Comparison of sound propagation from stage and pit to stalls and boxes in an Italian opera house

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The features that separate an opera house from a concert hall are the semi-closed performance area, orchestra pit, and the compartmental audience areas, or boxes. The sound propagated from the orchestra pit reaches listeners through barriers and diffraction effects. As well, the sound arriving to listeners seated in the boxes is further limited because it must cross the box openings. In this study, to assess the sound fields of opera houses, the maximum sound pressure of direct sound coming from an impulse response measured in the *Teatro Nuovo di Spoleto* is investigated using G_{re} (relative strength), which is the ratio of the sound pressure measured in a hall to an equivalent sound pressure that would be measured at the same distance from the same source to the receiver in a free sound field. Impulse response analyses show that G_{re} is predicted mainly by the elevation angle from the source to the edges (pit rail and box rails), and that the values of G_{re} also have high correlations with the interaural cross-correlation coefficient (*IACC*). G_{re} is suggested as a useful parameter for quantifying the barrier effect of a pit and for evaluating the architectural design of opera house boxes.

Keywords: opera house, direct sound, orchestra pit, box seating

1. INTRODUCTION

A traditional Italian opera house is composed of two performance areas (the stage and the orchestra pit) and two audience areas (stalls and boxes). The different possible combinations of these four areas determine the different sound fields. The sound field achieved by a sound source from the stage to receivers in the stalls is similar to the sound field of a concert hall. However, the other opera house sound fields are acoustically different because the pit and box areas are semi-closed enough to limit sound propagation and to create indirect sound paths to the receiver. For example, a direct sound from the pit reaches the stalls after experiencing a diffraction effect caused by the pit rail (the wood balustrade or low wall separating the pit and stalls).

Therefore, because of these different sound fields, acoustical measurements in opera houses are more difficult than in concert halls in terms of selecting source and receiver positions. Pompoli and Prodi proposed technical means for scientific quantification in the form of operative guidelines for acoustical measurements inside baroque opera houses [1]. In their guidelines, the sound sources are set at two positions, the stage and the pit, with one additional pit source being located under the forestage according to the shape of the orchestra pit. The receivers are distributed across nine positions located either in the stalls or in the box areas. Acoustical measurements with a few sound sources are generally carried out to investigate the acoustical characteristics in the audience area [2–4]. In some studies, to examine the different sound propagations between the stage source and the pit source, more source positions are used to cover both performance areas [5,6]. However, Sakai and Ando conducted acoustical measurements by placing multiple receiver positions limited to only one box [7].

Although, by taking measurements with a number of source and receiver positions, a massive amount of acoustical data can be obtained, there is no acoustical parameter, extracted from the measured data, to evaluate the diffuseness of the sound fields. In this study, using a swept-sine signal, impulse responses were measured moving both the source and the receiver into a number of positions distributed across both the performance areas (stage and orchestra pit) and the audience areas (stalls, i.e. main floor, and box areas) of an Italian opera house, the *Teatro Nuovo di Spoleto* (volume 3000 m^3 and capacity 800 seats). The orchestra pit (floor 12.15 × 12.84 m^2 and height 2.22 m) is extended so that the majority of the pit is concealed by the forestage, and the open areas of the boxes (floor 2.14 × 1.67 m^2 and height 2.25 m) face toward the stage

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and not the pit for viewing purposes. Unlike a well-diffused sound field, as in concert halls, these barrier structures characteristically dominant sound fields in opera houses.

The sound attenuation of direct sound in the measured impulse responses, ΔL, were compared to investigate the different sound propagation paths and the sound limitations caused by the barrier effect of the pit rail and box rail (the balustrade of the box compartments). Then, G_{re} (relative strength) was calculated from the direct sounds of impulse responses. G_{re} in dB is the logarithmic expression of sound pressure that refers to the sound pressure that would be measured with the same source and receiver positions but in a free sound field [8]. When the value of G_{re} is zero, sound is not affected by diffraction and reverberation.

In terms of sound attenuation ΔL, the estimation of diffraction loss in the shadow zone concealed by the barrier has been investigated using geometrical considerations [9–14], and some theories have been introduced in acoustical simulation models for sound fields [15,16]. The edge impulse response for a finite edge is based on the argument that the local reaction to an impulsive incident wave at the edge is instantaneous. The edge diffraction impulse response can be written in the form of

$$h_{diffr}(t) = -\frac{v}{4\pi}\int_{z_1}^{z_2} \delta(t - \frac{m+l}{c}) \frac{\beta(\alpha, \gamma, \theta_S, \theta_R)}{ml} dz \qquad (1)$$

where v is a “wedge index” describing the wedge’s concavity ($> \pi$) or convexity ($< \pi$), m and l are distances to the source S and the receiver R, and β is an analytical edge-source directivity-function that depends on the location of the source and the receiver related to a given edge ($z_1 < z < z_2$) [11] (see Fig. 1). This study presented a comparison between the ΔL from measured impulse responses and ΔL from an estimation method within the geometrical situation of an opera house.

