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OBJECTIVE MEASUREMENT OF THE LISTENING CONDITION IN THE OLD ITALIAN OPERA HOUSE "TEATRO DI SAN CARLO"

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The Teatro di San Carlo (Naples—Italy) is known to be the oldest working theatre in Europe. Since its opening on 4 November 1737 (41 years before the opening of La Scala in Milan and 51 years before the opening of La Fenice in Venice) a number of famous singers, musicians, conductors, and other artists as well, have brought great prestige to this theatre. The San Carlo is not short of praise for its acoustics but, to the knowledge of the authors, no objective study about this subject has ever been published. This paper reports the results of acoustic measurements carried out with the aim of obtaining objective parameters describing the acoustics of the San Carlo from the point of view of the listeners. They disclose a behaviour of the theatre that is typical of the Italian style opera house

1. INTRODUCTION

Opera is a kind of show that implies both a visual and an acoustic involvement that gives rise to a special relationship between the spectator and the event in course. If only acoustical aspects are considered, the listening experience appears to be quite different from that of a listener in a concert hall. Actually, the singers perform on the stage platform and the orchestra plays in the pit between the singers and the audience.

Opera is an old art form that was born in Italian courts at the end of the 15th century. After its initial growth in the courts, it was also offered as a public show. As a consequence of its commercial success, some theatres were built for the purpose. Teatro di San Cassiano, that was opened in Venice in 1637, is reported to be the first opera house. It had the distinctive feature that for the first time the orchestra was placed between the stage and the audience. To meet an increasing public demand other theatres were built in Venice, and so at the very start of the 18 century the fundamental form of the Italian style opera house had already been established. Teatro di San Carlo in Naples and Teatro alla Scala in Milan are now the largest surviving implementation of the traditional Baroque theatre for opera.

It is not hard to believe that the opera masterworks of the Italian composers have been conceived with the acoustics of these spaces in mind. If the legacy of the intentions of these composers is to be saved in the construction of new opera houses, the acoustics of the surviving theatres should be studied thoroughly and reported widely. The aim of the work presented in this paper is to contribute to this knowledge.

2. HISTORICAL OUTLINE AND MAIN FEATURES OF THE TEATRO DI SAN CARLO

The Teatro di San Carlo (TDSC) was built by King Charles of Bourbon who wished to provide his capital city with a new theatre to replace the old and crumbling theatre of San Bartolomeo. On 4 March 1737 a contract was signed with the architect Giovanni Antonio Medrano and the contractor Angelo Garasale. This contract was honoured and the San Carlo was opened on 4 November 1737. After a long period of splendour, during which the outside of the theatre was renewed by the architect Antonio Niccolini on the orders of Murat, the TDSC was completely destroyed by a fire on 12 February 1816. Only six days after the fire King Ferdinand of Bourbon entrusted architect Niccolini to rebuild and restore the TDSC as it had been before the fire. By respecting Medrano's plans the auditorium remained horseshoe-shaped, 28·6 m long, 22·5 m wide; 184 boxes were arranged in six tiers, including the royal one. The stage was enlarged (33·1 m × 34·4 m). The decorations were renewed and a still existing painting by Giuseppe Cammarano embellished the ceiling. It depicts Apollo introducing the greatest poets in the world to the goddess Minerva. Apart from the introduction of the orchestra pit, which was suggested by Giuseppe Verdi in 1872, the substitution of the central chandelier by the electrical lighting in 1890, and the construction of the new *foyer* with a new wing given to the dressing rooms of artists, the theatre has undergone no substantial changes. The auditorium is the same today as when Stendhal saw it the evening of the theatre reopening on 12 January 1817. "*There is nothing in all Europe, I won't say comparable to this theatre, but which gives the slightest idea of what it is like…, it dazzles the eyes, enraptures the soul…*".

Today, due to safety regulations, the seating capacity of the TDSC is only 1500. The volume of the auditorium is nearly 14 000 m^3 without including a 2·3 m deep air space above the canvas by Cammarano. The volume of the stage house is about 27 000 m^3. The chairs in the stalls are heavily upholstered and covered with red velvet: instead those in the boxes have a light upholstering.

The orchestra pit has an average transverse length of 15·8 m and a width along the centreline, from the stage to the railing, of 7·2 m. Its depth is 2·3 m at the edge of the stage. The orchestra pit can be given a variable overhung for opera or ballet performance, otherwise it can be closed completely to enlarge the stage floor. Figure 1 shows a view of the auditorium from the royal box toward the stage. Figure 2 shows a view of the auditorium toward the royal box.

