Acoustical measurements in "*Teatro Nuovo*" (Spoleto, Italy), changing sound source position in performance area

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Like in other Italian opera houses, "*Teatro Nuovo*" in Spoleto (Italy) has horse-shoe shaped stalls and boxes in the balconies; however, the ceiling of the hall presents a strongly concave shape, and the orchestra pit is extraordinary extensive in consequence of some reconstruction works in the past. These geometrical characteristics influence the acoustical field for performance, and we have explored it with a measurement campaign moving the source positions in the performance areas (20 sound source positions either in the stage or in the pit). From the results, it comes out that the values of acoustical parameters calculated from 20 binaural impulse responses (BIRs) are too various to represent only one mean source position like usual measurements putting many receiver positions in the audience spaces. Moreover, in *Teatro Nuovo*, the concaved ceiling modifies the strength of reflections from it according to the source positions, and the large but low orchestra pit (floor; 12.15×12.84 m^2 and height; 2.22 m) induces some resonance effects especially in the pit source positions covered by the forestage. The peculiar resonance can be visualized by introducing autocorrelation analysis of *BIR* after passing through the low-pass filtering (< 500 Hz). The acoustical parameters from the normalized *ACF* (Autocorrelation Function) of *BIR* would be useful to explain features of sound fields or to detect an acoustical problem like a flutter echo.

Keywords: Acoustical measurement, Italian opera house and performance area

1. INTRODUCTION

1.1. General Introduction

In Italian classical opera houses, there are two performance areas, a stage for singers and an orchestra pit for musicians. Normally the orchestra pit is located between the stage and the stalls in the plan and some limited area of the orchestra usually extends under the stage. In "*Teatro Nuovo*" in Spoleto (Italy) the orchestra pit is so extensive that its rear wall reaches as far as the middle position of the stage. In this study, owing to this characteristic of that opera house, the acoustical measurements for each of the two performance areas were carried out for 20 source positions; the stage and orchestra pit were sqared off, so obtaining a 2×2 m grid of 4 rows×5 columns, then the source was located in the crosses one after another. The binaural impulse responses (*BIRs*) from each source position towards two different receivers in the stalls and in a box were measured.

In a previous measurement campaign, the sound field from a source either in the stage or in the pit was investigated changing the receiver positions (8 receivers in the stalls and 29 in the boxes) [1]. Even recent studies of opera house's acoustical quality have been developed quite always from the point of view of the audience [2–4], and the parameters suited to evaluate this kind of acoustical quality of a theater have been standardized by ISO 3382 [5]. In usual measurements, acoustical responses from one sound source are recorded at some receiving positions to know the changes of acoustical parameters in the audience area, and in this course guidelines for acoustical measurements inside historical Italian opera houses have been proposed [6]. These guidelines suggest to put sound sources in several positions in the stage and in the pit, having in mind to get or preserve the acoustical quality both for the audience and performing areas. During a lyrical performance, singers are moving on the stage while several kinds of instruments are distributed in the orchestra pit; so, as *G* (Strength) and *EDT* (Early Decay Time) parameters show, different responses can be collected from the various source positions to the same receiving positions.

In this measurement campaign, the receiver either in the stalls or in the box is only in one position for the evaluations of the performance areas. The position in stalls was selected as one of those positions where some particular effect stood out during the previous measurement campaign [7]. In the first measurement of *Teatro Nuovo*, it was put in evidence that the sounds from the orchestra pit included some acoustical difficulties like a flutter echo. The orchestra pit of *Teatro Nuovo* is large; however the major part of it is concealed under the forestage, and this closed and limited area can be one cause of the acoustical difficulties.

1.2. Historical References

The idea of raising *Teatro Nuovo* begins to be materialized in 1853 when the task was committed to Ireneo Aleandri, a well known architect for his works in theater's planning, like the "*Sferisterio*" in Macerata, the Theater of *Ascoli Piceno* and the Theater of *San Severino* in the central part of Italy.

His collaboration with the architect Luigi Poletti contributed to the acoustical knowledge in theaters as reported in some documents of 1851 [8] and in many letters dealing with technical data about theaters (materials, shapes, proportions etc). It seems that, during his design work on Teatro Nuovo, Aleandri asked Poletti for some suggestions about planning problems regarding first of all architectural acoustics, but surely he didn't follow Poletti's thought about the shape of the ceiling of the main hall that was built much more concave than suggested. Aleandri studied also some documents of another architect in Mantova (Italy) dating back of almost two centuries, Fabricio Motta, who wrote one of the earliest textbooks about plans for theaters [9] with particular attention to acoustical aspects.

The idea to build a theater rose about seven years before (1846), when a group of townspeople decided to constitute a society aimed to produce, almost entirely, the building.

Teatro Nuovo in Spoleto opened in the 1864 in spite of some vicissitudes; the stalls plan are horse-shoe shaped in the style of the classical Italian opera house, and the frontage of the four box rows or orders faces directly to the stalls. The last box order was crowned by a loggia or a balcony, and the ceiling was connected to it by a kind of coupling called "*Vanvitelli*" style or "*Umbrella*", typical in that period (see Fig. 1). Boxes and loggia are located within a wooden structure made by beams and pillars starting from the lowest balcony's floor and rising until to the ceiling; the central sides of the beams are linked together by a curved wood structure supporting the ceiling frame (see Fig. 2).

Stalls, boxes and loggia can contain a maximum of 800 persons. This theatre is the main seat of an international classical music and ballet event called "*Two Worlds' Festival*", created and organized by Maestro Gian Carlo Menotti, and also seat of the "*Experimental Lyrical Theatre*", a kind of high school for lyrical singers, with competitions and experimental performances too.

Teatro Nuovo readjusting works have been carried out in different occasions, and the most striking changes were the reduction of the stage, so enlarging the orchestra place, in 1914 (see Fig. 3). Such a modification has probably damaged the good balancing between singer on the stage and orchestra in the pit: furthermore, now some musical instrument plays under a flat reflecting surface and some sound reach the stalls more than 0.5 seconds late than the direct one. This hypothesis is based on the fact that now the singers cannot reinforce their voices utilising the reflections from

Fig. 1. Audience area of *Teatro Nuovo* in Spoleto.

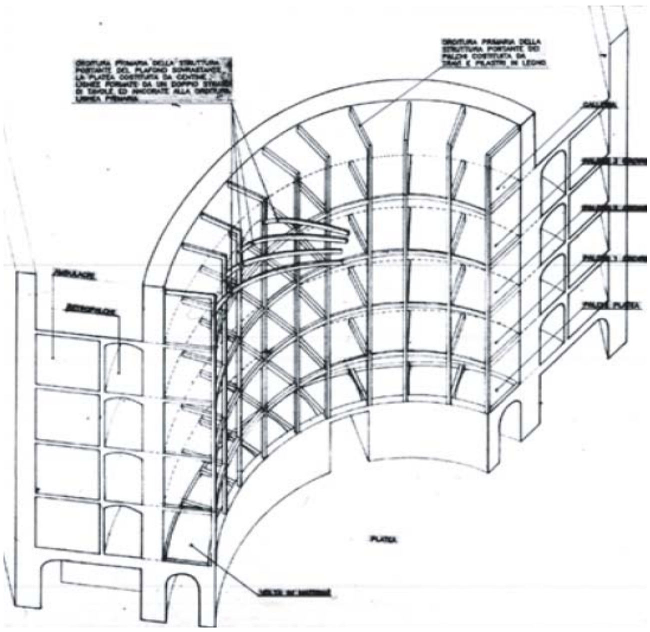


Fig. 2. Structure isometric view of the boxes wood frame and plafond.

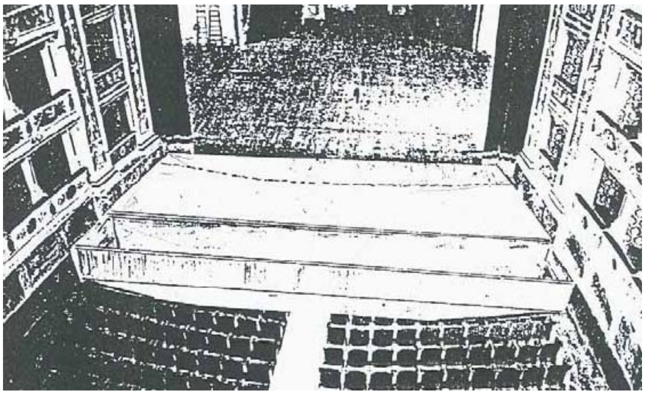


Fig. 3. Forestage and orchestra pit before 1914.

the proscenium arch, as they can not reach the best position for this result [1].

Additionally to these modifications, some other changes have been carried out. In 1933 all the original floors were renewed to withstand the new regulations for the building safety and then the stage has been dismantled to change its structure almost throughout substituting steel to wood. In 1950 the works started for the orchestra pit to extend its proper space in depth under the stage, until now when the official restoring works approved by the Regional Authorities are intended to give also some acoustical improvement.

