Acoust Aust
DOI 10.1007/s40857-016-0059-2

TECHNICAL NOTE

Sound Focusing Effects in Horseshoe Plan Theatre

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Received: 2 March 2016 / Accepted: 17 May 2016

Abstract This paper is aimed to study the sound focusing effects in the theatre with horseshoe-shaped plan. It was considered as a case study in the theatre "Vincenzo Bellini" in Catania (Italy), a horseshoe-shaped opera house where both opera and symphonic concerts can take place. This configuration, at the time, was considered to be the best solution for both a good sound quality as well as a good view of the stage for the spectators sitting in the boxes. The geometry of the theatre determines some gaps due to a concentration of the early sound reflections on the back of the room, involving the last rows of seats, thus causing a non-uniform spread of sound in the theatre. This concentration of reflections does not create optimal conditions for good acoustics due to excessive reverberation and negative influence on the listening to music performances.

Keywords Sound—focusing effects · Horseshoe plan · Theatre · Acoustics

1 Introduction

From an acoustic point of view, the Italian-style opera houses with horseshoe plan present a common feature: due to the curvature of the lower part of their lateral walls, a sort of partial wave-guiding effect in the stalls, like the well-known "whispering gallery" effect is produced. This effect is responsible for the concentration of early sound energy at the seats located back in the stalls.

As much as the global room impression depends on the early part of the impulse response, it can be supposed that the perceived sound quality of the singers' voice and instrumentalists' music performed on the stage will be significantly different for the listener seated in the last row in relation to the other locations of the stalls area. Focusing effects can cause high sound pressure levels, echo and sound coloration [1].

The aural effects of concave curved surfaces have been studied by several authors [2,3]. Wulfrank et al. [4] studied the sound focusing effect in the "Wigmore Hall" in London but in current literature, there are no complete studies on the sound focusing effect in the rooms.

In this paper, the evaluation of the acoustic focusing effects in an Italian-style opera house was investigated. The Teatro Massimo "Vincenzo Bellini" in Catania was considered as a case study. In particular, the curvature of the parapet of the lowest boxes tier could foster the concentration of the sound in the last rows of seats in the stalls area.

This paper presents the results of acoustic measurements performed to evaluate the acoustic characteristics of the theatre and the average spatial distribution of the sound energy due to the early reflections as well as to verify the existence of the acoustic focusing phenomenon.

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Fig. 1 Views of the Teatro Massimo “Vincenzo Bellini” interiors: from the stage (on the *left*) and towards the stage (on the *right*)

2 Methods

2.1 Architectural Features

The Teatro Massimo “Vincenzo Bellini” is the most prestigious and representative monument of Catania. The opera house was designed by the architect Carlo Sada in the second half of the XIX century and opened in 1890, with the representation of Bellini’s Norma [5]. The theatre appears as an harmonic artwork, well inserted in the urban context. The facade, in an eclectically style, was inspired by Garnier’s Opera in Paris. It resumes classic architectural elements, although enriched with elaborate decorations echoing the baroque buildings of the historical city. Two side wings connect the façade to the existing buildings on the square, making an unicum which is the theatrical backdrop of the outside square.

The theatre interior was designed in the traditional horseshoe shaped with four tiers of boxes and the gallery. The stalls area is about 19.5 m long (just at the longitudinal axis) and 19 m wide along the transverse axis as well as 15 m width at the orchestra pit. The latter is 6.5 m long and is located at about 1.5 m lower than the stalls area.

Access to the room is through a main entrance, on the back of the stall area in correspondence to the longitudinal axis, as well as two side doors, located along the transverse axis.

Sixteen rows of seats for a total of 396 seats are in the stalls area, while about 756 seats are in both the 114 boxes (on average 6 seats for each box) as well as the 8 stage boxes. The boxes are accessible by anti-boxes, communicating with the distribution corridors. In front of the stage, upon which there is the main entrance to the stalls area, there is the main box for the Head of State, whose height corresponds to the second and third tiers.

Boxes parapets are in wooden and decorated with gilded ornaments, different for each tier. Only the parapets of the first tier of boxes are coated with smooth venetian plaster and have no ornaments. The auditorium floor is made of poplar wood, covered with a red carpet and is slightly sloped towards the stage. The floor of the stage and the orchestra pit is also wooden. The walls of the boxes are covered with a paper upholstery. The ceiling is constituted by a frescoed elliptical vault (about 28 m × 23 m, with a very large radius of curvature) made of reeds and plaster. It is joined to the vertical walls through lunettes decorated with stuccos and gilded friezes. The maximum height of the vault from the auditorium floor is about 21 m.

Table 1 Main dimensions of the theatre

Volume (m^3)	12.056
Length (m)	26.0
Width (max values) (m)	20.8
Height (max values) (m)	19.0
Number of seats	1.359

In the stalls area there are padded and covered in velvet seats, whilst in the boxes overstuffed chairs. The opening of the proscenium is 14 m wide and the stage is 21 m long. Figure 1 shows the interiors of the room from the stage (on the left) and towards the stage (on the right) whilst the main dimensions of the theatre are reported in Table 1.