3. OBJECTIVE ACOUSTIC CRITERIA FOR OPERA HOUSES

Unfortunately, very little research has been performed in the area of opera house acoustics in comparison with the efforts that have been made to capture the secrets

Figure 1. A view of the auditorium of the Teatro di San Carlo towards the stage.

Figure 2. A view of the auditorium of the Teatro di San Carlo towards the royal box.

of sound quality in concert halls. This may be due to the lack of a comparable demand of new opera houses. As the culture of opera has spread out of the borders of traditional circles, the need for new shapes and larger capacity theatres has drawn attention to opera house acoustics. To the knowledge of the authors, up to the late 1970s only the reverberation times of a few important opera houses have been published. More recently, modern objective criteria measured in various opera houses have been reported.

Barron [1] summarizes the aims of the design of an opera house in qualitative terms stating that the speech should be intelligible, the orchestral sound should have a suitable clarity and convey an adequate sense of reverberance. Both the voice of the singer on the stage and the sound of the orchestra in the pit should reach every listener with sufficient loudness. Of utmost importance are the balance between the singer and the orchestra and the fact that the acoustics of the theatre must favour the former. It is the opinion of Barron that the sound envelopment is of minor importance with respect to the requirements of loudness and balance. He investigated on the acoustics of three British opera houses along these lines. One—The Royal Opera House, Covent Garden, London—is of the Baroque-type. The aspects relevant to the orchestral music were described by the objective measures that Barron had already considered in a concert hall survey, namely, the reverberation time RT, the early dacay time EDT, the early to late ratio (that is the clarity index C_{80}), the total sound level (that is the sound strength G) and the early lateral energy fraction LF. The definitions of these parameters can be found in reference [1] and, e.g., in reference [2].

A first objective descriptor related to the sung voice was the definition index D, proposed by Thiele [3]. It was measured with a sound source approximating the directivity of the human voice roughly. This sound source was placed on the stage at the usual location of the singer's head facing the audience. Although aware of more powerful descriptors of the speech intelligibility, Barron preferred the above-mentioned simple measure because it appeared to be linked clearly enough with the early reflections in a room excited by a real speaker. The same sound source was used for measuring the sound strength G related to the loudness of the singer's voice. The objective descriptor of the balance considered by Barron was the difference between the sound strength G measured at a receiving location with the directive source on the stage and the sound strength G measured at the same location with a non-directive sound source in the pit. Both sound sources emitted the same sound power.

Recently, Hidaka and Beranek [4] have reported on the results of a subjective/objective study based on subjective/objective data collected for 15 opera houses. Their work was aimed at ascertaining whether the objective measures, that they found well correlated with the global judgements about the aoustic quality of concert halls, could be useful for the same purpose for opera houses. The judgements have been expressed by interviewed orchestra conductors and other experts. The authors measured RT, EDT, C_{80}, the bass ratio BR, the inter aural cross-correlation coefficient $IACC_{E3}$ and the initial time delay gap $ITDG$. These objective parameters, that are defined in reference [5], were evaluated for each opera house and averaged over more than ten listener locations with only one sound source position on the stage. During the measurements the auditoria were unoccupied and the fire curtains were open. In most instances major musical instruments and chairs were present in the pit.

The main conclusions of the study are that (1) RT, G, BR, $IACC_{E3}$ and $ITDG$ are independent parameters in the observed opera houses and, (2) if G and BR are acceptably large and RT is appropriate, $ITDG$ and $IACC_{E3}$ are important objective parameters for estimating opera house total quality.

In the light of the available knowledge about the topic of subjective acoustical aspects and related objective criteria in opera houses, the present authors decided to analyze the listening conditions in the TDSC by considering objective parameters similar to those reported by Barron in connection with his survey of three British opera houses. The main difference is the use of the same omnidirectional sound source both on the stage platform and in the orchestra pit when the TDSC was fitted for an opera performance. This choice was made because (1) a sound source simulating the directivity of the human voice was not available when tests were performed and (2) until such a sound source will be standardized for the purpose, a non-directive sound source yields results that can be compared better with those of others who use a non-directive sound source.

4. MEASUREMENT AND RESULTS

Measurements were performed in order to evaluate meaningful objective criteria for listeners in the auditorium. Owing to the geometrical symmetry of the theatre, receiving points were considered only in the right-side half of the auditorium. Eight receiving points were located at ear height in the stalls, roughly uniformly. Seven further points were located at ear height at the very front of seven boxes.