2. ACOUSTICAL MEASUREMENTS

2.1. Measurement set up

To obtain binaural impulse responses, a logarithmically sine-swept FM chirp was generated by a PC [10] (see Appendix A). These sine-swept signals were emitted by an omni-directional loudspeaker put in the stage or in the orchestra pit. The responses were picked up by a dummy head with microphones in the left and right ear. When the source signals were generated and the responses were saved in the PC, a *Layla*24 board with AD/DA converters of 24 bit resolution employed the cording with a sampling rate 44.1 kHz and a 32-bit sampling size. The recorded responses hold information of reflections at boundaries for each harmonic distortion order separately. These responses were convoluted with an inverse filter that was a reversed sine-swept signal in terms of time, and the linear impulse responses were obtained immediately.

2.2. Arrangements of sound source and dummy head

In this measurement, the omni-directional sound source was located one by one in 20 positions on the stage and in 20 positions in the pit, arranged as shown in Fig. 4, while the receiver was located either in the stalls or in a box.

For sake of convenience, the 3-dimensions in the theater are named here as depth (front–rear for the audience in the stalls), width (left–right for it) and height (down–up for it). The floors of stage and orchestra pit were marked with a 2 m×2 m grid and the sound source was put one after another in the 5 (for the width direction)×4 positions (for the depth direction) as shown in Fig. 4(a). The frontal sources in the stage (*a*1–*a*5) and the frontal sources in the pit (*a*1–*a*5) were located in the 1st row (row *A*), and the followings in the 2nd row (*b*1–*b*5; row *B*), 3rd row (*c*1–*c*5; row *C*) and 4th row (*d*1–*d*5; row *D*) in order. The height of the sound source was 1.4 m in the stage and 1.2 m in the orchestra pit. The receiver in the stalls was put in the middle of the stalls (for the depth direction) and the right (for the width direction) as shown in Figs. 4(a) and 4(b). The box keeping the receiver was located in the rear (for the depth direction) and the right (for the width direction) at the third floor (for the height

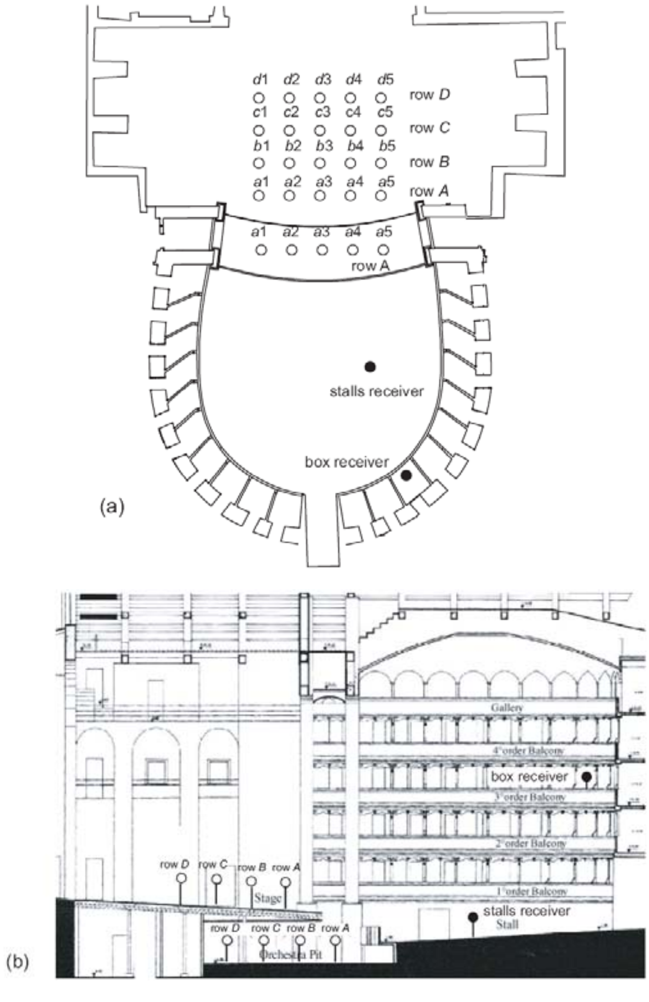


Fig. 4. Position of the sound sources and the receivers in (a) the plan and (b) the section.

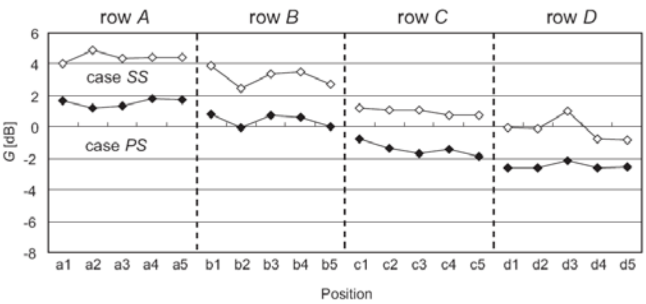
direction). In the box, the dummy head was brought near to the opening and chairs were moved close to the door. In each receiver position, the height of the dummy head above the floor level was 1.1 m in base of the ear position when a listener sits down. The face of dummy head was turned to the center of the stage during the measurements. The stage did not contain any scenery, and there were no musical instruments or chairs in the orchestra pit.

3. RESULTS AND DISCUSSION

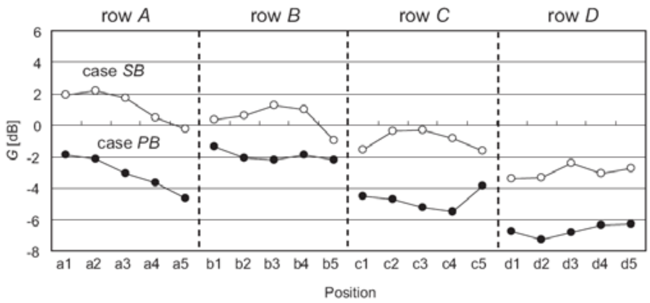
3.1. Acoustical Parameters

Having converted to 16 bit of resolution the 80 binaural impulse responses, they were analyzed using *Sound Analyzer* 5.0.5.2 to extract values for the selected acoustical param-