At the Theatre Massimo Bellini, both opera and symphonic concerts take place; acting companies involved in prose, operetta, ballet and jazz performances are exceptionally hosted.

2.2 Acoustic Measurements

In order to evaluate the acoustic quality of the theatre and to map the spatial distribution of the sound due to the early-reflected sound in the stalls area of the investigated opera house, acoustic measurements were carried out.

According to ISO 3382 [6], the measurement points were equally distributed throughout the theatre so as to obtain the spatial average values of the acoustic parameters: 16 points were chosen in the stalls area and 12 points in the boxes.

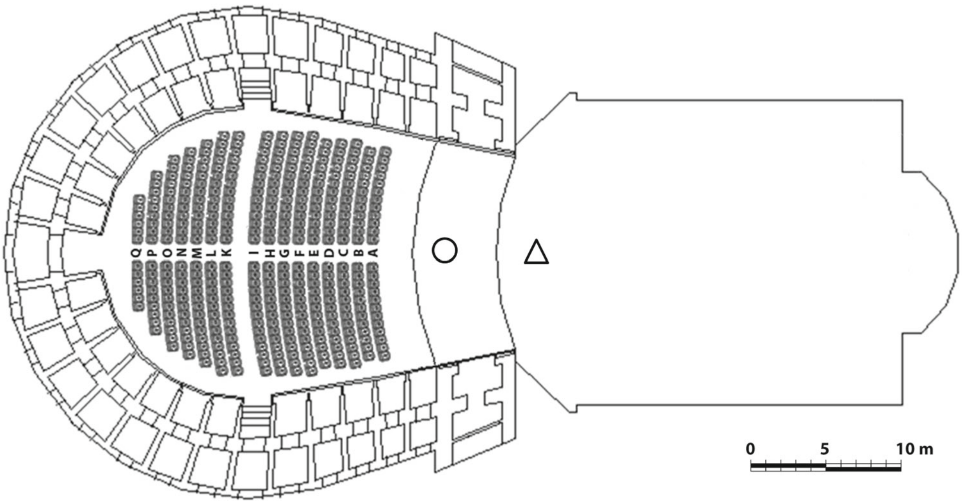

Fig. 2 Plan of the theatre with the positions of the sound sources (*hollow circle* in the orchestra pit and *hollow triangle* on the stage)

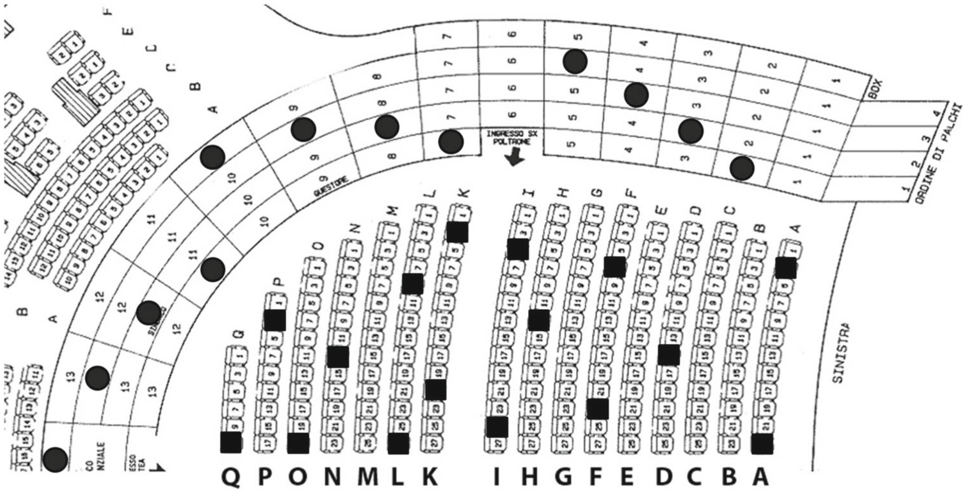

Fig. 3 Plan of the *left half* of auditorium with the position of the measurement points (*filled squares* in the stalls and *filled circles* in the *boxes*)

The microphone was placed 1.2 m high from the floor, corresponding to an average height of the seated listener's ear [1].

The sound source was placed alternately on the stage and in the orchestra pit at a height of 1.6 m.

Due to the symmetric geometric shape of the theatre and the symmetric position of the sound source, the measurements were performed just in a half of the stalls area.

In Fig. 2, the positions of the sound sources on the stage and in the orchestra pit are shown, whilst in Fig. 3 those of the measurement points in the stalls and in the boxes are indicated.

