Sound-focusing effects in the plan of horse-shoe shaped opera theatres

Gino Iannace[a] and Elvira Ianniello[b]

[a]Built Environment Control Laboratory Ri.A.S., Second University of Naples, Abazia di S. Lorenzo, 81031 Aversa, Italy
[b]DIMEC - University of Salerno, via Ponte don Melillo, 84084 Fisciano, Italy
gino.iannace@unina2.it

An acoustical feature reported specifically for Italian-style opera houses is the non uniformity of early sound in the stalls. The curvature of the lower part of the lateral walls produces a sort of partial wave-guiding effect, like the well known “whispering gallery” effect. It is responsible of the concentration of early sound energy at seats located back in the stalls when the sound source radiates from the foreground of the stage floor. As much of the global room impression depends on the early part of the impulse response it can be supposed that the perceived sound quality of singers’ voice and instrumentalists’ music performed on the stage will be much different if the listener seats in the last rows with respect to different locations in the stalls. This paper reports an objective analysis on this subject based on measurements carried out in the stalls of “The Teatro di Corte della Reggia di Caserta”. Relevant computer simulations were also implemented.

1 Introduction

The “Teatro di Corte della Reggia di Caserta” is a small theatre within the majestic Royal Palace built for King Charles III of Bourbon in Caserta (Italy) by the famous architect Luigi Vanvitelli. He conceived the theatre since 1756, however it was completed and opened in 1769 during Carnival time. Vanvitelli himself took care of each detail conjugating late baroque style with classicism. The result was a masterwork stemmed from the skill of the involved craftsmen. Many types of materials were used for its finish. In particular, wood and papier maché simulating other materials. It is reported that papier maché was also used for room-acoustics aims. During its splendour age from 1769 to 1798 musical performances, operas, and comedies and tragedies as well, were staged in The Court Theatre. An earthquake on July 23 1930 damaged the small theatre severely. It was restored and reopened in 1994, so the first author with colleagues had the opportunity to measure and report relevant room-acoustical parameters for the first time [1]. This theatre has been revisited recently to deal with the issue of sound focusing in the back of the stalls in more depth. A complain about this drawback is reported in the words of the late Prof. Cremer [2] : “… *when the National Theatre in Munich had to be rebuilt after the war it was decided to do it in the traditional form, This not only meant some places with visual restrictions, it also included an acoustical risk. The National Theatre has the usual curved horse-shoe shaped ground-plan with its focusing areas near the sidewalls. Because of the strict preference for specific stylistic requirements Helmut Müller and I, who were responsible for the acoustics, could not introduce any diffusing elements on the walls to avoid this.”*. This statement stimulated objective measurements and computer simulations in order to quantify the effect of sound focusing in a real-life case.

2 Architectural features

The Teatro di Corte shows many architectural characters of a Baroque-type theatre. The auditorium has a marked horse-shoe shaped plan and five tiers of boxes. It displays 41 boxes and the royal box whose height is three tiers. The rear of the royal box is open toward a corridor that leads to a couple of rooms and then to the open air. This determines an acoustic coupling of the corridor with the auditorium. The frescoed vault is sustained by twelve stone pillars with leaning half columns of alabaster. The lunette shape of the of boxes of the highest tier configure the dome vault like a seashell. The stage-house has a large door in the back wall. In the past it could be opened on the famous gardens of the Royal Palace that could become part of the scene visible through the proscenium arch. 110 heavily upholstered seats are in the stalls and about 200 wooden seats in the boxes. The length from the stage edge to the rear wall of the auditorium is 14 m. Its maximum width is 12.5 m. The volume is about 2000 m^3. The stage area is 20 m (depth) x 11 m (width) and its volume is 2800 m^3. The Teatro di Corte is not endowed with an orchestra pit. Fig. 1 shows a view of the Teatro di Corte toward the stage (upper part) and a view of the auditorium from the stage (lower part).

Fig.1 – Views of the Teatro di Corte in the Royal Palace in the Reggia di Caserta (Italy). Toward the stage (upper part) and from the stage (lower part).