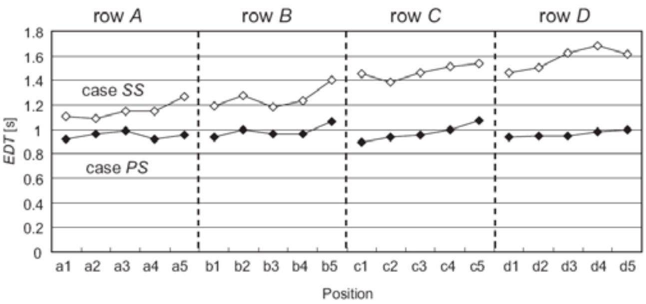
(a-1) *G* in the stalls receiver



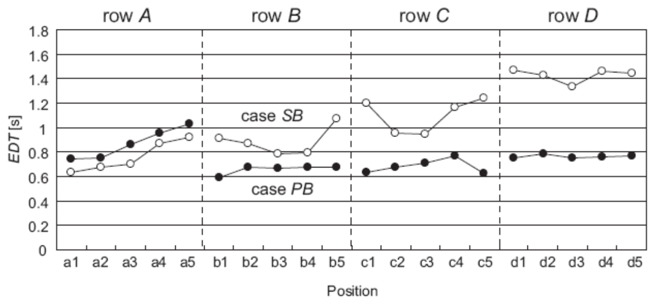
(a-2) *G* in the box receiver



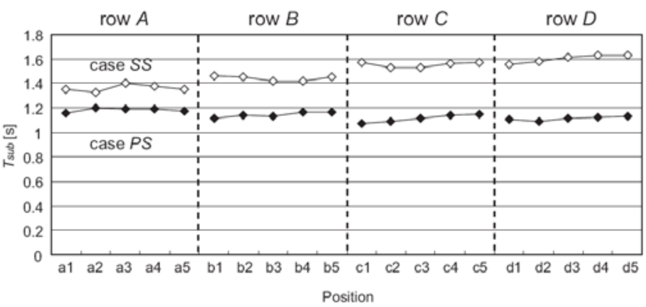
(b-1) *EDT* in the stalls receiver



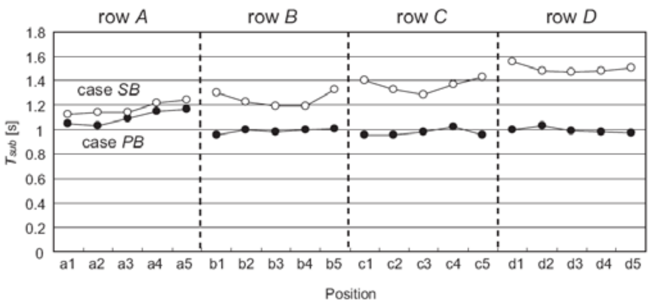
(b-2) *EDT* in the box receiver



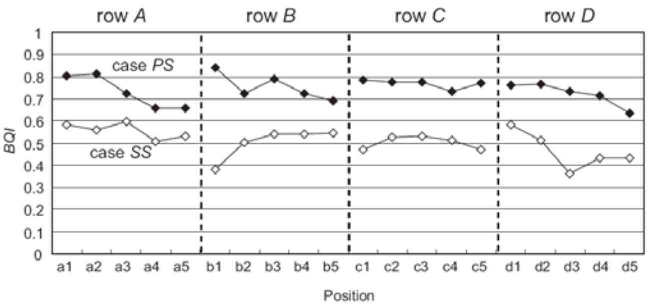
(c-1) T_{sub} in the stalls receiver



(c-2) T_{sub} in the box receiver



(d-1) *BQI* in the stalls receiver



(d-2) *BQI* in the box receiver

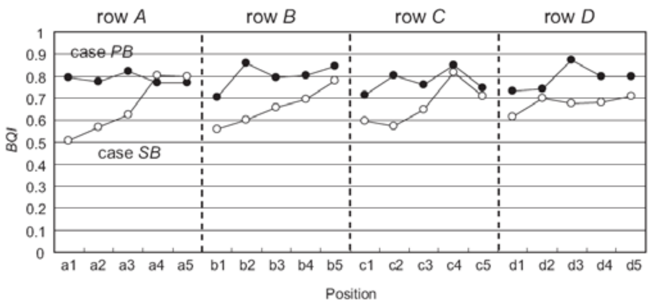


Fig. 5. Acoustical parameters as a function of source position. The acoustical parameters are (a) *G*, (b) *EDT*, (c) T_{sub}, and (d) *BQI*, and the symbols indicate the combinations among source positions and receiver positions "case *SS*" (◇), "case *PS*" (◆), "case *SB*" (○), and "case *PB*" (●).

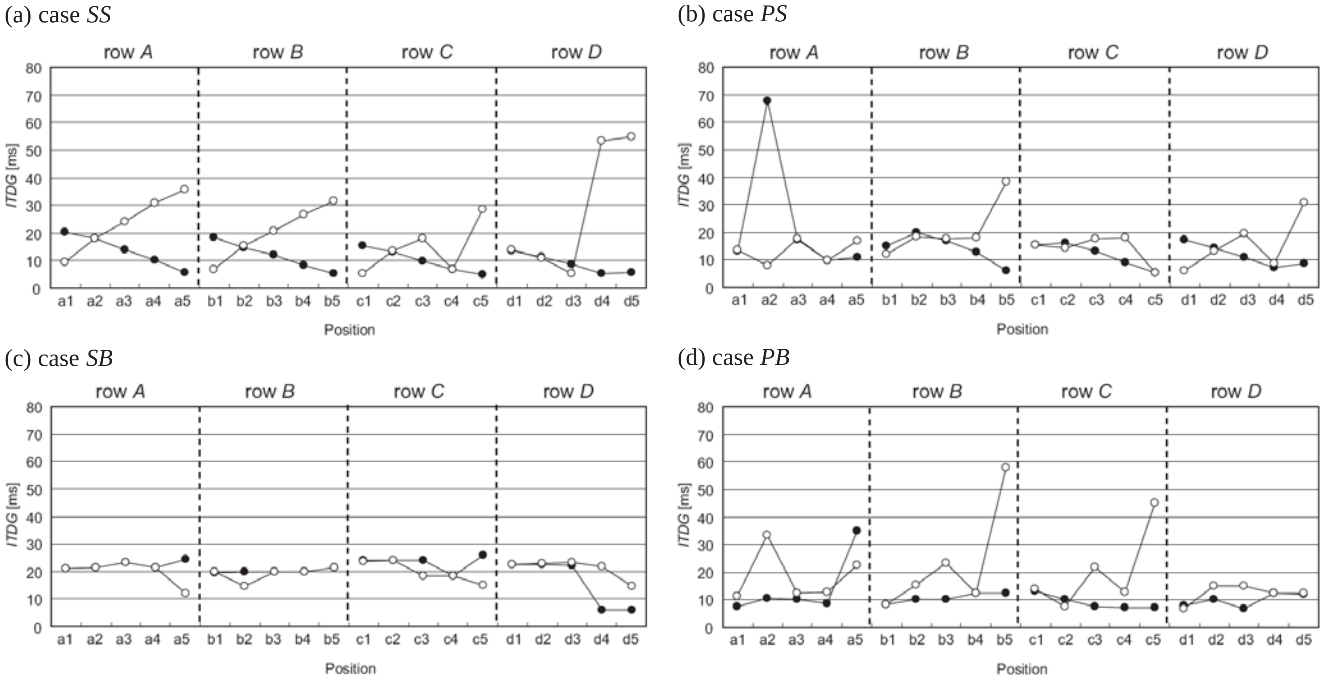


Fig. 6. Δt_1 as a function of source position in the different conditions of (a) "case *SS*", (b) "case *PS*", (c) "case *SB*", and (d) "case *PB*". The different symbols indicate the results recorded at left (○) and right (●) ears' positions of the dummy head.

eters. The acoustical factors used in this study are *G* (strength), *EDT* (Early Decay Time), T_{sub} (subsequent reverberation time), *BQI* (Binaural Quality Index), and Δt_1 (Initial Time Delay Gap). Except for *BQI* and Δt_1, all values of acoustical parameter are averaged among those calculated in left and right ears of the dummy head (see Fig. 5). For Δt_1, the difference of values in left and right ears is presented and discussed (see Fig. 6). The definition of each acoustical parameter is shortly described in the following Appendix B. Figures 5 and 6 show the results of acoustical parameters as a function of the stage and pit source positions.

The combinations among sources and receivers are 4, stage source–stalls receiver, pit source–stalls receiver, stage source–box receiver, and pit source–box receiver. In the following, for convenience, these cases are called "case *SS*", "case *PS*", "case *SB*", and "case *PB*", respectively.

G (strength)

The values *G* are larger in the case of source position in the stage (cases *SS* and *SB*) than in the pit (cases *PS* and *PB*) because the direct sound emitted by source in the stage can arrive at the receivers stronger than that coming from the pit, and the sound paths from the pit are not so widely diffused towards the hall to emphasize the *G* by many strong reflections, as confirmed by some geometrical situation not shown here: in fact, the wooden balustrade (pit rail in the following), that separates the stalls from the pit, and the plane of the stage covering the pit (see Figs. 3 and 4) interfere with sound coming from the pit and confer to this source a particular directivity. As the sources are separated from the receivers further, the value of *G* become smaller in the most cases. Only in the case *PB*, *G* of sound coming from the row *A* (1st row) is slightly lower than that from the row *B* (2nd row): the pit source in the row *A* is concealed to the box receiver by the pit rail, while the sound from the row *B* arrives to the box receiver directly. Differently from the stalls, the direct sound path is maintained from some *PB* position, so that the sound attenuation is not dependent only on the distance but also on the direction of sound path way from the pit opening.

And it is also worth to observe the change of *G* along the horizontal change in the row *A*. For the stalls receiver, the distribution of *G* seems quite independent from source positions, while the *G* measured at the box receiver is larger for the sound from the a1 than that from *a*5. Figure 7 shows the examples of binaural impulse responses measured in the case *SB*. In most of the responses, the largest reflections were recorded with the same delay; so that it seems possible to attribute these reflections to the same surface. When the sound speed is taken into account, the reflection delay corresponds to the difference of the path lengths between the direct sound and the reflection from the ceiling of the hall. The response