The two chosen source positions allow to evaluate the acoustic performance of the theatre during an opera performance. In particular, the source was placed on the stage so as to evaluate the effects due to the singer, whilst in the pit to evaluate the effects of the orchestra.

During the acoustic measurements, the theatre was unoccupied, without any noise from outside and staged for an opera. Figure 4 shows the sound source on the stage from the proscenium and from the stalls area whilst in Fig. 5 the microphone position is reported.

According to ISO 3382 [6], for each microphone position and for the two sound source configurations, the following room acoustic monaural descriptors were measured: reverberation time T_{30}(s), early decay time EDT (dB), definition $D_{50,}$ clarity C_{80} (dB), sound strength G (dB) and centre time T_s (ms).

The measurements of the acoustic characteristics of the theatre were carried out with an omnidirectional dodecahedral sound source fed by a power amplifier, connected to a MLSSA single-channel analyzer, recording the impulse response by a signal MLS [7,8]. The MLS signal was recorded by an omnidirectional measuring microphone of 1/2 inch, while a sound level metre (Solo 01 dB) was used for the measurement of the equivalent sound pressure level (L_{eq}) inside the room, from which the G parameter was calculated in accordance with the following formula:

Fig. 4 Views of the sound source placed on the stage from the proscenium (on the *left*) and from the stalls area (on the *right*)

Fig. 5 Acoustic measurements in the stalls area, with the indication (in *yellow*) of the measuring microphone at a seat

$$G = L_p - L_w + 31\,(dB)\,,$$

where L_p (dB) is the sound pressure level at the receiver point re 20 µPa and L_w (dB) is the sound power level of the omnidirectional source re 1 pW. The use of parameter G, as a descriptor of the "strength", provides the predisposition of a room to make the sound intensity for a given sound power emitted by the source. The parameter G was measured in octave band frequencies from 125 Hz to 4 kHz [9].

3 Results and Discussion

3.1 Measurement Results

The results of the measures performed in the four configurations are reported below. Figure 6 shows the average values and the standard deviations of the acoustic parameters measured in the stalls area with the sound source positioned on the stage at first and in the pit orchestra subsequently. While Fig. 7 shows the average values and the standard deviations of the acoustic parameters measured in the boxes for the two above-described positions of the sound source.

For the receivers in the stalls, the mean values of T_{30} and EDT increase at low frequencies, while at medium frequencies they are comparable to those recommended in the literature for opera houses. Similar results are obtained for the mean values of C_{80}. The analysis of these descriptors shows a good clarity to the music in the stalls area when the source was placed both on the stage as well as in the orchestra pit.

Figures 6 and 7 show that the variation of the T_{30} standard deviation is low, while for the EDT, C_{80} and D_{50}, the variations of the standard deviations are evident. Therefore, while the T_{30} parameter does not vary spatially within the hall, the parameters EDT, C_{80} and D_{50} are influenced by the measurement positions, with a consequent spatial variation in the hall.

To improve the graph readability and to avoid overlay of error bars, the standard deviation is represented for the red lines (sound source in the pit and receivers in the stalls, Fig. 6), or in the boxes (Fig. 7) in the upper part of the graph. For the black lines (sound source on the stage and receivers in the stalls Fig. 6), or in the boxes (Fig. 7) in the lower part of the graph.

Regarding the perceived intensity, the G values are relatively uniform at the medium frequencies. The G values are higher when the sound source was placed in the pit orchestra, because of the shorter distance of the receivers [9]. The analysis of the measured values shows a non-uniform trend between the front rows in the stalls area (up to row "F") and the rear ones. The latter is affected by an excessive noise tail in the midrange bands (500 Hz and 1000 Hz), adversely affecting the clarity C_{80} and the definition D_{50}. This effect is

