervals are long. Especially, when the source is in the orchestra pit, the periodicity can be observed clearly in the ACF of realBIR_ops. It seems that the sound propagated from the pit source repeats reflections between the floor and the forestage covering the pit.

![Figure 3](image.png)

**Figure 3.** Wave forms (upper) and ACF (lower) of realBIR_css (a), realBIR_oss (b), and real BIR_ops (c).

2.3. The stereo-dipole technique in the Virtual Environment
Following is shown the procedures of the single stereo-dipole technique with 2 loudspeakers and the dual stereo-dipole technique with 4 loudspeakers. Both techniques were conducted in the Arlecchino listening room previously mentioned.
The first step includes the measurement of BIR. Figure 4 shown the sets of the equipment employed: 2 loudspeakers (Montarbo W400A) are placed in front of a dummy head (Neumann) and the other 2 loudspeakers (Montarbo W400A) are located in rear of it. In order to obtain BIR in the room, a logarithmic swept-sine signal was generated by Adobe Audition and is generated alternately by the four loudspeakers. The signals recorded by the dummy head was de-convoluted to obtain the impulse response of the listening room for the front and rear loudspeakers. Finally, the envelopes of IR are smoothed in order to remove extra reflections and isolate the direct sound.

Figure 4. Arrangement of 4 loudspeakers and a dummy head in the Arlecchio listening room

The second step was the generation of cross-talk canceling filter. Using Adobe Audition and the “Invert Kirkeby” plug-in, the smoothed IR was converted into cross-talk canceling filter and generated for the frontal loudspeakers and for the rear loudspeakers. The calculation conditions are shown in Table 1.

Table 1. Properties of Invert Kirkeby plug-in.

| Property                  | Filter A | Filter B |
|---------------------------|----------|----------|
| Filter length [sample]    | 2048     | 2048     |
| IN-band parameter         | 1        | 0.001    |
| OUT-band parameter        | 10       | 1        |
| Lower cut freq. [Hz]      | 80       | 80       |
| High cut freq. [Hz]       | 16000    | 16000    |
| Width                     | 0.33     | 0.33     |

As shown in Figure 5, the filters produced have distinct spectral characteristics. This was possible by regulating IN-band and OUT-band parameters in Invert Kirkeby plug-in. Observing the figure 4 (right image) the cross-talking canceling filters are spectrally flat for the rear loudspeakers because of the arrangements separating them in broad angle, while (left image) the B filter has rich spectral power for the front loudspeakers in the low-frequency range. Moreover, the A filter is in short supply of the low-frequency power.

The third and last step was related to the presentation. The anechoic swept-sine signal was convoluted with the IR of the concert hall and the opera house, and consequently, the echoic swept-sine signals were convoluted by the cancelling filters for the four loudspeakers. The resulted signals are presented by the frontal loudspeakers for the single stereo-dipole and the frontal and rear loudspeakers for the dual stereo-dipole. Therefore, the sounds were recorded by the dummy head reproducing the same conditions in which the impulse response of the Arlecchino listening room was measured.
Finally, the impulse response was generated by deconvolution of the recorded signals; following, it is defined as “virtualBIR” in order to distinguish the “realBIR” that was measured in the concert hall and in the opera house.

![Spectral power vs Frequency](image)

**Figure 5.** Spectra of filter A (solid line) and filter B (dot line) generated from BIR of the frontal loudspeakers (left) and from BIR of the rear loudspeakers

### 3. Results

#### 3.1. The single stereo-dipole (only fronts)

The performance of virtualBIR is assessed comparing the IACF (Interaural Cross Correlations Function) of real and virtual BIRs in order to verify the precision of the sound field representation with the single stereo-dipole.

The results of the virtualBIR_css related to the Kirishima Concert Hall are presented in Figure 6: the left figure represents the results obtained by means of A filter, while the right figure, the results obtained by means of B filter. It can be observed that the virtual sound reproduction is archived in high correlation.

Results related to the Teatro Nuovo opera house of virtualBIR_oss (with the source in the stage), and virtualBIR_ops (with the source in the pit), are depicted in figures 7 and 8. Observing it, it can be noticed that, as well as in the concert hall, the accuracies of stereo-dipole in terms of IACF are maintained in high correlation when filter A is used to generates the virtual BIRs. However, it is noticed that the IACFs of virtual BIRs are shifted to higher value than those of real BIRs when filter B is used.