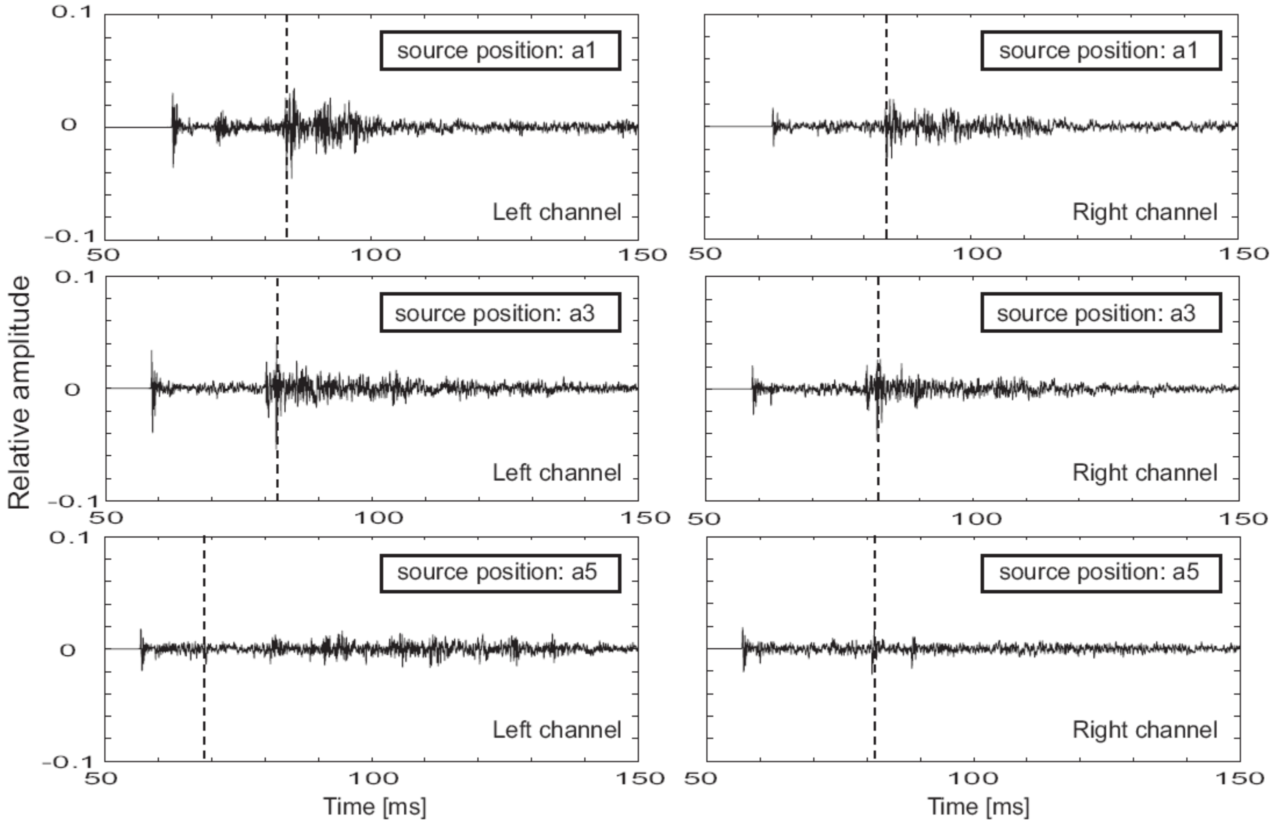


Fig. 7. Examples of binaural impulse responses measured in “case *SB*”.

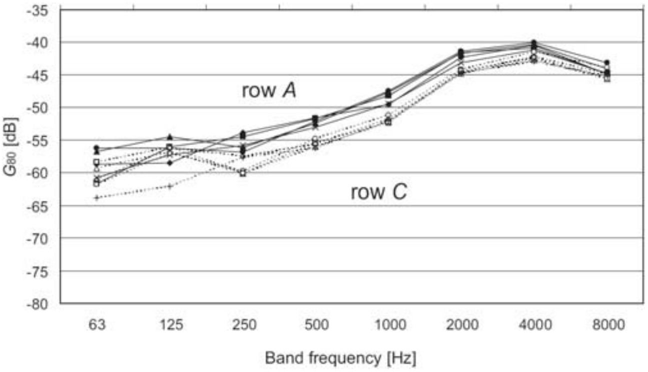
from *a*1 holds the larger reflection, while it is difficult to find the critical reflection in the response from *a*5. Unlike other traditional Italian opera houses, the ceiling of Teatro Nuovo presents a strongly concave shape as shown in Fig. 4(b); the so curved surface, unlike that suggested by Poletti, may lead to the inequality of sound strength in the box receiver according to the source positions.

As shown in Fig. 5(a-1), in the case *PS*, the strength is weakened as the source positions become far from the stalls receiver; on the other hand, in the case *PB* (Fig. 5a-2), the strength in row *B* is larger than that in row *A*, in disagreement with the sound attenuation by distance. Figures 8(a) and 8(b) show the spectral characteristics of G_{80} calculated in the early part (0 - 80 ms) of the *BIR* of the pit sources. The solid lines indicate the results in the row *A*, and the dot lines are the results in the row *C* in the case *PS* and the results in the row *B* in the case *PB*. In the case *PS*, G_{80} is compared between the row *A* under the pit opening (open area) and the row *C* under the forestage (closed area); and in the case *PB*, G_{80} is compared between the row *A* invisible from the box receiver by the pit rail (invisible area) and the row *B* visible from it (visible area). The row *D* is omitted in this discussion because the position is too deep in the orchestra pit to compare with the other rows. In the high frequency range, the values of G_{80} are decreased when the pit sources are in the row *C* in the case *PS* (closed area) and in the row *A* in the case *PB* (invisible area); however, in the low frequency range, the difference becomes obscure. The barrier effects of the pit rail and the forestage are effective in disturbing the propagation toward the box receiver in the high frequency. Although the sound strength is attenuated as the component frequency becomes lower, the increases of sound pressure at 125 Hz can be found in the row *C* in the case *PS* (see Fig. 8a).

EDT (Early Decay Time) and T_{sub} (subsequent reverberation time)

EDT and T_{sub} are factors related to the reverberation; so that their behaviors as a function of the row are similar each other as shown in Figs. 5(b) and 5(c), however some differences are observed among source-receiver positions in the values of *EDT*. Sounds from the stage source are more reverberate than those from the pit source, and sounds to the stalls receiver are more reverberate than those to the box receiver. These results may be related, from the point of view of the statistical acoustics, to the difference of volumes among the 4 acoustical rooms (stage, pit, stalls, and box). With the source in the deeper positions on the stage, reverberation goes on for longer time due to the high volume of the stage room. In

(a) case *PS*



(b) case *PB*

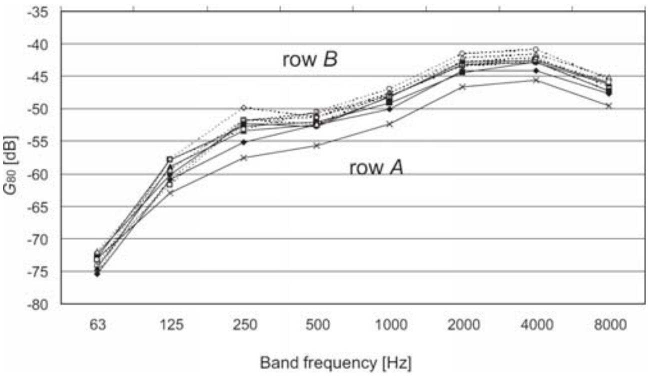


Fig. 8. G_{80} as a function of 1-octave bandpass frequency in the different conditions of (a) “case *PS*” in the row *A* (rigid line); *a*1 (●), *a*2 (▲), *a*3 (■), *a*4 (◆) and *a*5 (×) and in the row *C* (dot line); *c*1 (○), *c*2 (△) *c*3 (□), *c*4 (◇) and *c*5 (+), and (b) “case *PB*” in the row *A* (rigid line); *a*1 (●), *a*2 (▲), *a*3 (■), *a*4 (◆) and *a*5 (×) and in the row *B* (dot line); *b*1 (○), *b*2 (△) *b*3 (□), *b*4 (◇) and *b*5 (+).

the case *PS*, the reverberation time is not changed by the pit source positions; however, the spectral characteristics of the reverberation time change according to the pit source positions. Figure 9(a) shows the *EDT* from the row *A* (open area) and from the row *C* (closed area) in the case *PS* as a function of one-octave frequency bands; the *EDT* value in the closed area is shortened in the low frequency range, especially at 125 Hz, instead is extended in the middle and high frequency range from 1k to 8k Hz, due to the interference of standing waves with the low height of the deep pit.

The sounds from the pit to the box are more reverberated in the row *A* as shown in Figs. 5(b) and 5(c): since the pit sources in the row *A* are under the pit opening (open area), the pit sources are affected by the reverberant effect of the hall room and the reflections from the ceiling. Figure 9(b) shows the spectral characteristics of *EDT* in the box receiver from the open area (row *A*) and the closed area (row *C*) of the pit: it is evident that *EDT*s in the open area (row *A*) of the pit become longer uniformly for all frequency bands.

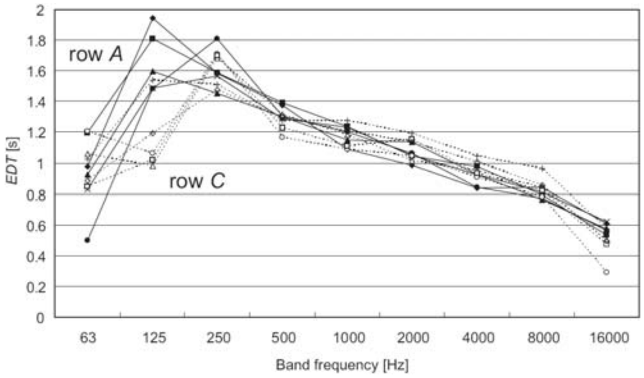
BQI (Binaural Quality Index)

The results of *BQI* show a difference between sounds from the stage and the pit. Regardless of the positions of receiver, the *BQI* from pit position is larger than that from stage position. The direct sounds from the pit sources are weakened by the barrier effect of the pit rail balustrade, so that in general it is more difficult to perceive the direction of sound coming from the orchestra pit, although some values for stage sources are larger than those for the pit sources in the case of the box receiver (see Fig. 5d-2).