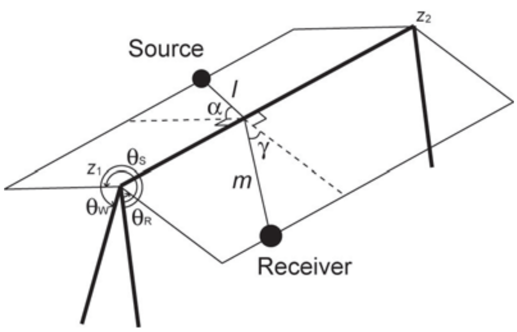

Fig. 1. Geometry of a finite wedge. The positions of the source and receiver are indicated in cylindrical coordinates.

The G (strength) value is a parameter very similar to Sound Pressure Level (*SPL*) and Listening Level (*LL*) and delivers confused information about the effects of distance from the source, the support coming from reverberation and the eventual barrier effects. However, the value of G_{re} is sensitive to the barrier effects caused by pit and box rails in opera houses. In our earlier study, we investigated the comparison between G and G_{re} calculated from whole impulse responses measured in a concert hall [8]. The results showed that G and G_{re} represent reflections coming from walls close to the source and the receiver, respectively. We concluded that G and G_{re} are useful for acoustical evaluations of architectural structures in the stage and in the stalls areas, respectively. On the other hand, the values of G_{re} in this study were obtained only from direct sounds, so that the characteristics of semi-closed areas (i.e. the orchestra pit and boxes) should also be well visualized in G_{re}.

2. ACOUSTICAL MEASUREMENTS IN *TEATRO NUOVO*

Two kinds of acoustical measurements were carried out in the Italian opera house, *Teatro Nuovo di Spoleto*. In the first measurement campaign, sound sources were located one by one in 20 positions on the stage and 20 positions in the pit, and one receiver located either in the stalls or in the box areas recorded the sound from each sound source. In the second measurement campaign, on the other hand, a sound source was positioned either on the stage or in the pit, and the receivers were located one by one among 34 positions in the stalls and 13 positions in the boxes. The sound source, receiver, and interface between them were the same for both the measurement campaigns.

2.1. General measurement set-up

The sound signal utilized during these measurements was a sine-swept FM chirp (see Appendix A). Although there is a trend to use a directional loudspeaker for the stage source in opera houses, assuming the sound directivity of singers’ voices, this study limited discussions to evaluations of sound fields with the principle of a point source, so the signal was presented by an omni-directional loudspeaker (Look Line: dodecahedral configuration). The height of the sound source was 1.4 m on the stage and 1.2 m in the orchestra pit. The response was recorded by a dummy head (Neumann: KU100) with a height of 1.1 m above the floor level like for the ear position when a listener sits down. In the boxes, the dummy head was brought near the opening, and chairs were moved close to the door. When the source signals were generated and the responses were saved in a PC, a Layla24 board with 24 bit resolution AD/DA converters was employed for the recording with a sampling rate 44.1 kHz and a 32-bit sampling size. These responses were convolved with an inverse filter, i.e., a reversed sine-swept signal in terms of time, and the linear binaural impulse responses were obtained directly. Instead of measuring the acoustical out-put power of the sound source, the reference sound pressure was measured at a distance of 1 m away from the sound source.

2.2. Arrangement of sound source and receiver positions

For the sake of convenience, here the two plan theater dimensions are named width (left - right) and height (up - down), each from the perspective of the audience. For the direction of the depth dimension, for sources, “front” refers to the part faced to the audience, while for receivers “front” refers to the part faced to the stage.

In the first measurement campaign, the floors of the stage and orchestra pit were marked with a 2 m $\times$ 2 m grid, and the sound source was placed one after another in 5 positions (for the width dimension) $\times$ 4 positions (for the depth dimension), as shown in Fig. 2 (source varied condition). The receiver in the stalls was put in the middle (for the depth dimension) and the right (for the width dimension) of the stalls, as shown in Fig. 2. The box, containing the receiver, was located in the rear (for the depth dimension) and the right (for the width dimension) on the third floor (for the height dimension). The dummy head was kept facing the center of the stage during the measurement.