3 Measurements and results

Acoustic measurements were carried out in the aim of mapping the early reflected sound in the stalls of The Teatro di Corte. The auditorium was unoccupied and the stage house was almost free of scenery. Because of the geometric symmetry of the hall and the symmetric location of the sound source, measurements were performed only in a half of the stalls area. A grid of receiving points was defined by locating the measurement microphone at each seat of the above mentioned area at the height of the ear of an average seated listener in the unoccupied theatre. A dodecahedral loudspeaker was used and it was located at the centre of the forestage as depicted in Fig.2.

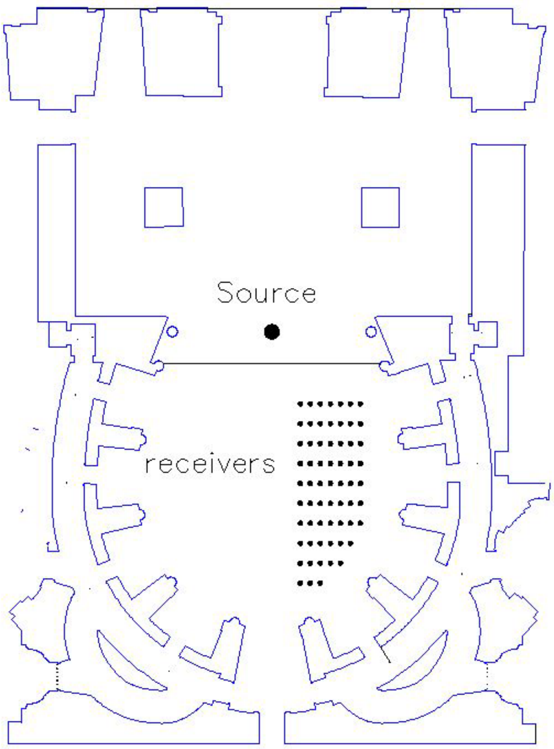

Fig. 2 – Plan of the Teatro di Corte showing locations of the sound source S and 55 receivers in the right half of the stalls area.

Impulse responses were recorded with a MLSSA™ single-channel analyser that fed the dodecahedral loudspeaker with MLS sequences [3]. Care was taken to maintain a constant set-up of the measurement chain. This assured that the over-all gain of the system was constant so that the relative amplitude of the responses was preserved. To give evidence to the early reflected sound the impulse responses were ridded of the direct sound. In fact, 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-energy that is deemed to be useful for speech intelligibility. 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. Fig. 3 shows the maps of the level of the early energy for the octave bands at 500 Hz, 1000 Hz and 2000 Hz. To get non negative values for a better graphical representation, the dB scale in each 1 octave-band map was referred to the corresponding measured minimum value of the early energy. Concentrations of the early energy up to 7 dB can be observed at seats back in the stalls. Most seats nearer to the sound source (blue areas) are supplied with poorer early-reflected sound energy. Room-acoustics parameters like D_{50} and C_{50} [4] were less sensitive in revealing this focusing effects.