Δt_1 (Initial Time Delay Gap)

Figure 6 shows the Δt_1 of all measurement conditions distinguishing results at the left and right ear of the dummy head. For the case *SS*, when the sound source is in the left side, Δt_1 at the left ear is shorter than that at the right ear, and when the sound source was right, Δt_1 at the right ear is shorter

(a) case *PS*



(b) case *PB*

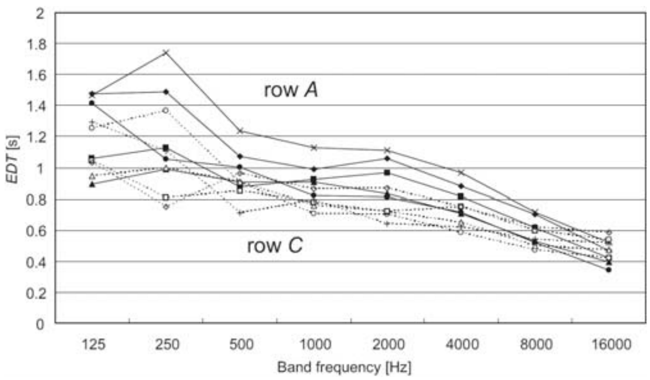


Fig. 9. *EDT* as a function of 1-octave bandpass frequency in the different conditions of (a) “case *PS*” and (b) “case *PB*” The symbols indicate the results in the row *A* (rigid line); *a*1 (●), *a*2 (▲), *a*3 (■), *a*4 (◆) and *a*5 (×) and in the row *C* (dot line); *c*1 (○), *c*2 (△) *c*3 (□), *c*4 (◇) and *c*5 (+). As the *EDT*s at 63 Hz for the box receiver are too long to extend the vertical axis of this figure extremely, only these values are removed for the reason of view.

than that at the left ear. From these results, it is evident that in this case the first reflection arrives from the lower lateral walls of the stalls basement. On the other hand, independently from the left-right source position, the first reflection from the stage source reaches the receiver in the box with the same delay of about 20 ms in Fig. 6(c); as mentioned in the discussion about *G*, the reflections may be radiated from the ceiling of the hall. For the pit sources, Δt_1 is not so clearly readable both for the stalls and box receivers, because it is difficult to find an early critical reflection in the *BIR* as chaotic reflections are repeated in the narrow orchestra pit.

3.2. Resonance in particular low frequency

3.2.1. Autocorrelation function (ACF) of binaural impulse response (BIR)

In *Teatro Nuovo* in Spoleto, some listeners placed in particular seats in the stalls give evidence that flutter echoes can be perceived when a sound source is in the orchestra pit; while researching in the selected place for stalls receiver, this effect was perceived even by the Authors. A flutter echo occurs when a sound source is put between two parallel and low-absorbing walls not so far to produce a real echo. Since the flutter echo is difficult to observe in a waveform of a signal, some researches support the usefulness of visualizing the echo by means of autocorrelation function of it [12-14]. The original signals in these investigations were a white noise and a bandpass noise; in this study we carried out the autocorrelation analysis of *BIR* after low pass filtering in order to detect the repetitive feature in a low particular frequency. The *BIR*s were low pass filtered (< 500 Hz) using

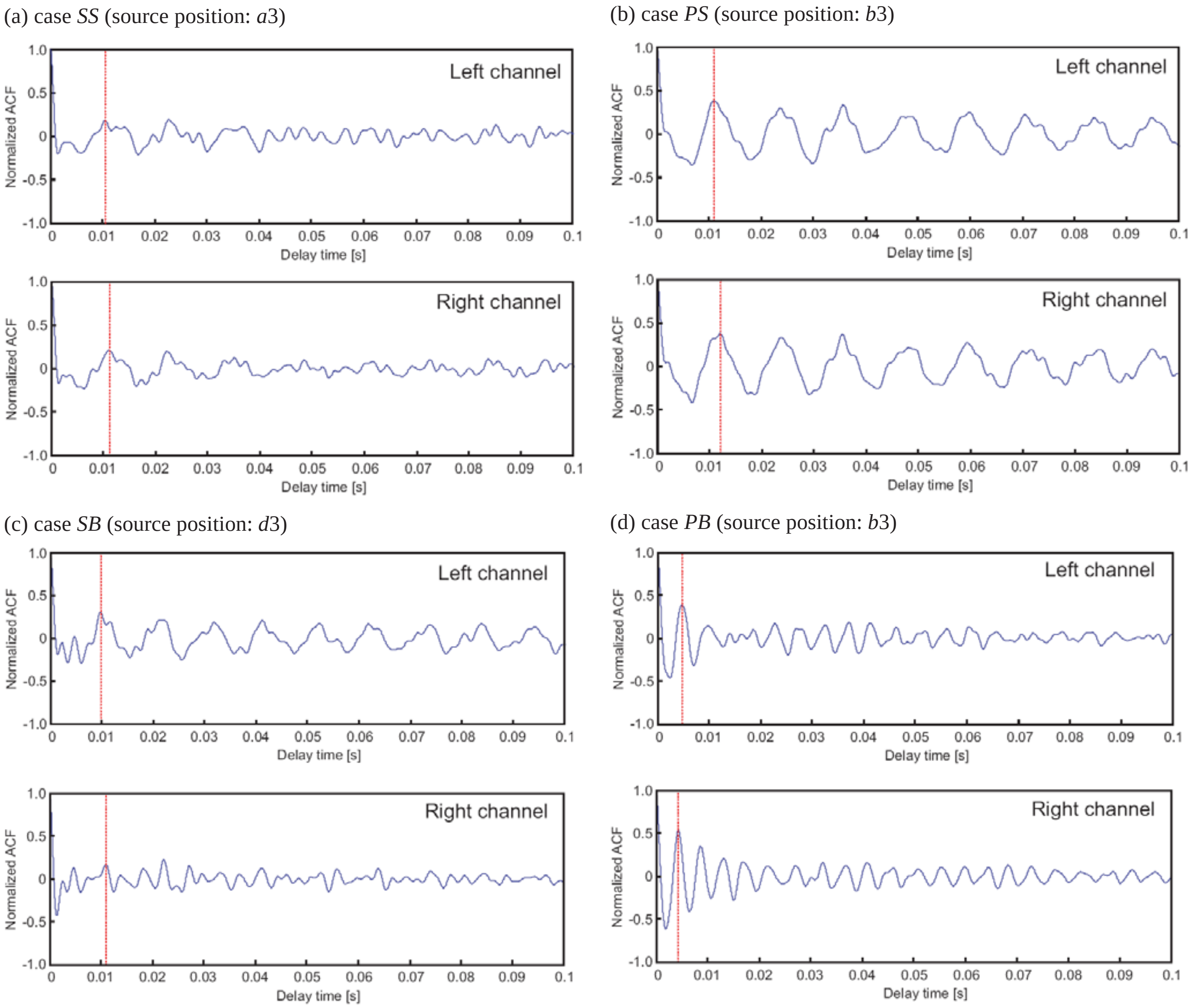
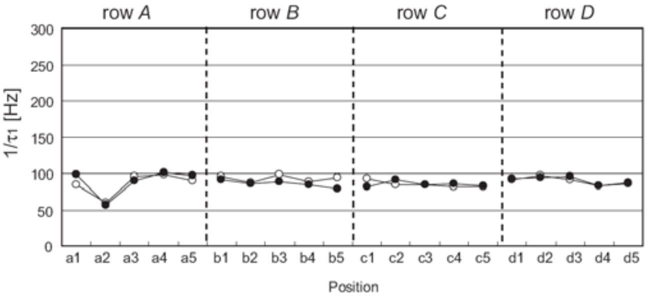


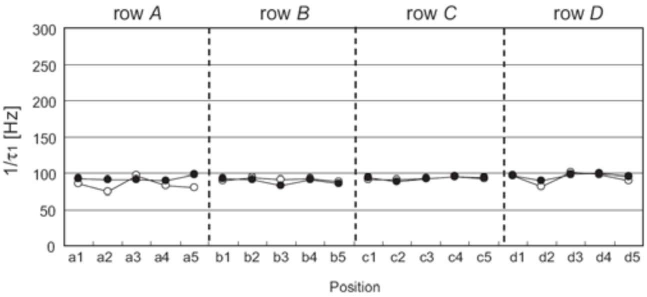
Fig. 10. Normalized *ACF* of binaural impulse response in the conditions of (a) “case *SS* (the source position: *a*3)”, (b) “case *PS* (*b*3)” (c) “case *SB* (*d*3)”, and (d) “case *PB* (*b*3)”. The dot line indicates τ_1.