In the second measurement campaign, the receiver positions were distributed in 34 positions in the right half of the stalls

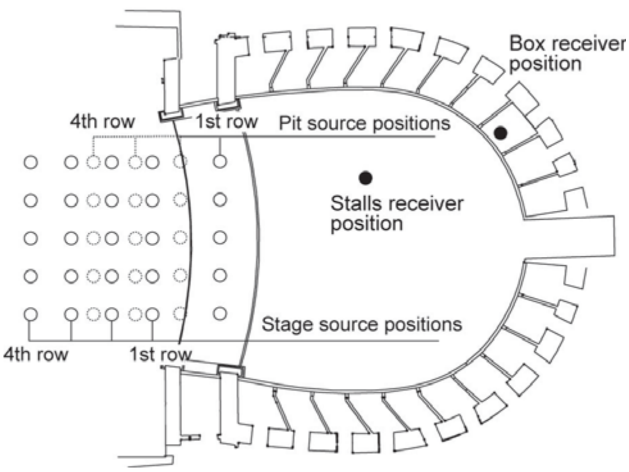

Fig. 2. Plan of the theater and arrangement of sound sources and receivers in the source varied condition (First measurement campaign).

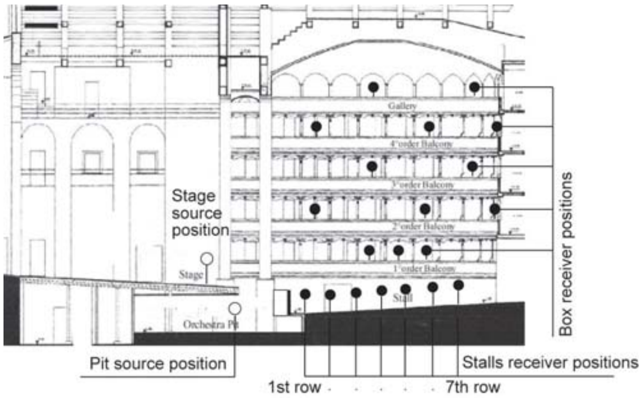

Fig. 3. Section of the theater and arrangement of sound sources and receivers in the receiver varied condition (Second measurement campaign).

and in 13 positions in the right sides of the boxes, as shown in Fig. 3 (receiver varied condition). The sound source on the stage was located 2 m away from the edge of the stage, and the sound source in the pit was placed 3.6 m away from the pit rail. The two source positions for the width dimension were located in the center. In each measurement, the direction in which the dummy head faces has been adjusted to the source position.

3. RESULTS

3.1. Attenuation of direct sound, ΔL

The direct sound is assumed to be the maximum peak of the impulse response in an interval of 1 ms starting from the first positive amplitude (see Fig. 4). The temporal origin of the arrival time is the moment of sound generation by the sound

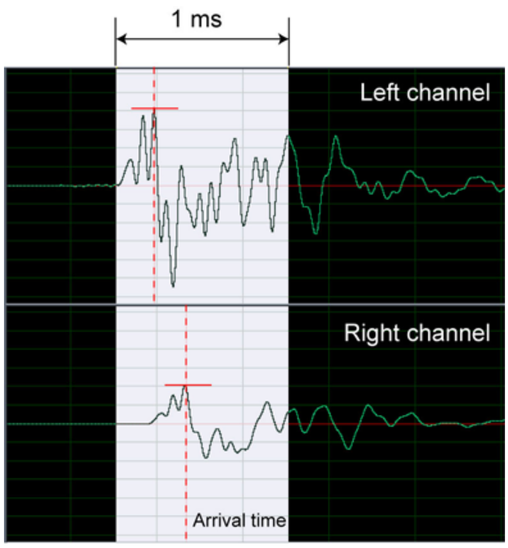

Fig. 4. Example of binaural impulse response around the arrival time of direct sound.

source.

In total, there are four combinations of sources and receivers: stage source - stall receiver; pit source - stall receiver; stage source - box receiver; and pit source - box receiver. In the following, for convenience, these cases are referred to as "*SS*," "*PS*," "*SB*," and "*PB*," respectively.

Figures 5 and 6 show the sound attenuation of direct sound, ΔL dB, as a function of the arrival time. ΔL means the attenuation of direct sound from the power level (*PWL*) of the original source. In case *SS* of the source varied condition (see Fig. 5), the direct sounds were attenuated as the arrival times increased, while the direct sounds in case *PS* were emphasized as the arrival time increased, in that case the amplification was +6.2 dB for the double-distance increase. This means that the sound source in the deeper position of the pit presented a stronger direct sound to the receiver. In case *SB*, the direct sound was not notably affected by the arrival time same as the distance. In case *PB*, there was a peak of ΔL connected with the sources in the 2nd row, which is the only path way connecting directly to the box receiver without any barriers such as the pit rail or the forestage.