As shown in Figure 5 (observing the solid line in the left image), during the process of convolution with the echoic swept-sine signals, the filter A cuts off the spectral power in low frequency; moreover, the low-frequency repetitions of the real BIRs of the opera house, previously depicted in Figure 3, are also diminished. Consequently, the virtual BIRs are acoustically close to the real ones. On the other side (observing the dot line in the left image), the low-frequency power is emphasized by filter B and the periodic low frequency is viewable in the waveforms of the virtual BIRs.
Figure 6. Wave forms (upper) and IACF (lower) of virtualBIR_css (dot line) generated with filter A (a) and filter B (b). The solid line in the lower figure indicates IACF of realBIR_css.

Figure 7. Wave forms (upper) and IACF (lower) of virtualBIR_oss (dot line) generated with filter A (a) and filter B (b). The solid line in the lower figure indicates IACF of realBIR_oss.

3.2. The single stereo-dipole (only rears)
Although the rear loudspeaker cross-talk canceling filters appears to be flat-spectral (see Figure 5 to the right), the A and B filters also generate a virtual BIRs with a waveform periodic low frequency. The amplification in the low particular frequency can occur independently from the spectral linearity of the filters. This unless the filters cut off their low-frequency powers.
3.3. The dual stereo-dipole

Basing on the results shown, it is possible to state that, in terms of IACF, filter A is more suitable for generating virtual BIRs that are similar to real BIRs. However, since the filter A cuts off the low-frequency power, the other acoustical parameters like Sound Pressure Level and Early Decay Time, have some gaps between the real and virtual BIRs.

In order to solve the problem, the 4 loudspeakers (2 fronts and 2 rears) are used for the dual stereo-dipole; the frontal loudspeakers and the rear ones are assigned respectively to filter A and filter B. The two filter types compensate each other’s spectral power losses. Because two distinct sounds coming from both front and rear loudspeakers are reached to each ear, the interaural correlation of virtual BIR, that results shifted in high value, can be lowered. This is crucial in considering other sound generators when energy systems are upgraded or installed [26].

Figure 9 shows the results for virtualBIR_oss and virtualBIR_ops with dual stereo dipole: there is no visible periodic variation on virtual BIRs, and the IACFs are similar to the results for the real BIRs. Even if virtualBIR_ops IACF is not perfectly synchronized with realBIR_ops, the parallel shift of IACF toward to high value (see Figure 8 right) is not found in this case (Figure 8, right image).

**Figure 8.** Wave forms (upper) and IACF (lower) of virtualBIR_ops (dot line) generated with filter A (a) and filter B (b). The solid line in the lower figure indicates IACF of realBIR_ops.

**Figure 9.** Wave forms (upper) and IACF (lower) of virtualBIR_oss (a) and virtualBIR_ops (b). The solid lines in the lower figures indicate IACFs of realBIR_oss and realBIR_ops.
Other sound parameters, SPL and EDT, are compared with real and virtual BIRs in addition to IACF: results are shown in Figure 10. The virtual BIR is achieved by using filter A with a single stereo-dipole. The real and virtual BIRs are similar in SPL and EDT in high band frequencies. On the other side, SPL and EDT demonstrate some errors in the low frequency ranges for the sound fields representation; however, they are improved by the dual stereo-dipole, approaching the virtual SPL and virtual EDT by the real BIRs values.

4. Discussion
In this study, the single stereo-dipole with 2 loudspeakers and the dual stereo-dipole with 4 loudspeakers are conducted in the Arlecchino listening room in Bologna (Italy). The procedure of them is shown in the following. It calls for detailed design when energy retrofitting of existing buildings is done [27] or new sound sources occur for installation of HVAC [28]. Modeling software can actually help to avoid those discrepancies between expected and real performance [29]. Finally, the procedure must be coupled with all the physical performance for a comprehensive and compatible intervention in buildings [30].

5. Conclusion
In the opera house, some structural components disturb the propagation of the sound, particularly when the source is in the orchestra pit. In the less diffuse conditions, the repetitive reflection often takes place at a certain rate, and the stereo-dipole technique can be a challenge to replicate a virtual sound field. However, although the dual stereo dipole has 4 speakers in these inconvenient conditions the opera house is able to achieve a more accurate virtual sound filed by regulating the cross-talk canceling filter’s shape.

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