the butterworth filtering algorithm (Order = 5), then the normalized autocorrelation functions (*ACF*s) were calculated. The definition of normalized *ACF* is shown in Appendix C. Figure 10 shows the normalized *ACF*s of *BIR*s only for the cases of the selected sources and the receivers. In all cases, periodical peaks of *ACF*s can be observed in the low frequency range of *BIR*. The repetitive feature is not found for a well-diffused sound field. Since both the orchestra pit and the box are small regularly shaped enclosures, it is possible that the geometrical conditions generate standing waves in them. The normal mode emphasizes the sound pressure in the normal frequency according to the geometrical condition of rooms, and the low emphasized repetition is the cause of

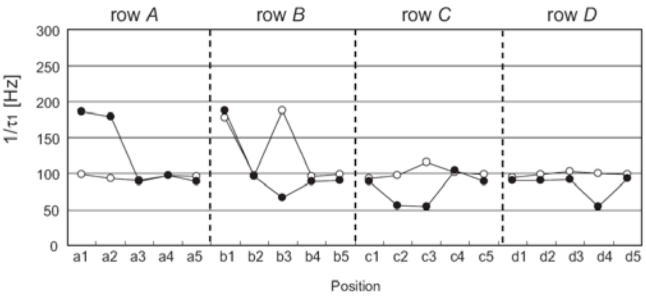
(a) case *SS*



(b) case *PS*



(c) case *SB*



(d) case *PB*

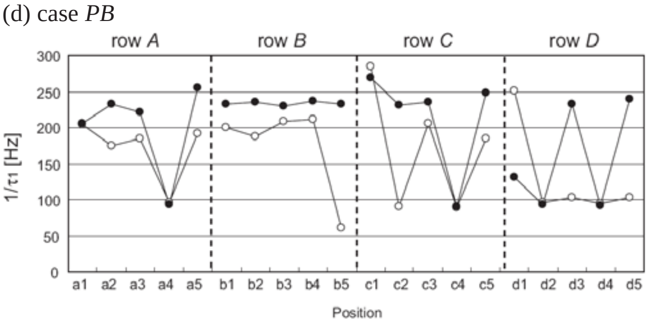
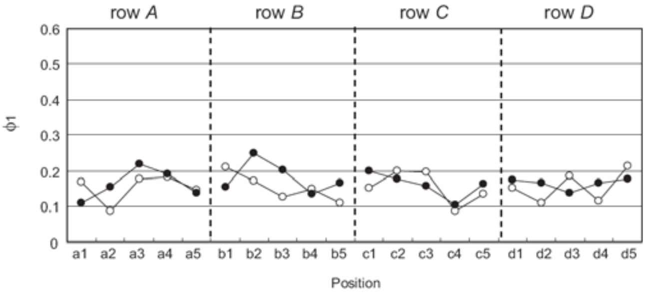
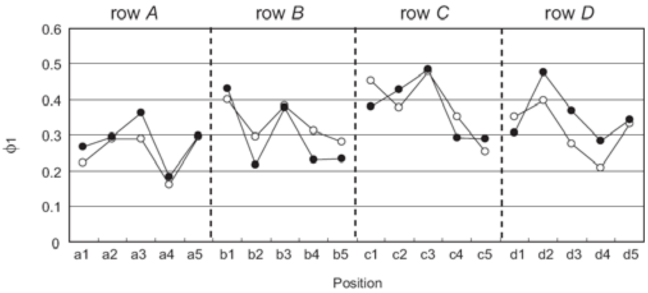


Fig. 11. $1/\tau_1$ as a function of source position in the different conditions (a) "case *SS*", (b) "case *PS*", (c) "case *SB*", and (d) "case *PB*". The different symbols indicate the results recorded at left (○) and right (●) ears positions of the dummy head.

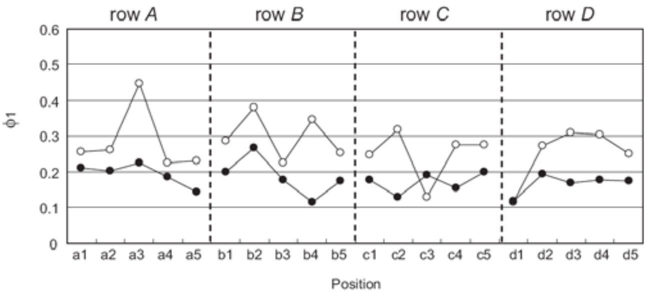
(a) case *SS*



(b) case *PS*



(c) case *SB*



(d) case *PB*

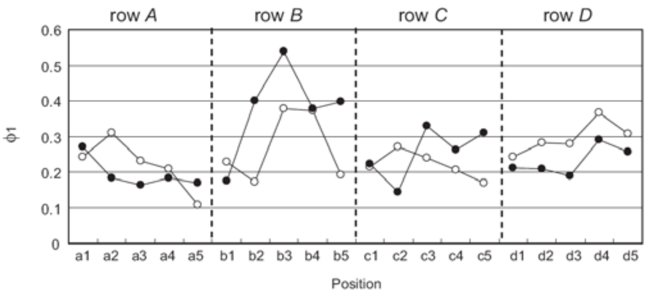


Fig. 12. ϕ_1 as a function of source position in the different conditions (a) "case *SS*", (b) "case *PS*", (c) "case *SB*", and (d) "case *PB*". The different symbols indicate the results recorded at left (○) and right (●) ears positions of the dummy

the perception of a little flutter echo, but the more evident effect is visible in Fig. 10(b), in the case *PS*, like it was possible to pick up while listening directly and according to people complains.

3.2.2. τ_1 and ϕ_1 in ACF

The delay time and the amplitude of the first peak in normalized ACF (τ_1 and ϕ_1) are corresponding to the pitch and the pitch strength of signal [11]. Atal et al. propose a criterion corresponding to a threshold of perceptible temporal coloration as $max[\Phi_s(\tau\neq0)]/\Phi_s(0)$ in Φ_s: short-time autocorrelation function [12]. As the *ACF* of *BIR* is attenuated simply as a function of delay time (see Fig. 10), the criterion can be equal to the ϕ_1. Figs. 11 and 12 show respectively the $1/\tau_1$ Hz and ϕ_1 in normalized ACF of BIR after passing thorough the low pass filtering (< 500 Hz). For $1/\tau_1$ in the stalls receiver (Figs. 11a and 11b), the values are quite all under 100 Hz. For $1/\tau_1$ in the box receiver (Figs. 11c and 11d), the values from the stage sources come together again mainly around 100 Hz; however the values from the pit sources are scattered between 100 Hz and 250 Hz. The ϕ_1s in the case *SS* are quoted around 0.16; while the ϕ_1s in the case *PS* are higher and grow up when the pit sources are in the inner part (row *C* and row *D*). The ϕ_1 in the case *SB* is not so influenced by the stage source position; while the ϕ_1 in the case *PB* are the highest in the row *B*. As the rises of ϕ_1 can be observed quite always in the cases with the pit sources, the reason must be searched in the shape of the orchestra pit which is constructed with a low ceiling (2.22 m) and an extensive floor (12.15×12.84 m^2). Only in some cases related to *PB*, the amplified frequency is around 200 Hz as shown Fig. 11(d). In this case, the mode production may be related additionally to other geometrical conditions like the proportion of the box room (height; 2.25 m, and floor; 2.14×1.67 m^2) or the height of the ceiling in the audience room (15.87 m).

These particular amplifications in low frequency have influences on the early part of G_{80} (strength) of the *BIR*. As shown in Fig. 8(a), the increase of G_{80} within the octave band centered on 125 Hz, when sound is coming from the closed area (row *C*) of pit to the stalls, might be caused by the low repetitive frequency under 100 Hz in the *BIR*.

3.3. Stage–pit balance based on G

The balance has been quantified by means of the difference of sound pressure level (*SPL*) for a receiver in the audience area when the same power level is emitted by two different sound sources either in the stage or in the pit. Barron [15] proposed the range between –0.9 and +4.5 dB as a good balance criterion based on the difference of *SPL* that audience can listen during opera performances.

Table 1 shows the difference of *G* between the stage and pit sources both for the stalls and box receivers. The colored zone indicates the combinations among two sources that are in the good balance criterion, from –0.9 to 4.5. For both receivers, the balance gets worse in the rear pit source positions (rows *C* and *D*). Especially in the frontal stage sources of the rows *A* and *B* where singers are usually standing during performances, balance of singings and music performed in the rear pit position is far from the good balance criterion. And for the box receiver (see Table 1b), there are some unbalanced combinations between the frontal stage sources (rows *A* and *B*) and the frontal pit sources (row *A*). The problem seems to be due respectively to the inequality of sound reflections from the curved ceiling and to the sound interception of the pit rail, as mentioned in the discussion about *G*.