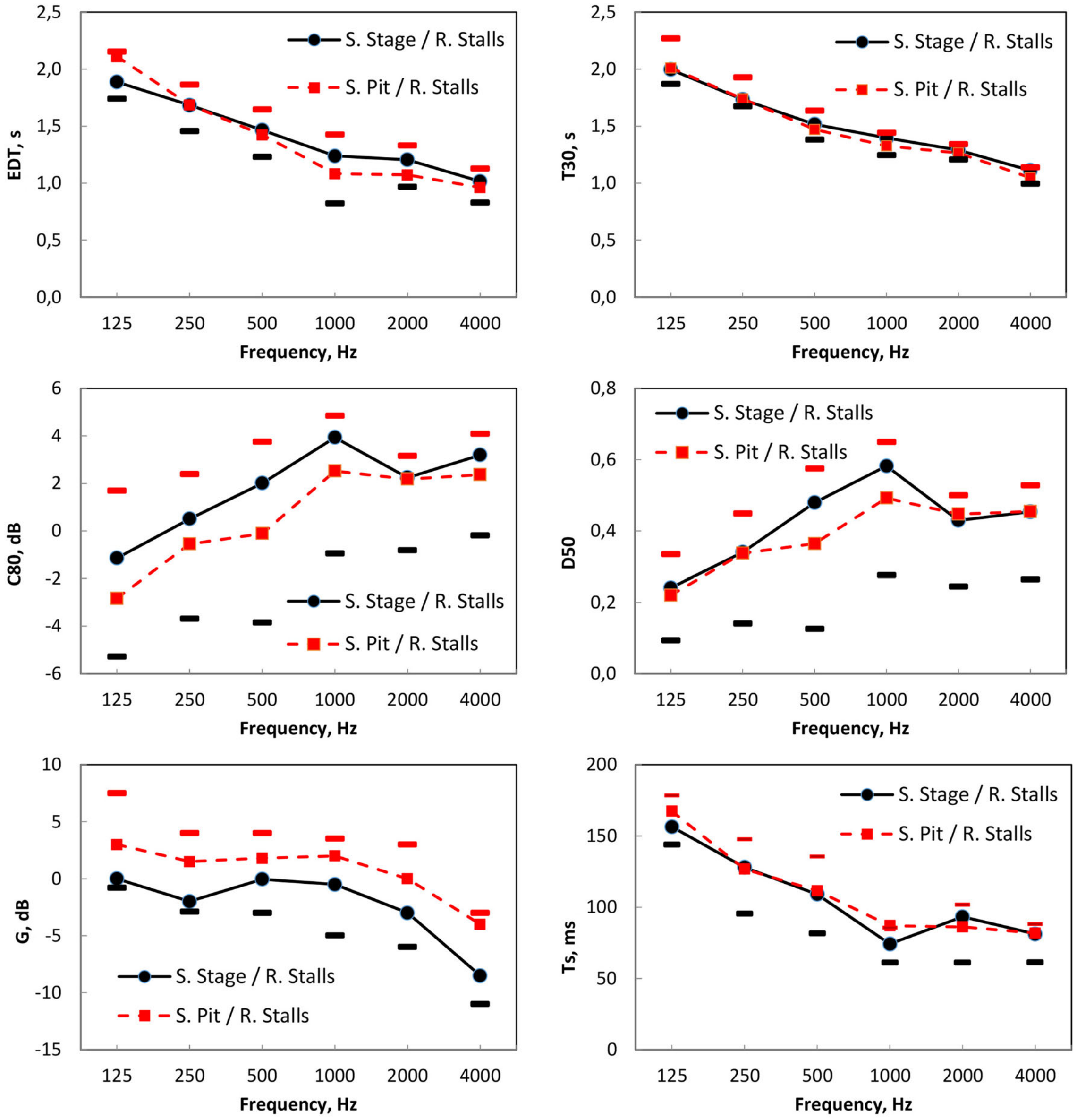

Fig. 6 Average value and standard deviations of the measured acoustic parameters in the stalls area when the sound source was positioned on the stage (*black dots*) and in the orchestra pit (*red squares*)

due to the geometry of the theatre and to the first tier of boxes parapet, with a rigid and smooth surface, which focuses the reflected sound beams in the back rows of the stalls area (from row M onwards).

The points belonging to the initial rows in the stalls area, between the rows A and F, show a high clarity. For the receivers in the boxes, the T_{30} values are quite short. The average values of clarity C_{80} are included within the values proposed in the literature only for the mid frequencies. The "strength" (G) is uniform at the middle frequencies and tends to decrease at high frequencies due to the effects of the absorbing materials in the room. When the source is placed in the pit, the room shows a good clarity C_{80}.

In the boxes, the reverberation is more homogeneous. The room has an overall good clarity and an excellent perceived intensity. The definition D_{50} is better in the boxes.

3.2 Sound Focusing Effects

The opera houses with "horseshoe" plan are characterized by an acoustic phenomenon: the concentration of the early sound energy on the back of the stalls due to the curvature of the lower part of the lateral walls. The effects of this architectural shape, responsible for a sound focusing area producing a sort of partial wave-guiding effect in the stalls, are discussed in [2,11].