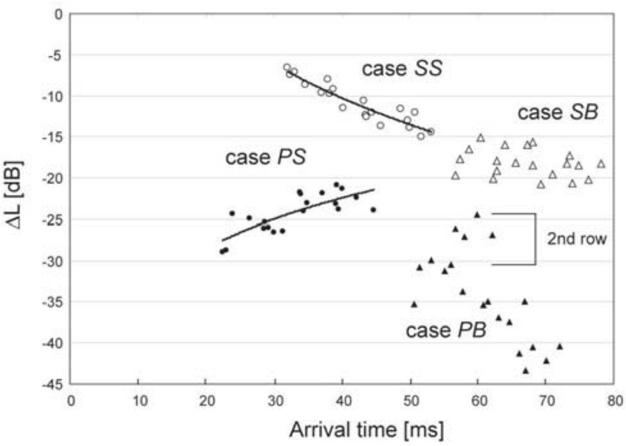

Fig. 5. ΔL as a function of the arrival time of direct sound in the source varied condition. The different symbols indicate cases *SS* (○), *PS* (●), *SB* (△), and *PB* (▲).

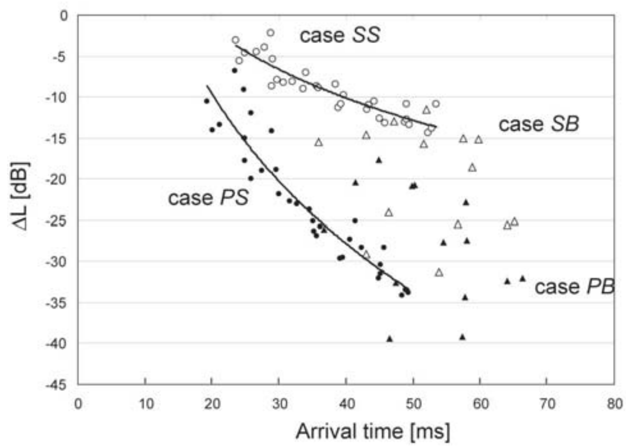

Fig. 6. ΔL as a function of the arrival time of direct sound in the receiver varied condition. The different symbols indicate cases *SS* (○), *PS* (●), *SB* (△), and *PB* (▲).

In the receiver varied condition (see Fig. 6), the direct sound in case *SS* was attenuated at a rate of –8.4 dB for the double-distance increase, like the sound attenuation in case *SS* of the source varied condition. The direct sound in case *PS* was also attenuated, but in a ratio of –18.2 dB for the double-distance. In both cases *SB* and *PB*, the attenuation of the direct sound was independent from the arrival time and the distance. In case *PB*, ΔL was more attenuated than in case *SB*.

Apart from the length of the sound pathway, the degree of attenuation seems to be dependent on the barrier effects of the pit and box rails. To investigate this effect, a new impulse response model for the edge diffraction from finite edges was carried out, inserting the geometrical relative data among the rail, source, and receiver [11]. Figures 7 and 8 compare the measured ΔL and the calculated ΔL by the Equation (1). For case *PS* (see Fig. 7), the relative locations of the source and

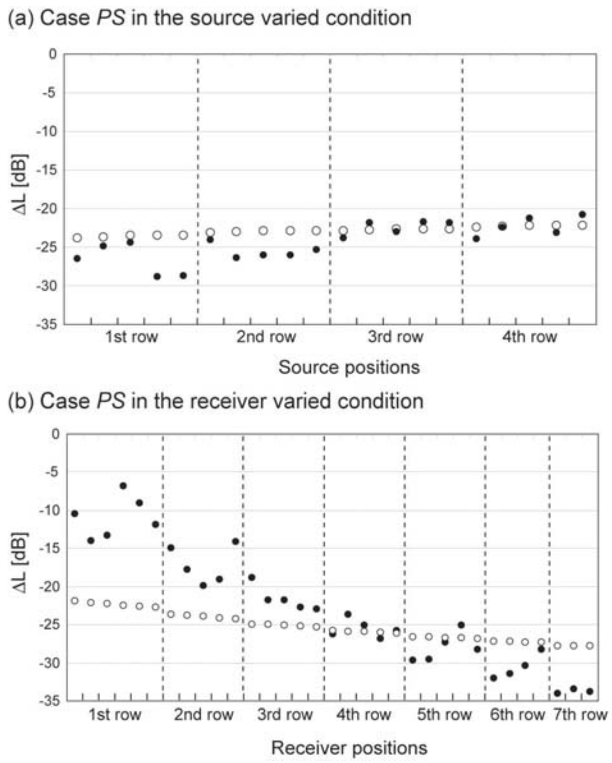

Fig. 7. Measured ΔL (●) and calculated ΔL (○) according to the source or receiver position. (a) Case *PS* in the source varied condition and (b) case *PS* in the receiver varied condition.