4. CONCLUDING REMARKS

Broadly speaking, an Italian opera house is composed by a stage room, a pit room, a hall room and box rooms, and the combinations between the performance rooms and the audience rooms realize the different sound fields. The sound field from the stage source to the stalls receiver is close to the condition of sound field in concert halls; however the sound fields from the pit source is distinguished from it in terms of the sound propagation. The orchestra pit is a semi-closed small room, and the sound in it is radiated through the pit opening and some barrier effects and diffraction effects often result at the pit rail. Moreover the reflections backward and forward in it occasionally induce standing waves. In this study, the characteristics of sound propagations from the two kinds of performance areas (stage and pit) were observed by changing the source positions in them. The Italian opera house, *Teatro Nuvo* in Spoleto, holds the traditional Italian styles represented by the horse-shoe shaped stalls and the box audience room in the balcony; however, the area of orchestra pit is much more extensive than others, and the ceiling of the hall room is curved strongly in a concave shape. The large orchestra pit is suitable to put the sources in 40 positions.

The barrier effect of the pit rail has influences on the acoustical parameters measured in the stalls receiver. For the stalls receiver, *G* (strength) of the pit source is smaller than that of

Table 1. Balance of G between the stage source and the pit source. The bold values are the combinations of sources that satisfy the good balance criterion proposed by Barron [15].

(a) For stalls receiver

			Pit source position																			
			row A					row B					row C					row D				
			1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Stage source position	row A	1	**2.3**	**2.8**	**2.6**	**2.2**	**2.3**	**3.2**	**4.0**	**3.3**	**3.4**	**4.0**	4.8	5.4	5.7	5.4	5.9	6.6	6.6	6.1	6.6	6.5
		2	**3.2**	**3.6**	**3.5**	**3.1**	**3.1**	**4.1**	4.9	**4.1**	**4.3**	4.9	5.6	6.2	6.6	6.3	6.7	7.5	7.5	7.0	7.5	7.4
		3	**2.7**	**3.1**	**3.0**	**2.6**	**2.6**	**3.5**	**4.4**	**3.6**	**3.8**	**4.3**	5.1	5.7	6.0	5.7	6.2	7.0	7.0	6.5	6.9	6.9
		4	**2.7**	**3.2**	**3.0**	**2.6**	**2.7**	**3.6**	**4.4**	**3.7**	**3.8**	**4.4**	5.2	5.8	6.1	5.8	6.3	7.0	7.0	6.5	7.0	6.9
		5	**2.8**	**3.2**	**3.1**	**2.7**	**2.7**	**3.7**	**4.5**	3.7	3.9	**4.5**	5.2	5.8	6.2	5.9	6.3	7.1	7.1	6.6	7.1	7.0
	row B	1	**2.2**	**2.7**	**2.5**	**2.1**	**2.2**	**3.1**	**3.9**	**3.1**	**3.3**	**3.9**	4.7	5.2	5.6	5.3	5.8	6.5	6.5	6.0	6.5	6.4
		2	**0.8**	**1.2**	**1.1**	**0.6**	**0.7**	**1.6**	**2.5**	**1.7**	**1.8**	**2.4**	**3.2**	**3.8**	**4.1**	**3.8**	**4.3**	5.1	5.1	4.5	5.0	4.9
		3	**1.7**	**2.2**	**2.0**	**1.6**	**1.7**	**2.6**	**3.4**	**2.6**	**2.8**	**3.4**	**4.2**	4.7	5.1	4.8	5.3	6.0	6.0	5.5	6.0	5.9
		4	**1.8**	**2.2**	**2.1**	**1.7**	**1.8**	**2.7**	**3.5**	**2.7**	**2.9**	**3.5**	**4.3**	4.8	5.2	4.9	5.3	6.1	6.1	5.6	6.1	6.0
		5	**1.0**	**1.5**	**1.4**	**0.9**	**1.0**	**1.9**	**2.7**	**2.0**	**2.1**	**2.7**	**3.5**	**4.1**	**4.4**	**4.1**	4.6	5.3	5.4	4.8	5.3	5.2
	row C	1	**-0.5**	**0.0**	**-0.2**	**-0.6**	**-0.5**	**0.4**	**1.2**	**0.5**	**0.6**	**1.2**	**2.0**	**2.5**	**2.9**	**2.6**	**3.1**	**3.8**	**3.8**	**3.3**	**3.8**	**3.7**
		2	**-0.6**	**-0.2**	**-0.3**	**-0.7**	**-0.6**	**0.3**	**1.1**	**0.3**	**0.5**	**1.1**	**1.9**	**2.4**	**2.8**	**2.5**	**2.9**	**3.7**	**3.7**	**3.2**	**3.7**	**3.6**
		3	**-0.6**	**-0.2**	**-0.3**	**-0.7**	**-0.7**	**0.3**	**1.1**	**0.3**	**0.5**	**1.1**	**1.8**	**2.4**	**2.8**	**2.4**	**2.9**	**3.7**	**3.7**	**3.2**	**3.7**	**3.6**
		4	-0.9	**-0.5**	**-0.6**	-1.0	-1.0	**0.0**	**0.8**	**0.0**	**0.2**	**0.8**	**1.5**	**2.1**	**2.5**	**2.2**	**2.6**	**3.4**	**3.4**	**2.9**	**3.4**	**3.3**
		5	-0.9	**-0.5**	**-0.6**	-1.0	-1.0	**-0.1**	**0.8**	**0.0**	**0.2**	**0.8**	**1.5**	**2.1**	**2.5**	**2.1**	**2.6**	**3.4**	**3.4**	**2.9**	**3.4**	**3.3**
	row D	1	-1.7	-1.3	-1.4	-1.9	-1.8	**-0.9**	**0.0**	**-0.8**	**-0.7**	**-0.1**	**0.7**	**1.3**	**1.6**	**1.3**	**1.8**	**2.6**	**2.6**	**2.1**	**2.5**	**2.5**
		2	-1.8	-1.4	-1.5	-1.9	-1.8	-0.9	**-0.1**	**-0.9**	**-0.7**	**-0.1**	**0.7**	**1.2**	**1.6**	**1.3**	**1.7**	**2.5**	**2.5**	**2.0**	**2.5**	**2.4**
		3	**-0.7**	**-0.2**	**-0.3**	**-0.8**	**-0.7**	**0.2**	**1.1**	**0.3**	**0.4**	**1.0**	**1.8**	**2.4**	**2.7**	**2.4**	**2.9**	**3.7**	**3.7**	**3.1**	**3.6**	**3.5**
		4	-2.5	-2.0	-2.2	-2.6	-2.5	-1.6	**-0.8**	-1.5	-1.4	**-0.8**	**0.0**	**0.6**	**0.9**	**0.6**	**1.1**	**1.8**	**1.9**	**1.3**	**1.8**	**1.7**
		5	-2.5	-2.1	-2.2	-2.6	-2.6	-1.7	**-0.8**	-1.6	-1.4	**-0.9**	**-0.1**	**0.5**	**0.9**	**0.5**	**1.0**	**1.8**	**1.8**	**1.3**	**1.8**	**1.7**