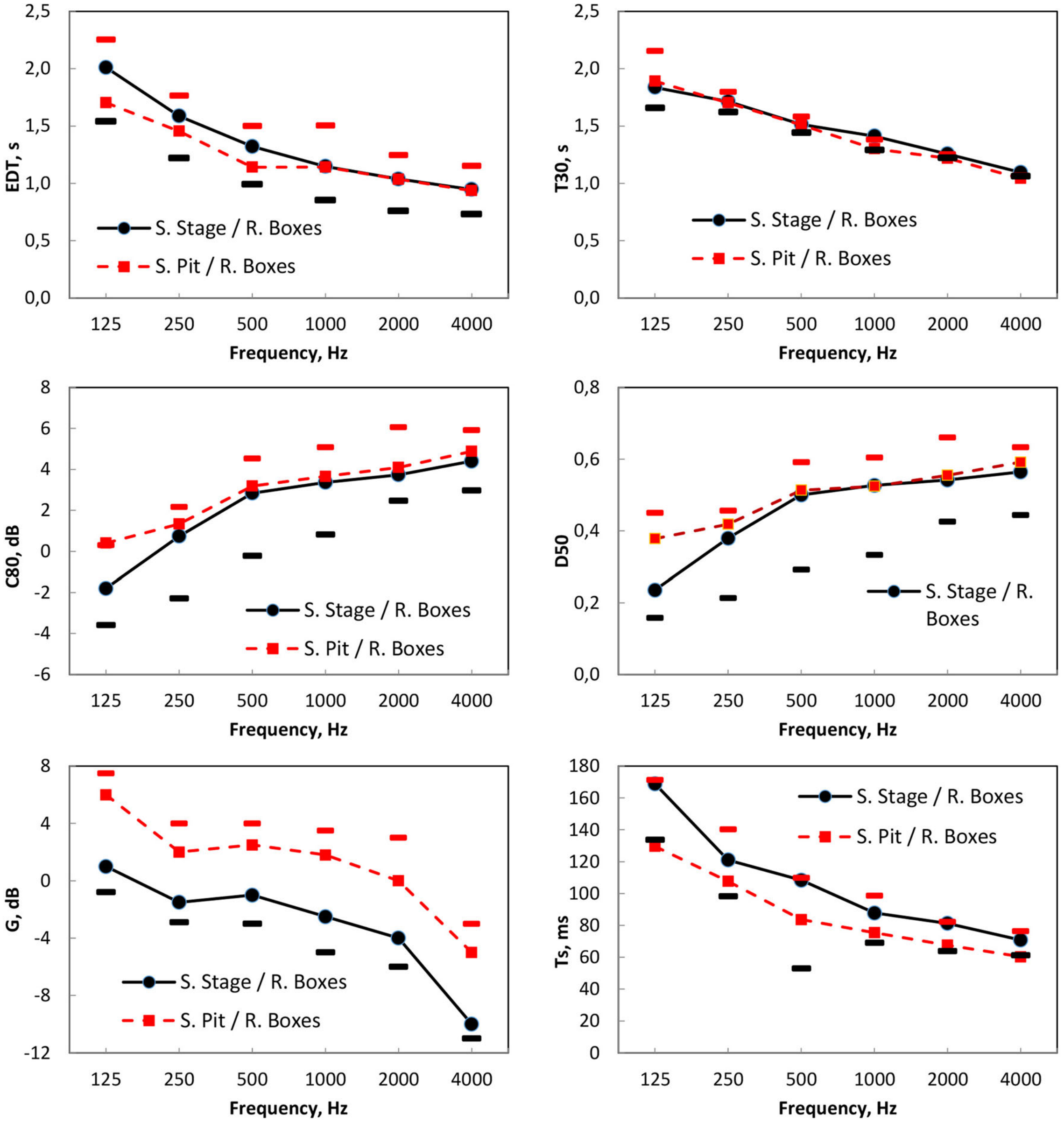

Fig. 7 Average value and standard deviations of the measured acoustic parameters in the boxes when the sound source was positioned on the stage (*black dots*) and in the orchestra pit (*red squares*)

Acoustic measurements were carried out with the aim to investigate the sound focusing effects at the back of the stalls area.

The theatre was empty during the acoustic measurements and no scenery was on the stage.

Due to the symmetrical plan, the measurements were performed in the left half of the stalls area, with a higher concentration on the rear sector.

The acoustic measurements were carried with the equipment set as described in par. 2. "Acoustic measurements". The omnidirectional dodecahedral sound source placed on the stage at the height of about 1.60 m whilst the measuring microphone of 1/2 inch at a height of 1.20 m from the floor of the stalls in the 66 different measurement points as shown in Fig. 8.

Care was taken to maintain a constant setup of the measurement chain. This assured that the overall gain of the system was constant so that the relative amplitude of the responses was preserved. In order to give evidence to the early-reflected sound, the impulse responses of the direct sound were cleared. They were time-windowed with a lower limit at 5 ms after the arrival time of the direct sound and an upper limit at 50 ms after the same reference time. The 45-ms-long records contained most of the reflected early