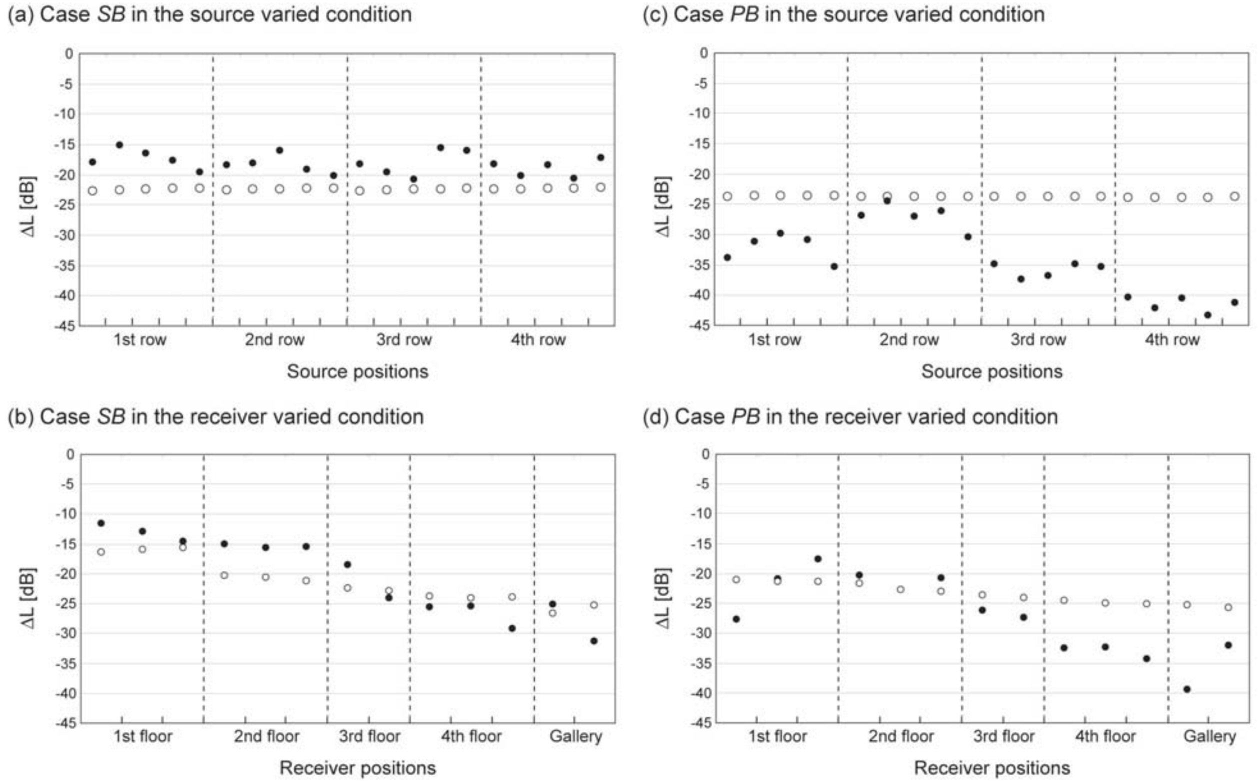

Fig. 8. Measured ΔL (●) and calculated ΔL (○) according to the source or receiver position. (a) Case *SB* in the source varied condition, (b) case *SB* in the receiver varied condition, (c) case *PB* in the source varied condition, and (d) case *PB* in the receiver varied condition.

receiver were based on the pit rail. In the source varied condition, the measured ΔL and the calculated ΔL had the same trend, and the values were close. In the receiver varied condition, however, the attenuation of the measured ΔL was more extreme than the attenuation of the calculated ΔL as the distance between the source and receiver was increased. Figure 8 indicates the results of the box receivers, and the relative locations of the source and receiver were based on the box rail. In case *SB* (see Figs. 8(a) and 8(b)), the diffraction model had a good relationship with the measured ΔL. In case *PB* (see Figs. 8(c) and 8(d)), the sound from the pit source arrived to the box receiver after receiving interference from not only the box rail but also the pit rail. In case *PB* of the source varied condition, the sound attenuations were predicted closely only for the sources in the 2nd row, because the sound pathways are maintained from these positions to the boxes without the barrier of the pit rail. In case *PB* of the receiver varied condition, the pit source under the pit opening is open toward the box receiver. However, the estimation errors were remarkably at variance for the box receivers located on the higher floors.