A set of tests was carried out when the unoccupied TDSC was fitted for a symphonic concert. As shown in the plan in Figure 3 the pit was closed completely and the stage house was decoupled acoustically, to a certain degree, from the main hall by a thin wooden curtain covered by a velour glued over its surface. A dodecahedral omnidirectional sound source was placed under the top of the proscenium arch at a height of 1·2 m above the stage floor. It was fed with a maximum length sequence signal generated by a MLSSA analyzer [6] that yielded a sound pressure impulse response for each measuring microphone location.

In this set of tests, and in the following as well, besides a primary microphone location a coupled secondary microphone location was considered for each receiving point. Their mutual distance was 5 cm. The primary and the secondary microphone locations, where a single omnidirectional microphone recorded two impulse responses in sequence, defined approximately a dipolar receiver in the frequency range corresponding to the octave bands having their centre frequency from 125 Hz to 1 kHz. These microphone locations were such that the equivalent dipolar receiver had a direction of zero sensitivity pointed towards the source point. The digital treatment of the paired impulse responses yielded a signal equivalent to the output of a figure of eight microphone.

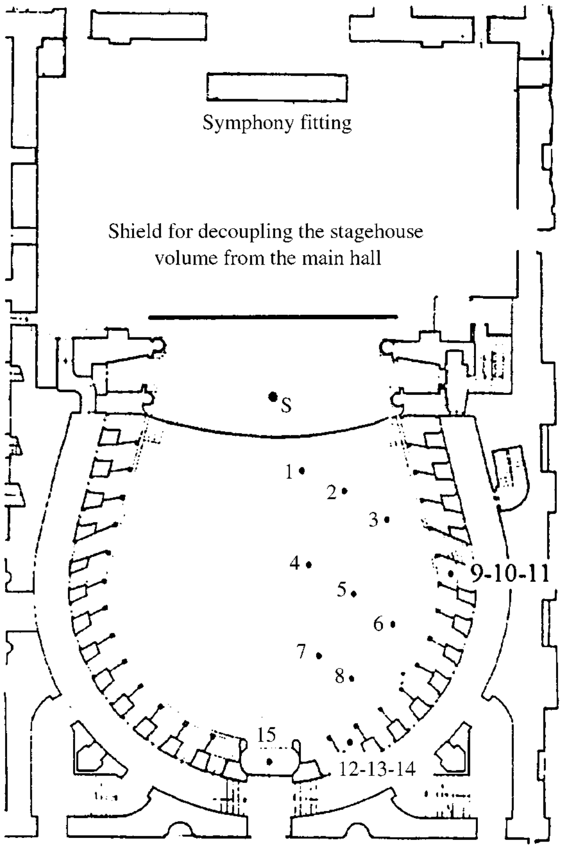

Figure 3. Plan of the Teatro di San Carlo showing the sound source S on the stage platform and the receiver locations in the stalls and in the boxes (projected on the plan). The theatre was fitted for a symphony concert.

The same measurement procedure was followed for a second set of measurements carried out when the TDSC was fitted for an opera performance (see Figure 4). In this event the orchestra pit was open almost completely and the stage house was fitted with a scenery for the performance in course. The sound source was located at first on the stage, at a height of 1·5 and 3·0 m from the stage platform edge. Later the sound source was located at the centre of the pit fitted with music stands and chairs. Its height was 1·2 m above the pit floor.

The collected impulse responses allowed the calculation of the octave band values of the following acoustic parameters: the reverberation time RT ($-5/-35$ dB), the early decay time EDT, the clarity index C_{80} and the sound strength G. The paired impulse responses were prefiltered in the frequency range from 88 to 1414 Hz to obtain the average lateral fraction LF, as defined in references [1, 2], for the frequency range corresponding to the octave bands having the centre frequency from 125 Hz to 1 kHz.