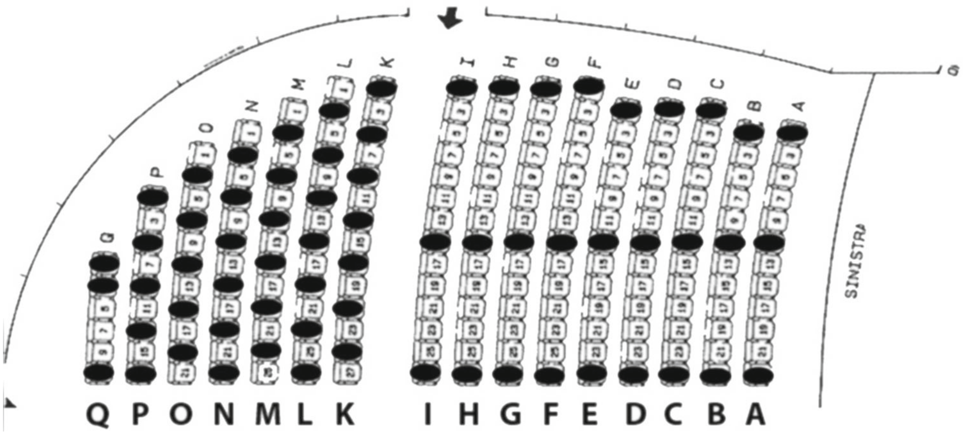

Fig. 8 Plan of the left half of auditorium with the position of the measurement points (*filled ovals*) for the evaluation of the sound focusing effects

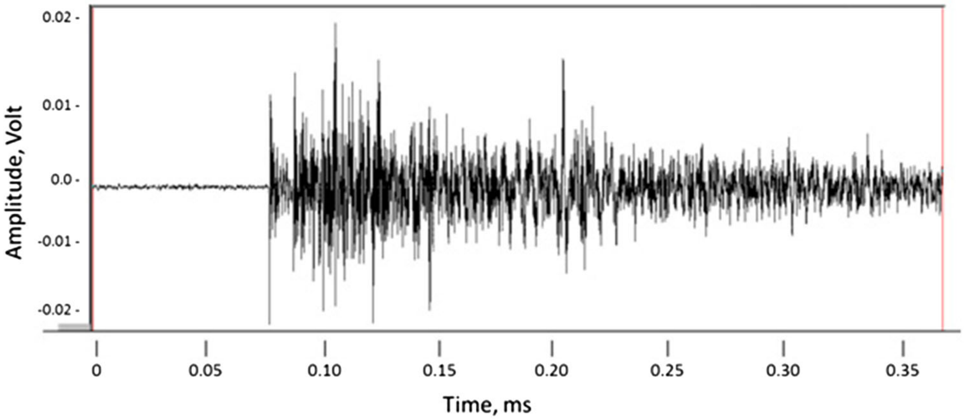

Fig. 9 Impulse response measured on the stage in the sound focusing effect area (seat Q11)

energy that was deemed to be useful for speech intelligibility [11].

Each 45-ms record was 1 octave band filtered and 10 Log of the squared signal was taken as a relative level of the early-reflected energy in the relevant 1 octave band.

From the impulse responses measured in the back, there is an important component of sound reflection (for the time equal to 0.35 ms) following the direct wave with a time delay compatible with the distance of the measuring point from the balustrade (Fig. 9); where the contribution due to each of the reflections to the sound field can be evaluated by means of the image-source method. The first impulse is due to the direct sound component (source–receiver distance is 27 m); the second one to the reflection of the source on the stage floor; whilst the successive impulses are due to the contributions of sound reflections on the side walls of the room. By applying the image-source method to the sound reflections in the rear part of the room (sound focusing effect), the impulse to 21 ms, corresponds to a 71.5 m path.

Room-acoustics parameters like D_{50} and C_{80} were less sensitive for the focusing effects survey.

In fact, Fig. 10 (a–c), shows the spatial distribution of C_{80} at the octave band frequencies of 500 Hz (a), 1000 Hz (b) and 2000 Hz (c), respectively, without any indications of the focusing effects.

Figure 11 shows the T_{30} average spatial values in the octave band at the frequency of 1000 Hz. The curved surfaces delimiting stalls area determine a not uniform sound distribution, which instead focuses on certain areas of the stalls.

In particular, the map shows a sound concentration in the bottom of the stalls area, where the T_{30} maximum value (2.2 s) is recorded, corresponding to an increase greater than 25 % compared to the central part of the hall where the T_{30} minimum value (1.5 s) is measured (Fig. 12).

To get non-negative values for a better graphical representation, the dB scale in each one octave band map was referred to the corresponding measured minimum value of the early energy. Concentrations of the early energy up to 10 dB can be observed at the seats back in the stalls. The seats closer to the sound source are supplied with poorer early-reflected sound energy. For areas in the bottom of the pit emerges a greater intensity of the sound energy due to the significant contribution of the reflected waves, compared to the direct wave. An higher concentration is detected at the frequency of 2000 Hz, while at the frequency of 500 Hz the distribution is more uniform.