3.2. Relative strength, G_{re}

G_{re} is the ratio of an equivalent sound level measured in a hall using a sound source to an equivalent sound level that would be measured at the same distance from the source to the receiver in a free sound field. Different from the more well-known *G* (strength), the referent sound pressure is changed according to the distance between the source and the receiver. It is expressed by

$$G_{re} = 10\log_{10}\frac{\int_0^T p^2(t)dt}{\int_0^T p_x^2(t)dt} \quad \text{[dB]}. \tag{2}$$

In this study, p corresponds to the maximum pressure of the direct sound measured at the receiver position at x (in m.) from the source, and p_x corresponds to the theoretical pressure at x (in m.) in the free sound field, such as

$$p_x = \frac{\rho c}{4\pi x^2}W \qquad \text{[N/m}^2\text{]} \tag{3}$$

where ρc is an impedance of air, and W is an acoustical power of the sound source. The G_{re} of the direct sound indicates the sound attenuation (or reinforcement), with the exception of the attenuation by distance (e.g., barrier or focus).

In case *SS* of both conditions, the values of G_{re} were constant and close to 0 dB, although the source and receiver positions were changed. This is because the sound attenuation from the stage to the stalls depends largely on the distance. Except cases *SS*, Fig. 9 shows the G_{re} arranged as functions of elevation angle, which is looking up to either the pit rail or the box rails. The values of G_{re} had good correlation with the elevation angles, maintaining the relationship of

$$G_{re} = -35.5\theta_e \tag{4}$$

where θ_e is the elevation angle in radian ($R = 0.89$). The rear pit source positions (2nd, 3rd, and 4th rows) in case *PS* of the source varied condition, the concealed pit source position (3rd and 4th rows) in case *PB* of the source varied condition, and the rear stalls receiver (2nd to 7th rows) in case *PS* of the receiver varied condition were outside of the relationship trend.

Acoustical parameters, which are determined by an early-to-late arriving sound energy ratio, are dependent on G_{re}. Figure 10 shows the relationship between the G_{re} and the acoustical parameter, interaural cross-correlation coefficient (*IACC*), calculated from the binaural impulse responses. Appendix B explains the definition of the *IACC*. The values of the *IACC* remained around 0.1 when the values of G_{re} were below −15 dB, but in when G_{re} was more than −15 dB, the values increased in relation to the higher values of G_{re}. The G_{re} of −15 dB corresponds to the θ_e of 0.43 (25 degrees). Figure 11 illustrates the zones of the boxes in which the *IACC* is kept at low values.

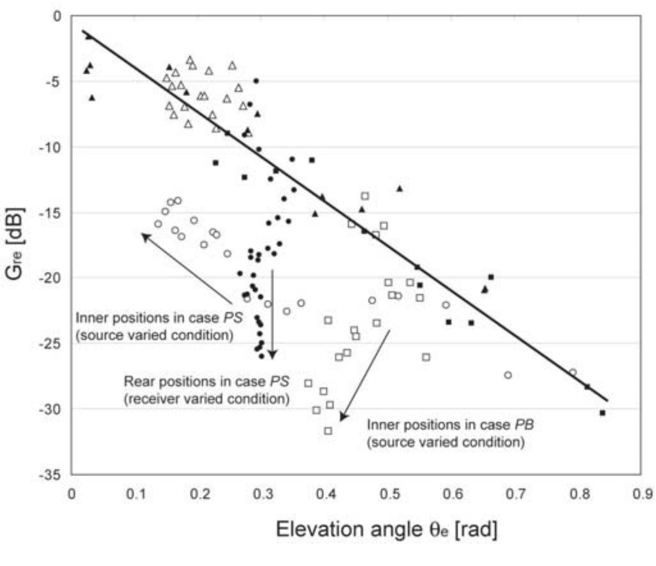

Fig. 9. G_{re} as a function of the elevation angle θ_e looking up the edge of the rails from the sources. The different symbols indicate cases *PS* (○), *SB* (△), and *PB* (□) of the source varied condition, and cases *PS* (●), *SB* (▲), and *PB* (■) of the receiver varied condition.