Figure 5 shows the average values of RT, EDT, C_{80} and G, for both the eight receiver locations in the stalls and the seven receiver locations at the front of the

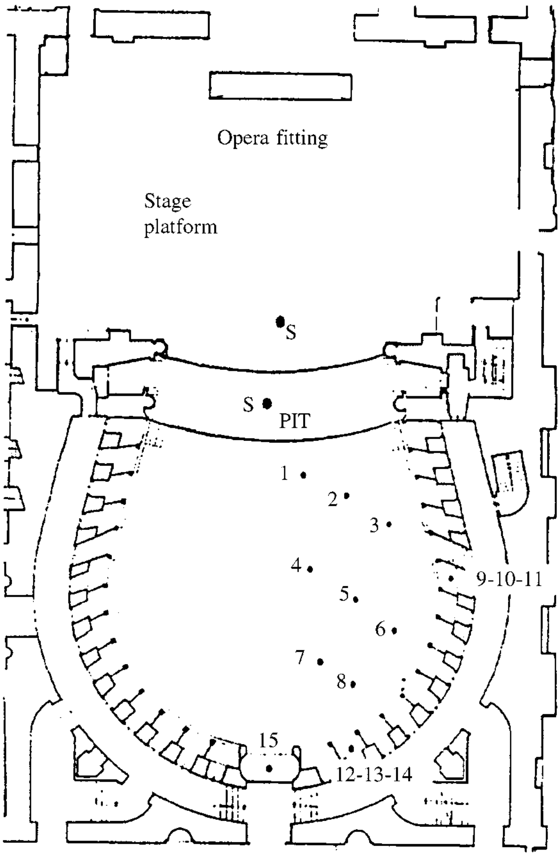

Figure 4. Plan of the Teatro di San Carlo showing the locations of the sound source on the stage platform and in the pit. The receiver locations in the stalls and at the front of the boxes (projected on the plan) are also shown. The theatre was fitted for an opera concert.

boxes for the symphony fitting. The same parameters are reported in Figure 6 for the opera fitting and the sound source in the orchestra pit. These values are representative of the relevant average subjective attributes when the orchestra performs on the stage and in the pit respectively.

Figure 7 refers to the values of the average parameters related to the listening conditions of the voice of the singer on the stage. RT measured with the sound source on the stage fitted for opera has been omitted as its values are quite similar to those reported in Figures 5 and 6. ΔG, the measure of the balance between the sound of the orchestra in the pit and the voice of the singer as perceived by the listeners, is taken as the difference between the G measured with the loudspeaker at the centre of the pit and that measured with the same sound source, radiating the same sound power, located on the stage. Positive values of ΔG denote only an objective dominance of the sound source in the pit.

Table 1 shows the mean values of the early lateral energy fraction obtained as briefly described before.

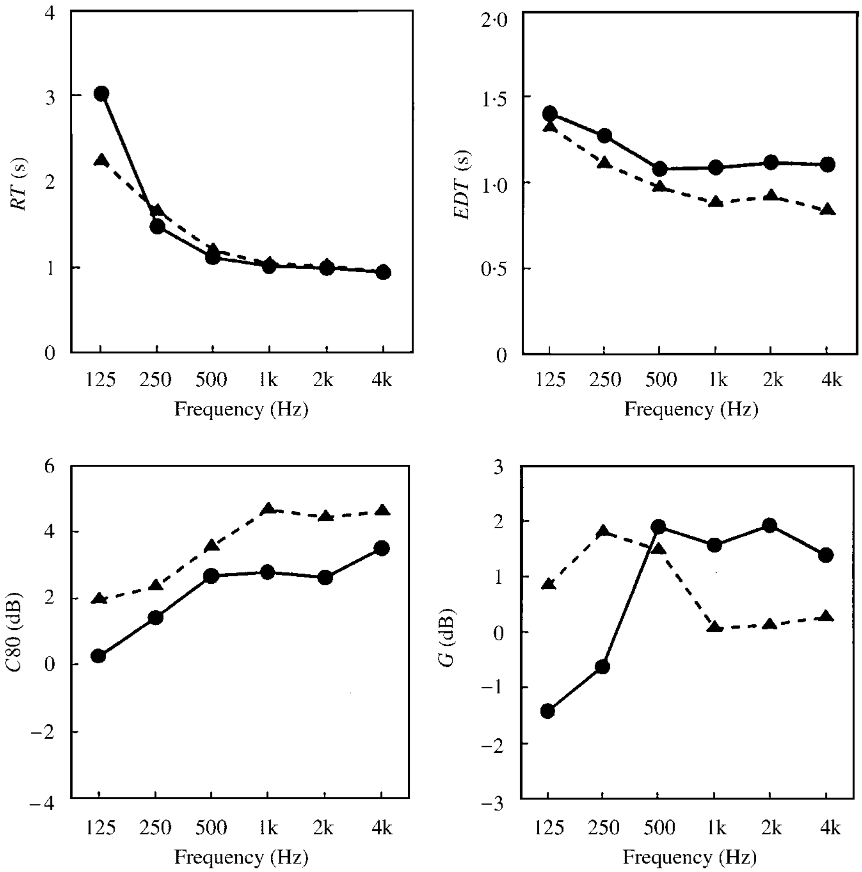

Figure 5. Average values of RT, EDT, C_{80} and G in the Teatro di San Carlo fitted for a symphony concert. Sound source on the stage platform. ●—●, stalls; ▲—▲, boxes.