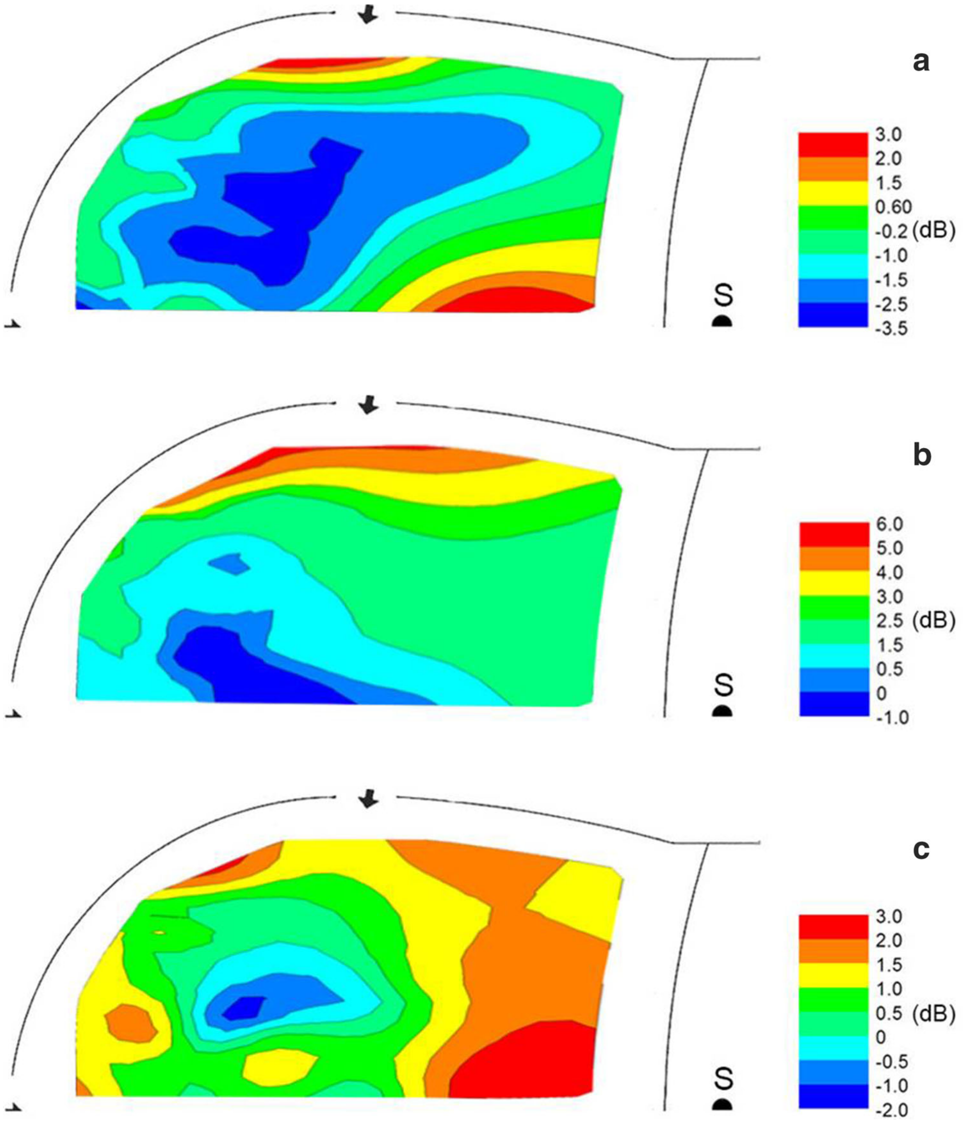

Fig. 10 C_{80} (dB), maps at one octave band frequency of: **a** 500 Hz; **b**)1000 Hz; **c** 2000 Hz

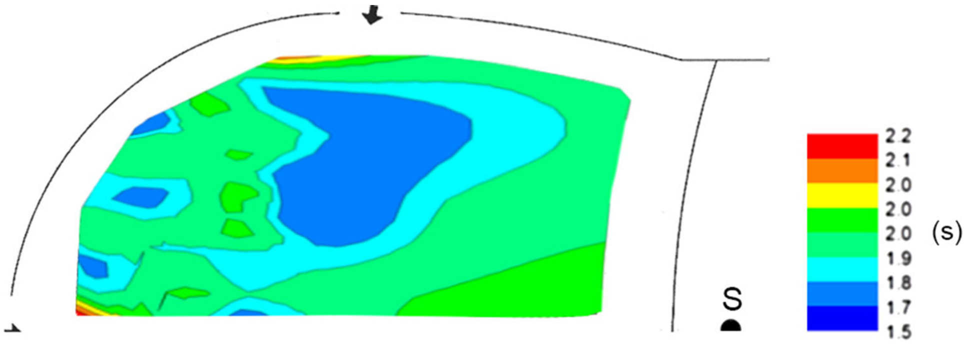

Fig. 11 T_{30} (s), map at one octave band frequency of 1000 Hz

This work emphasizes the sound focusing effect as an acoustic flaw characterizing the horseshoe plan theatres. Literature shows some solutions to apply for the correction of the sound focusing or the echo effects: the installation of diffusion panels to be installed over the rear wall of the underbalcony space was proposed by Kamisinski [12] for the Theatre of Opera and Ballet in Lviv (Ukraine); diffusion panels were also applied over the rear wall of Carnegie Hall to prevent echoes [13].