5. DISCUSSION AND CONCLUDING REMARKS

A direct sound emitted from a sound source arrives to a receiver in the shortest sound pathway. Thus, the decay of a direct sound measured by the receiver indicates distinct geometrical conditions and impedances of the sound propagation along the way. Traditional Italian opera houses are typically designed with horseshoe-shaped stalls and partitioned balconies around. In this study, in order to examine the various pathways of direct sound in such an Italian opera house, we obtained many impulse responses in the two measurement campaigns by changing 20 source positions, either on the stage or in the pit, and by changing 34 receiver positions in the stalls and 13 positions in the box areas. The attenuations of the direct sound pressures, ΔL, with respect to distance

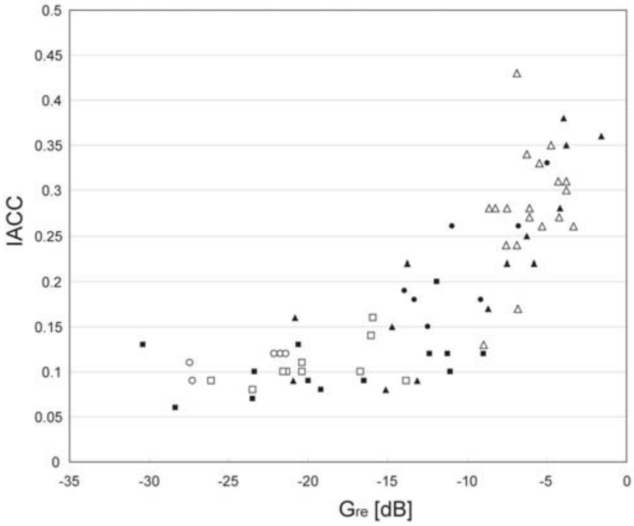

Fig. 10. *IACC* as a function of $G_{re.}$ The different symbols indicate cases *PS* (○), *SB* (△), and *PB* (□) of the source varied condition, and cases *PS* (●), *SB* (▲), and *PB* (■) of the receiver varied condition.

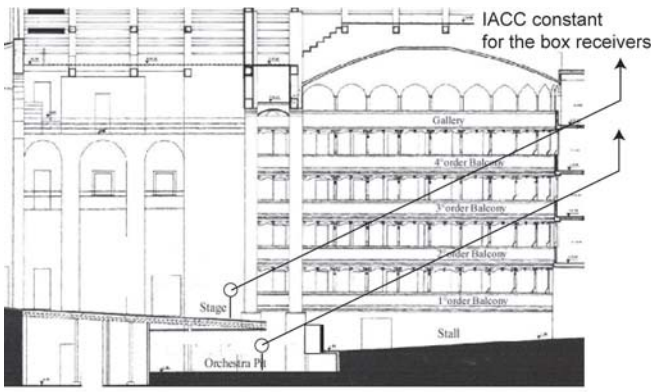

Fig. 11. Zones for which the *IACC* values remain low independent of the source positions and the box receiver positions.

were similar in case *SS* (stage to stalls) for both the source varied and receiver varied conditions. This result indicates that the sound intensity in case *SS* can be evaluated mainly by change in distance. On the other hand, in case *PS* (pit to stalls), sound pressures from the pit sources were found to be quite different between the two conditions. In the source varied condition, source positions further toward the pit presented higher sound pressures to the receiver located in the stalls, and in the receiver varied condition, the sound pressures were attenuated more extremely than in case *SS*. The ΔL for the box receivers, however, could not be characterized according to the distance. In case *PB* (pit to box) of the source varied condition, the direct sound pressure was the highest in the 2nd row positions, with direct propagation to box receivers without any barriers such as the pit rail or the forestage.

To estimate the diffraction loss by the pit and box rails, the impulse response model for the edge diffraction from finite edges, $h_{\mathrm{diffr}}(t)$, was applied using the geometrical conditions obtained from the auditorium CAD data. As shown in Figs. 7 and 8, according to this model estimation of the sound propagated in the opera house, the method showed good performance except for cases *PS* and *PB* of the receiver varied condition. Thus, it can be concluded that in opera houses it is difficult to predict the propagation of sound when influenced by the pit rail.

In contrast to $h_{\mathrm{diffr}}(t)$ calculated based on the location data, G_{re} is an acoustical parameter calculated from the measured impulse response. The value of G_{re} is related largely to the geometrical conditions surrounding the receiver position in particular [8], and therefore in this study it was useful to group results by geometrical angle for the estimation of the G_{re} in each box, as shown in Fig. 9. The G_{re} and the elevation angle toward the box rails had a linear relationship such as that in equation (4). This means that the sound pressure in the box receiver is determined almost solely by the elevation angle, measured from the source looking up to the box receiver. Since the lateral walls of boxes are arranged so that the boxes face toward the stage for viewing purposes (see Fig. 2), the elevation angle influences the value of G_{re} more than does the geometrical change for horizontal direction. For propagation from a pit source to a stalls receiver, G_{re} did not follow the relationship with the elevation angle, and the $h_{\mathrm{diffr}}(t)$ could not estimate the sound attenuation ΔL in the case *PS* of the receiver varied condition. Considering the much lower values of G_{re} for the more rear stalls receivers in the receiver varied condition (see Fig. 9), the sound passing through the pit opening most likely is greatly absorbed by the stalls seats.