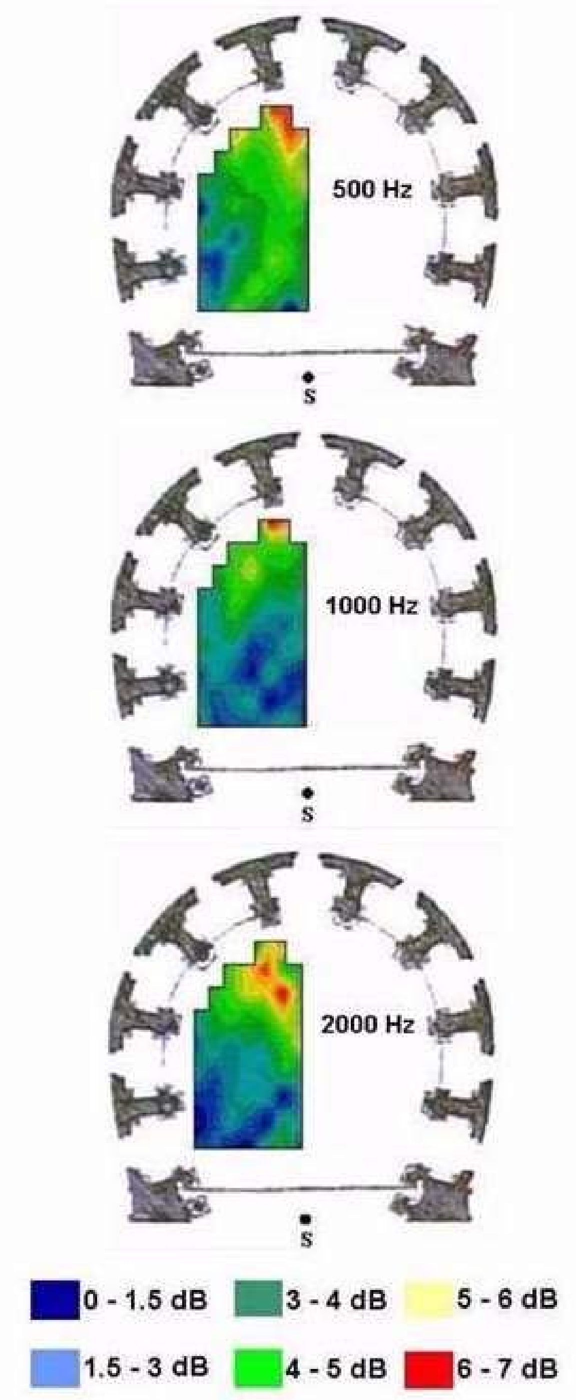

Fig.3 – Maps of the 1 octave-band early energy level measured in "The Teatro di Corte".

4 Computer simulation

A 3D CAD model of the Teatro di Corte including the sound source and 55 receivers was implemented and loaded into the commercial software Odeon^{TM} 7.1 which is suitable for room-acoustics simulations.

Initial trials with various input data-sets needed by the computerized procedure were carried out aiming at the minimization of the difference between the measured octave band, receiver-averaged, room-acoustics parameters (EDT, T_{30}, C_{80}, D_{50}) and the corresponding calculated values. This tedious empirical calibration-procedure of the numerical model of The Teatro di Corte did not succeed enough, e.g. a good match of the octave-band T_{30} curves did not correspond to a good match of the frequency curves for C_{80}. Probably, too many constraints imposed to the procedure prevented the achievement of an acceptable ensemble-minimization. So, the calibration was restricted to room-acoustics parameters calculable with Odeon^{TM} that are influenced more by the early sound of an impulse response, that is D_{50} and C_{80}. Furthermore, care was taken only of the three octave-bands having the centre frequencies at 500 Hz, 1000 Hz and 2000 Hz. Fig. 4 and Fig.5 show the results of the above mentioned calibration. The degree of matching appeared sufficient for the purpose The 55 impulse responses calculated with the numerical model were exported and processed with the same procedure used for the evaluation of the measured early energy mapped in Fig. 3, that is time-windowing, octave-band filtering of the signal of the 45 ms long records, squaring, summing and transforming each sum in a dB scale referred to the minimum sum found for each octave band. Fig. 6 displays the maps of the calculated relative level of the early energy of this work.

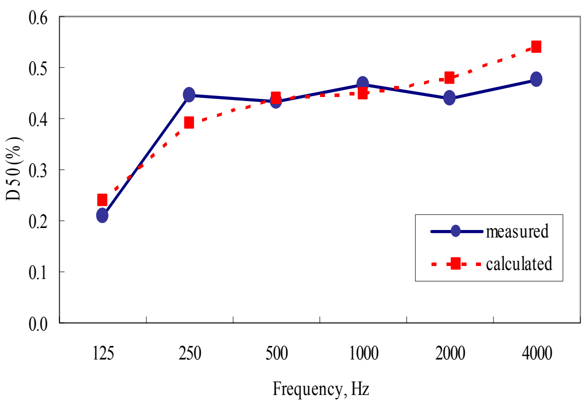

Fig. 4. Calibration of the numerical model of The Teatro di Corte. Measured receiver-averaged D_{50} compared to calculated values.