5. CONCLUSION

On average, the values of the reverberation time RT ($-5/-35$ dB) of the unoccupied Teatro di San Carlo in the octave bands having their centre frequency at 500 Hz and above are slightly in excess of 1 s. They are on the low side with respect to the average RTs measured in this frequency range in other well-known old opera houses like the Teatro alla Scala in Milan, the Opéra Garnier in Paris, the Royal Opera House in London and the Staatsoper in Vienna, to name a few. For the San Carlo, the RTs in the octave bands at 250 and 125 Hz are comparable with, or even higher than, the average values reported for the above-mentioned opera houses [5]. This might be explained by the non-negligible acoustic coupling between the auditorium and the large volume of the stage house at low frequencies. Although of a different degree, this coupling was effective for both the theatre fittings when the measurements were carried out. The reverberation times averaged with respect to the receiver location (see Figures 5 and 6) do not show any substantial dependence on the sound source location for the receivers, both for the stalls and the front of the boxes. On the contrary, the average values of EDT

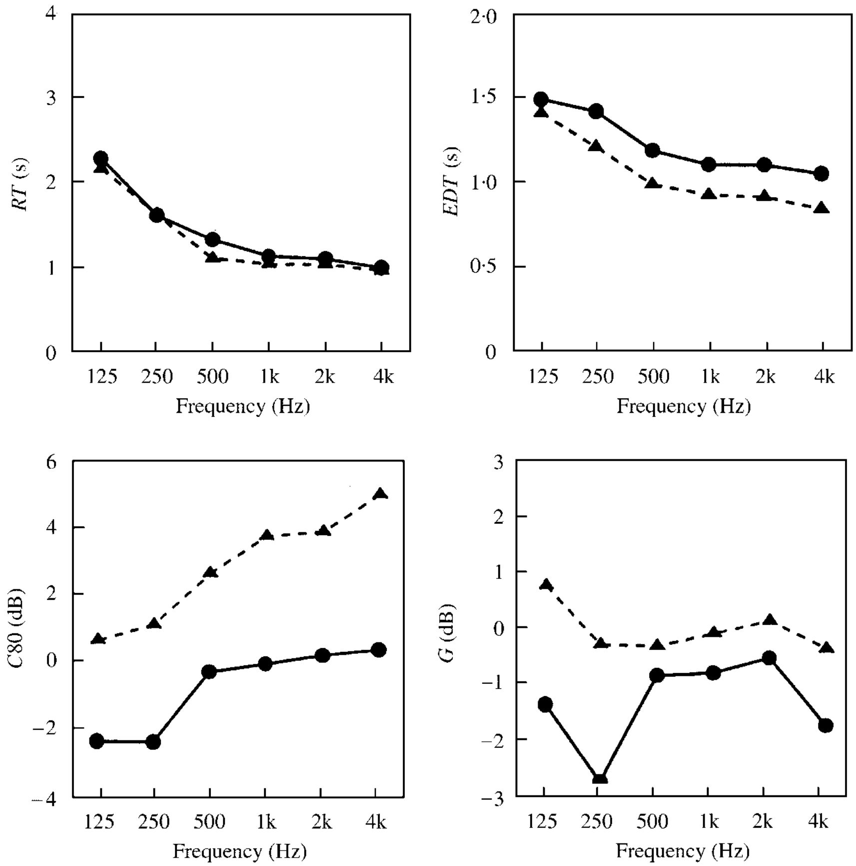

Figure 6. Average values of RT, EDT, C_{80} and G in the Teatro di San Carlo fitted for an opera performance. Sound source in the pit. ●—●, stalls; ▲—▲, boxes.

measured in the stalls are a little higher than those measured just leaning out of the boxes for all sound source locations and theatre fittings.

The highest clarity of music, as measured by C_{80}, is observed at the front of the boxes, both when the sound source is located on the stage platform and when the sound source radiates from the pit. In the latter case the direct sound cannot reach the receivers in the stalls, therefore a lower clarity is measured in this area.