(b) For the box receiver

			Pit source position																			
			row A					row B					row C					row D				
			1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Stage source position	row A	1	**3.8**	**4.1**	5.0	5.6	6.6	**3.3**	**4.0**	**4.1**	**3.8**	**4.1**	6.5	6.6	7.2	7.4	5.8	8.7	9.2	8.7	8.3	8.2
		2	**4.1**	**4.4**	5.3	5.8	6.9	**3.6**	**4.3**	**4.4**	**4.1**	**4.4**	6.8	6.9	7.5	7.7	6.1	9.0	9.5	9.0	8.5	8.5
		3	**3.6**	**3.9**	4.8	5.4	6.4	**3.1**	**3.8**	**3.9**	**3.6**	**3.9**	6.3	6.4	7.0	7.2	5.6	8.5	9.0	8.5	8.1	8.0
		4	**2.4**	**2.7**	**3.6**	**4.1**	5.2	**1.9**	**2.6**	**2.7**	**2.4**	**2.7**	5.1	5.2	5.8	6.0	**4.4**	7.3	7.8	7.3	6.8	6.8
		5	**1.6**	**1.9**	**2.8**	**3.4**	4.4	**1.1**	**1.9**	**2.0**	**1.6**	**1.9**	**4.3**	**4.4**	5.0	5.2	**3.6**	6.5	7.0	6.5	6.1	6.0
	row B	1	**2.2**	**2.5**	**3.4**	**4.0**	5.0	**1.7**	**2.5**	**2.6**	**2.2**	**2.5**	4.9	5.0	5.6	5.8	**4.2**	7.1	7.6	7.1	6.7	6.6
		2	**2.5**	**2.8**	**3.7**	**4.3**	5.3	**2.0**	**2.8**	**2.9**	**2.5**	**2.8**	5.2	5.3	5.9	6.1	**4.5**	7.4	7.9	7.4	7.0	6.9
		3	**3.2**	**3.5**	**4.4**	4.9	6.0	**2.6**	**3.4**	**3.5**	**3.2**	**3.5**	5.8	6.0	6.6	6.8	5.2	8.1	8.6	8.1	7.6	7.6
		4	**2.9**	**3.2**	**4.1**	4.6	5.6	**2.3**	**3.1**	**3.2**	**2.9**	**3.2**	5.5	5.7	6.2	6.5	4.8	7.7	8.3	7.8	7.3	7.3
		5	**0.9**	**1.2**	**2.1**	**2.7**	**4.4**	**0.4**	**1.1**	**1.2**	**0.9**	**1.2**	**3.6**	**3.7**	**4.3**	4.5	**2.9**	5.8	6.3	5.8	5.4	5.3
	row C	1	**0.3**	**0.6**	**1.5**	**2.1**	**3.1**	**-0.2**	**0.6**	**0.7**	**0.3**	**0.6**	**3.0**	**3.1**	**3.7**	**3.9**	**2.3**	5.2	5.7	5.2	4.8	4.7
		2	**1.5**	**1.8**	**2.7**	**3.2**	**4.3**	**0.9**	**1.7**	**1.8**	**1.5**	**1.8**	**4.1**	**4.3**	4.9	5.1	**3.5**	6.4	6.9	6.4	5.9	5.9
		3	**1.6**	**1.9**	**2.7**	**3.3**	**4.3**	**1.0**	**1.8**	**1.9**	**1.6**	**1.9**	**4.2**	**4.4**	4.9	5.2	**3.5**	6.4	7.0	6.5	6.0	5.9
		4	**1.1**	**1.4**	**2.3**	**2.8**	**3.8**	**0.5**	**1.3**	**1.4**	**1.1**	**1.4**	**3.7**	**3.9**	**4.5**	4.7	**3.1**	6.0	6.5	6.0	5.5	5.5
		5	**0.2**	**0.5**	**1.4**	**2.0**	**3.0**	**-0.3**	**0.5**	**0.6**	**0.3**	**0.5**	**2.9**	**3.1**	**3.6**	**3.8**	**2.2**	5.1	5.6	5.1	4.7	4.6
	row D	1	-1.5	-1.2	**-0.3**	**0.2**	**1.2**	-2.1	-1.3	-1.2	-1.5	-1.2	**1.1**	**1.3**	**1.9**	**2.1**	**0.5**	**3.4**	**3.9**	**3.4**	**2.9**	**2.9**
		2	-1.5	-1.2	**-0.3**	**0.3**	**1.3**	-2.0	-1.2	-1.1	-1.4	-1.2	**1.2**	**1.4**	**1.9**	**2.2**	**0.5**	**3.4**	**4.0**	**3.5**	**3.0**	**2.9**
		3	**-0.6**	**-0.3**	**0.6**	**1.2**	**2.2**	-1.1	**-0.3**	**-0.2**	**-0.5**	**-0.3**	**2.1**	**2.3**	**2.8**	**3.1**	**1.4**	**4.3**	**4.9**	**4.4**	**3.9**	**3.8**
		4	-1.2	**-0.9**	**0.0**	**0.6**	**1.6**	-1.7	-0.9	**-0.8**	-1.1	**-0.9**	**1.5**	**1.7**	**2.2**	**2.5**	**0.8**	**3.7**	**4.3**	**3.8**	**3.3**	**3.2**
		5	**-0.9**	**-0.6**	**0.3**	**0.9**	**1.9**	-1.4	**-0.7**	**-0.6**	**-0.9**	**-0.6**	**1.8**	**1.9**	**2.5**	**2.7**	**1.1**	**4.0**	**4.5**	**4.0**	**3.6**	**3.5**

the stage source, and *BQI* (Binaural Quality Index) of the pit is higher than that of the stage source because of obstructing the direct sound arriving. However, in fact, the restraint of sound propagation at the pit rail plays an important role to control the balance of *G* between the stage source and the pit source for the stalls receiver, although the orchestra pit of *Teatro Nuovo* is so extensive that the control of balance is not satisfactory in the most rear pit source positions.

On the other hand, for the box receiver, the geometrical relation between the pit opening and the pit source position is important to determine the sound characteristics. *G* of the pit becomes larger when the box receiver is visible from the pit source positions thorough the pit opening, and *EDT* (Early Decay Time) is longer when the pit source is put under the pit opening. And as the early and strong reflections from the ceiling of hall arrive to the box receiver, the values of *G* are affected also by the relationship of positions among the source, the ceiling, and the receiver. Since the ceiling of *Teatro Nuovo* has the strongly concaved shape, the reflections presented from some source positions are brought into focus. For example, the stage source positions in the same side of the box receiver (e.g. *a*4 and *a*5 in Fig. 5) produce faint reflections from the ceiling (see Fig. 7); as a result the values of *BQI* become larger in these positions (see Fig. 5d-2). The lack of uniformity of *G* causes the unbalance of the stage and pit sources for listeners in the box.

Finally we mention a normal mode possible to occur in small regularly shaped enclosure like an orchestra pit. As the amplification of low frequency is difficult to detect directly from the *BIR*, normalized *ACF* (Autocorrelation function) of *BIR* after passing through the low-pass filtering (< 500 Hz) was carried out, and the parameters extracted from the *ACF* are presented to explain the normal mode phenomenon in the pit. As results, clear periodical peaks can be observed in the normalized *ACF* especially from *BIR* of the pit sources. In this study, the delay time τ_1 and the amplitude ϕ_1 of the first peak in normalized *ACF* seem to be corresponding respectively to the normal frequency in the normal mode and to the strength of the normal frequency, and these parameters would have a good relationship with personal impressions of listening people. Not only the acoustical parameters from *BIR*, but also the parameters from normalized *ACF* of *BIR* seem to be an available and useful method supporting geometrical designs of the orchestra pit.

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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 like that

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

In this measurement, the stating frequency (ω_1) and the ending frequency (ω_2) were 40 and 20k Hz respectively. The total duration (*T*) was 18 s.

In comparison with MLS (Maximum Length Sequence) signal, the sine-swept signal is less dependent on minor time-variance of the system and on mismatch between the sampling clock of the signal generation and recording, so that simple and fast measurements are archived.

APPENDIX B; SHORT DEFINITION OF SOME ACOUSTICAL OBJECTIVE PARAMETERS

G (strength)

It is the ratio of an equivalent sound level measured in a hall using an omni-directional sound source to an equivalent sound level that would be measured at a distance of 10 m from the same sound source propagating in a free sound field. When sound pressure of the reference is defined by $p_{10}(t)$, the equation of *G* is

$$G = 10\log_{10}\frac{\int_0^T p^2(t)dt}{\int_0^T p_{10}^2(t)dt} \text{ dB.} \tag{B1}$$

The integration time (*T*) is 3 s in this calculation. When *T* is limited in 80 ms, the value is distinguished as G_{80}.

EDT (Early Decay Time) and T_{sub} (subsequent reverberation time)

EDT is the reverberation time obtained by a regression during the first 10 dB of sound decay. Beranek (2003) emphasizes the usefulness of the initial attenuation to qualify concert halls because most symphonic compositions include successive notes changing rapidly [16]. On the other hand, T_{sub} is the reverberation time calculated by the attenuation of the first maximum reflection at Δt_1. The preference tests produced by Ando (1998) also show the good correlation between subjective preference and musical motifs with different T_{sub} [11].

***BQI* (Binaural Quality Index)**

BQI is the only binaural acoustical parameter in this paper. We define *IACC* as the maximum correlation of impulse responses arriving at left and right ears as shown

$$IACC = \left| \frac{\int_{-T}^{T} p_l(t) p_r(t-\tau) dt}{\sqrt{\int_{-T}^{T} p_l^2(t) dt \int_{-T}^{T} p_r^2(t) dt}} \right|_{\max}, \quad |\tau| \leq 1\,\mathrm{ms}, \qquad \text{(B2)}$$

where $p_l(t)$ and $p_r(t)$ are the sound pressure as a function of time, then $IACC_{E3}$ is an *IACC* specified by the integration time (T) and the frequency range. "E" indicates the early part of time (0–80 ms), and "3" signifies that the value is the mean among three frequency bands (0.5, 1 and 2 kHz) responses when the impulse response is separated into three octave bands. *BQI* is then defined by

$$BQI = 1 - IACC_{E3}. \qquad \text{(B3)}$$

When the *BQI* is high, listeners cannot identify the direction of sound and feel as if the sound covers them. According to concert halls, it is said that more diffused sound field is good for listeners acoustically [11].

Δt_1 (Initial Time Delay Gap)

Δt_1 is a duration time between a direct sound and a reflection with the first maximum amplitude. It is important to supply the reflection to listeners in the suitable interval to avoid the acoustical difficulties such as interference and echo-disturbance.

APPENDIX C; AUTOCORRELATION FUNCTION OF A SIGNAL

Autocorrelation function (*ACF*) indicates a correlation between a signal at the origin and the same signal at a delay time, τ. The *ACF* can be expressed by

$$\Phi(\tau) = \frac{1}{2T} \int_{-T}^{T} p(t) p(t+\tau) dt \qquad \text{(C1)}$$

where $p(t)$ is the signal, and $2T$ is the integration time, and the normalized *ACF* is

$$\phi(\tau) = \frac{\Phi(\tau)}{\Phi(0)}. \qquad \text{(C2)}$$

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