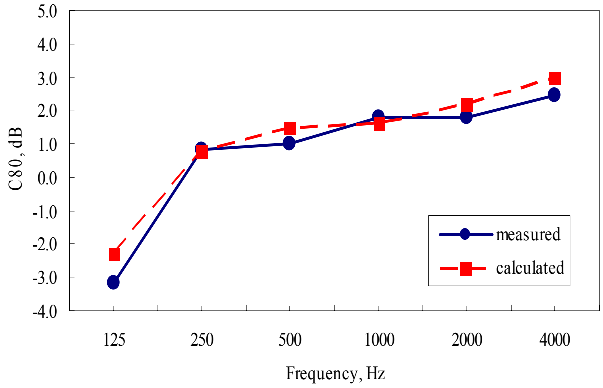

Fig. 5. Calibration of the numerical model of The Teatro di Corte. Measured receiver-averaged C_{80} compared to calculated values.

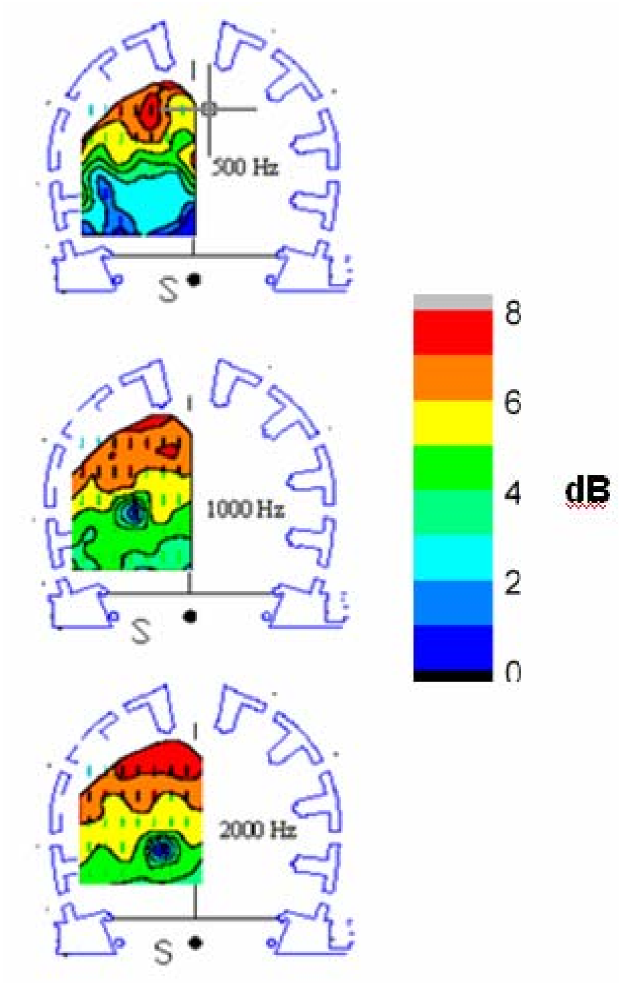

Fig.6 – Maps of the 1 octave-band early energy level calculated in The Teatro di Corte.

5 Conclusion

The reported experimental part of this study has shown objectively the existence of the focusing effect of the curved walls typical of Italian-style opera houses. The case study has quantified also the amount of spatial non homogeneity of the early reflected-sound in The Teatro di Corte" in the Royal Palace in Caserta (Italy) with reference to the frequency range important for speech intelligibility. Although with some approximation and drawbacks, this initial simulation yielded comparable maps showing early energy concentrations at locations back in the stalls. The accuracy of the numerical modelling can be ameliorated, e.g. by taking into account the scattering effect of seats that was neglected in this work. It is the hope of the authors that a better refinement of this model will yield precious information for the numerical modelling of other classical opera houses, a type that is not easy to model.

References

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