Higher average values of the sound strength G, related to the orchestra sound, were recorded when the sound source was located on the stage platform closing the orchestra pit for the symphony fitting. Lower values, instead, were obtained for the opera fitting with the sound source radiating from the open pit. This was found for the receiving locations both in the stalls and at the front of the boxes, although to a lesser extent in the latter case.

Data in Table 1 show that early lateral energy is conveyed more effectively to the receivers in the stalls than to the receivers at the box fronts. When the sound source is located in the pit, the highest lateral energy is recorded in the stalls because of the shielding of the direct sound.

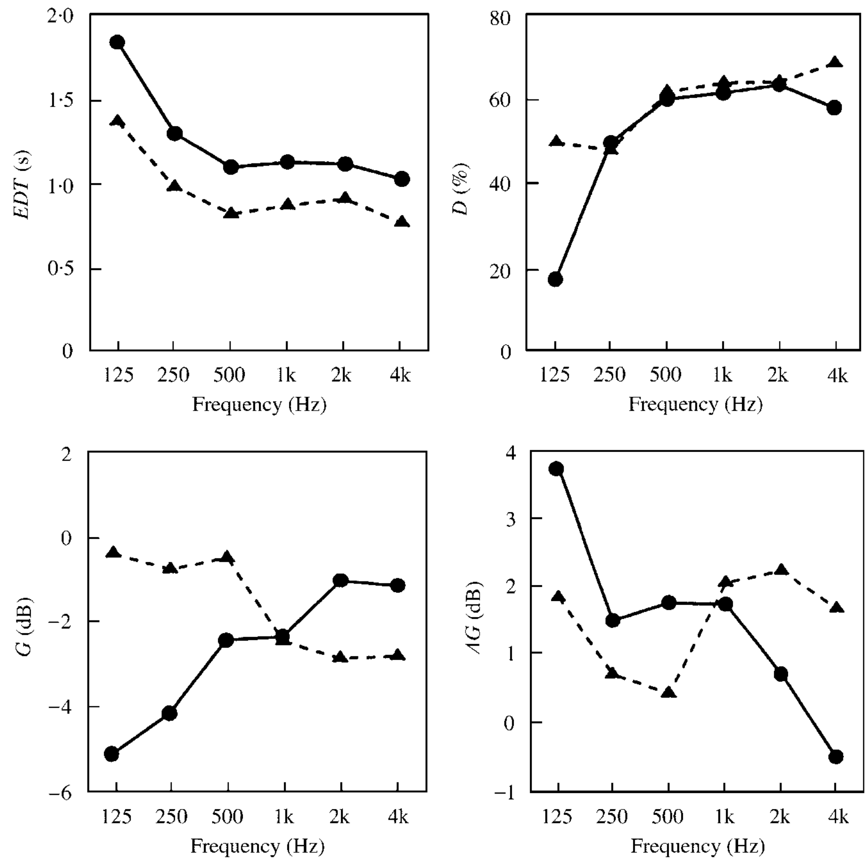

Figure 7. Average values of the parameters related to the voice of singers in the Teatro di San Carlo fitted for an open performance. *EDT*, *D* and *G* were measured with the non-directional sound source located on the stage. For ΔG also measurements with the source in the pit were considered. ●—●, stalls; ▲—▲, boxes.

TABLE 1

Mean values of early lateral energy fraction in the Teatro di San Carlo

	Symphony fitting	Opera fitting (source in the pit)	Opera fitting (source on the stage)
Stalls	0·24	0·31	0·18
Boxes	0·20	0·22	0·22

As regards the acoustic descriptors related to the singer's voice, data reported in Figure 7 show that a higher sense of reverberance associated with the voice of the singer is delivered to the listeners in the stalls. Although non-negligible differences for *EDT* were observed between the stalls and the front of the boxes, the voice definition *D* results were almost the same in the octave bands most relevant for the speech sound. The sound strength G for the voice, averaged over the above-mentioned octave bands, seems to be a little low with respect to the tentative criterion $G = 0$ dB given by Barron [1] for voice or speech sound level in an opera house. The objective balance ΔG appears to favour the sound source in the pit with respect to the same sound source at the singer's head location. No firm conclusion can be drawn from this finding as no criterion value has been proposed yet for ΔG or for other objective descriptors conceived as a measure of the balance between the singer and the orchestra. It is worth stressing again that this balance is a subjective aspect of crucial importance for opera that still requires deeper investigation.

ACKNOWLEDGMENTS

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