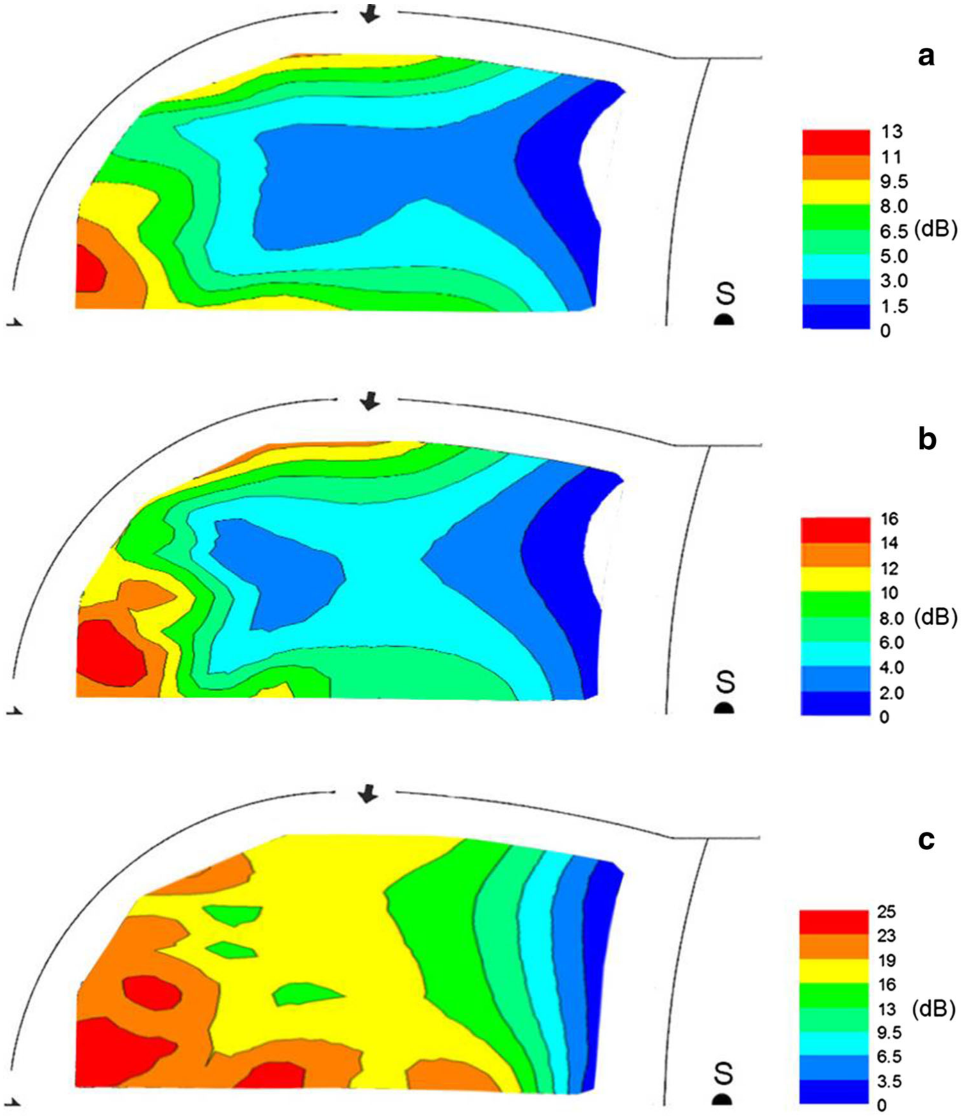

Fig. 12 **a**–**c** shows the maps of the level of the early energy for the octave bands at 500 Hz (**a**), 1000 Hz (**b**) and 2000 Hz (**c**)

4 Conclusion

The horseshoe shaped plan of Italian-style theatres is responsible for the concentration of the early sound energy at the seats on the back of the stalls area. This is also the case of the Teatro Massimo "Vincenzo Bellini" in Catania. This effect occurs especially when the sound source radiates from the centre of the stage. In this case, the focusing effect causes high sound pressure levels and sound coloration. As well as most of the global characteristics of the room, it depends on the impulse response of the environment. As a consequence, it can be assumed that the quality of the perceived sound is different if the listener is positioned in the back rows of the stalls area and close to the central hallway, rather than in any other place in the room. The geometry of the room allows for an increase of the focusing effect at the frequency of 2000 Hz, but this effect is reduced at low frequencies. Despite these effects of the sound focusing on the back of the room, the mean values of the measured acoustic parameters, complying with the limits suggested by the specific literature [14], and the positive judgments given by interviewed regular spectators suggest that the acoustics of the Theatre "Vincenzo Bellini" is quite good.

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