The acoustical parameters related to the spatial impression (e.g. *IACC* and Lateral Fraction, *LF*, explained in Appendixes B and C) can be controlled by changing both direct and reflected sounds. In the case of concert halls, the direct sound is not modified by any obstacles, so the designs of lateral walls and ceilings are important to provide for many reflections to listeners for more spatial impression. It is natural that the apparent source width (*ASW*), one element of the spatial impression, becomes broader by a sound field with lower *IACC* and higher *SPL* [17]. In the case of opera houses, the pit rail limits direct sound propagation from the pit source. One role of the pit rail is to maintain the balance of *SPL* between singers and orchestral sounds [18]. Since a soloist sings together with the music played by a large orchestra, the sound field has to help the singer keeping the sound from the orchestra down. Due to the limitation of sound propagation, direct sounds were also attenuated; consequently, the values of *IACC* remained lower than 0.35, as shown in Fig. 10. The opera house should have a sufficiently dry sound field for sung words to be clearly heard. In a low-reverberant opera house, the pit and box rails contribute both to the balance of *SPL* and to subjective diffuseness. Although the reduction of sound propagation is not a healthy method for acoustics, a negative acoustical design is one of the solutions to blend quite different sound performances inside one hall.

According to the acoustical design theory of concert halls proposed by Ando, a sound field with a lower *IACC* better suits the preferences of listeners [19]. The G_{re} of direct sound extracted from the measured impulse response is an indicator of the diffuseness of sound propagation in the sound field, and it correlates with *IACC* as shown in Fig. 10. In particular, it is worth noting that the *IACC* remained at around 0.1 when G_{re} was lower than -15 dB, and that it increased as G_{re} increased above -15 dB. By equation (4), the critical angle corresponds to 25 degrees. For concert halls, the sight line is controlled at an elevation angle of 15 degrees (30 degrees in maximum); so, within the angular range, G_{re} and *IACC* have always a linear-positive relationship. The independent relationship seen in an elevation angle of more than 25 degrees is a special characteristic of the classic Italian opera house. When the Ando's preference theory was applied for opera houses, the preferred box positions based on the *IACC* were located in boxes with elevation angle of 25 degrees or higher measured from the sources to the edge of the box handrail. It is observed that the gallery seats (audience area higher than the 4th floor balcony, or the *loggione* in Italian) had better acoustics in terms both of low *IACC* and the strong reflection from the ceiling than the

1st floor box seats, even though gallery seat ticket prices are lower cost than those of box seats.

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Appendix A: Sine-swept Signal

The sine signal with exponential varied frequency is defined by a starting frequency ω_1 Hz, an ending frequency ω_2 Hz, and a total duration T s, as follows:

$$x(t) = \sin\left[\frac{\omega_1 t}{\log(\frac{\omega_2}{\omega_1})}\left(e^{\frac{t}{T}\log(\frac{\omega_2}{\omega_1})} - 1\right)\right] \qquad \text{(A1)}$$

In this measurement, the starting frequency (ω_1) and the ending frequency (ω_2) were 40 and 20000 Hz, respectively. The total duration (T) was 18 s.

Appendix B: Interaural Cross-Correlation Coefficient (*IACC*)

The *IACC* is defined as the maximum correlation of impulse responses arriving at the left and right ears, as shown below:

$$IACC = \left|\frac{\int_{-T}^{T} p_l(t)\,p_r(t-\tau)dt}{\sqrt{\int_{-T}^{T} p_l^2(t)dt\int_{-T}^{T} p_r^2(t)dt}}\right|_{\max} \quad |\tau| \le 1\ [\text{ms}] \qquad \text{(B1)}$$

where p_l(t) and p_r(t) are the sound pressures of impulse responses recorded at the left and right ear positions of the dummy head. When *IACC* is 1, a listener can perceive a clear direction of sound coming. When *IACC* approaches to 0, a listener can hear the sound but it is difficult to perceive the location of the sound source.

Appendix C: Lateral Fraction (*LF*)

This parameter shows the share of sound energy that arrives during the first 80 ms from lateral directions. It can be obtained from an omni-directional and figure-of-eight pattern microphones, and the definition is shown like

$$LF = \frac{\int_5^{80} P_L{}^2(t)dt}{\int_0^{80} P(t)dt} \qquad \text{(C1)}$$

where P(t) and P_L(t) are the sound pressures measured respectively by the omni-directional and by the figure-of-eight pattern microphones.

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