ACOUSTICAL IMPROVEMENT OF A HISTORICAL OPERA HOUSE USING ROOM SIMULATIONS

L. Parati [a, *], A. C. Gade [b], R. Pompoli [a], J. H. Rindel [b]

[a] Dipartimento di Ingegneria, Università di Ferrara, Via Saragat 1, 44100 Ferrara, Italy (lparati, rpompoli)@ing.unife.it
[b] Ørsted-DTU, Acoustic Technology, Technical University of Denmark, build.352, Ørsteds plads, DK-2800, Kgs.Lyngby, Denmark (acg, jhr)@oersted.dtu.dk

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ABSTRACT:

In the field of acoustics new techniques have been developed in order to improve the acoustics of a room. Techniques, such as computer simulations, are especially useful in historical theatres where acoustical characteristics can be preserved during renovations or improved with well chosen minor alterations while still preserving the theatre's heritage. These new techniques have been applied to investigate the acoustical balance between a singer on the stage and the orchestra in the pit which is a relatively new concept in room acoustics. Simulations have been carried out in a model of the Royal Theatre of Copenhagen, which was inaugurated on the 15th of October 1874. By means of a few modifications in the type of materials, dimensions and shapes, some of the architectural elements controlling the balance have been identified and optimised.

1. INTRODUCTION

Historical opera houses are a heritage that has to be preserved. This heritage doesn't have to be based only on the architectural aspects but also on characteristics such as its acoustical qualities. The concept of acoustical heritage has been determined in a document called "Charter of Ferrara" (Prodi, Pompoli, 1999), and a scientific tool to quantify the acoustical heritage has been described in the "Guidelines for acoustical measurements inside historical opera houses" (Prodi, Pompoli, 2000).

ISO3382 (ISO3382, 1997) can be considered the normative reference for this kind of room-acoustical measurement and the above guidelines, aim at specializing the norm for these historical places. Nowadays the acoustics of the historical opera house can be modified and problems solved. Among them one of the new aspects which still has not been sufficiently investigated is the acoustical balance between the sound coming from the orchestra in the pit and that from the singer on the stage.

In order to best describe this acoustic aspect which is also important in modern opera houses, an omnidirectional sound source has to be placed in the orchestra pit and a directional one has to be placed on the stage (Parati, Otondo, 2003). By means of room acoustical simulations, it is possible to predict the acoustical behaviour.

The aim of this study is to determine a method to control the balance through modification of architectural elements, without affecting the other acoustic parameters. Furthermore it is desirable to enhance the acoustic qualities of an existing theatre, preserving the historical heritage by means of room acoustic simulations carried out in this case on a model of the Royal Theatre of Copenhagen.

The Royal Theatre (Royal Theatre websites) has been housed on Kongens Nytorv in Copenhagen since 1748. During the eighteenth and nineteenth centuries a new majestic theatre was built in the same place for a larger number of people. It was designed by the architects Vilhelm Dahlerup and Ove Pedersen. It was inaugurated on 15th October 1874. The theatre has an Italian Baroque style, the hall has a horseshoe shape and it houses 1400 people located in the stalls and the four levels of balconies. The stage tower has a volume of 13.000 m^3 with a stage area of 595 m^2 and a fixed proscenium of 115 m^2. The pit has variable configuration based on the required dimension suitable for the orchestra. The pit floor area can reach a dimension of 130 square metres, which means full orchestra. Nowadays it is used throughout the year for opera, ballet and drama. This is the theatre where August Bourhonville worked and founded his famous ballet tradition. Figure 1 shows a view of the theatre from the outside.

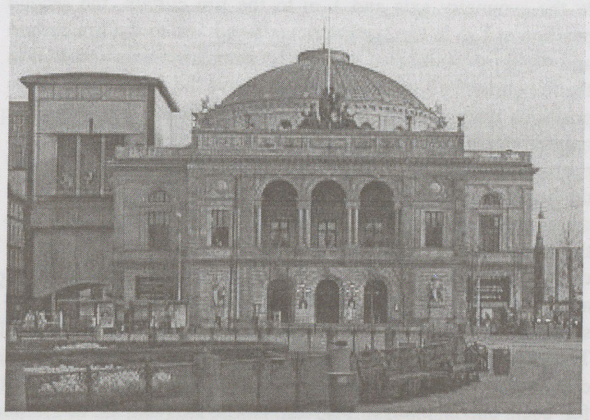

Figure 1: Exterior view of the Royal Theatre of Copenhagen.

* Corresponding author.

2. SIMULATIONS

Before the room acoustic computer models were developed the best way to make a prediction for room acoustics was through measurements in a scale model. Nowadays the room acoustic computer model has reached a good level of reliability (Rindel, 2000; Lynge Christensen, 2001). Modifications can be made in an easy way and in a short time and the results can be evaluated by listening too. Different softwares are available for room acoustic simulations. In this study the ODEON (Odeon websites) software package is used.

2.1 The simulation principles

For the acoustic simulation, a three-dimensional model has to be created (Fig.2). Materials with their absorptions coefficient and scattering coefficient have to be assigned to each surface in the model in order to obtain the desired acoustical behaviour. When the simulation is based on an existing room, the materials have to be assigned so that the model behaves like the real measured room. This procedure is called calibration. Then source and receiver positions have to be fixed. For the simulation algorithm two classical geometrical methods, Ray Tracing and Image Source Method, are combined for early reflections. For the late reflections a hybrid between Ray Tracing and Radiosity is used: a large number of rays are emitted in all the directions from a source point. The rays are traced around the room, loosing energy at each reflection depending on the surface's characteristics. At the same time a secondary source is generated every time a ray hits a surface. Its energy is a small portion of the primary source. The results at the receiver positions are obtained by the reflections collected at the receiver position. Through the impulse response, calculated in each receiver position, the acoustics parameters are obtained and shown in octave bands.

2.2 The simulation procedure

The calibrated room acoustic model of the Royal Theatre was used for all the simulations. Because of its symmetry just one side of the theatre was tested. The directional source was placed on the stage in three different positions: the first position at 1 m to the symmetry axis and 1 m to the fire curtain, the second position at 1 m to the symmetric axis and 5 m to the fire curtain and the third position at 4 m to the symmetric axis and 1 m to the fire curtain, all of them at 1.5 m above the stage floor. These positions were chosen as a singer's significant positions. The omnidirectional source was placed in the pit in three different positions as well: the first violin position, the oboe position and the brass position, all of them at 1.2 m above the pit floor. The directional and the omnidirectional sources were simulated with the same power level in each octave band in order to be comparable. The sound pressure level simulated by the software at each receiver position was the acoustic parameter used in this study.

The energetic average of the sound pressure level obtained at each receiver position (8 in the stalls and 13 in all the balconies) for each single source, playing one at a time in the three different positions on the stage and in the pit was calculated.

The balance was calculated as the difference between the energetic average of the sources on the stage and those in the pit. The results are showed as an average in two frequency band, each covering two octaves: 500 – 1000 Hz and 2000 - 4000 Hz. This process was repeated for each simulation.

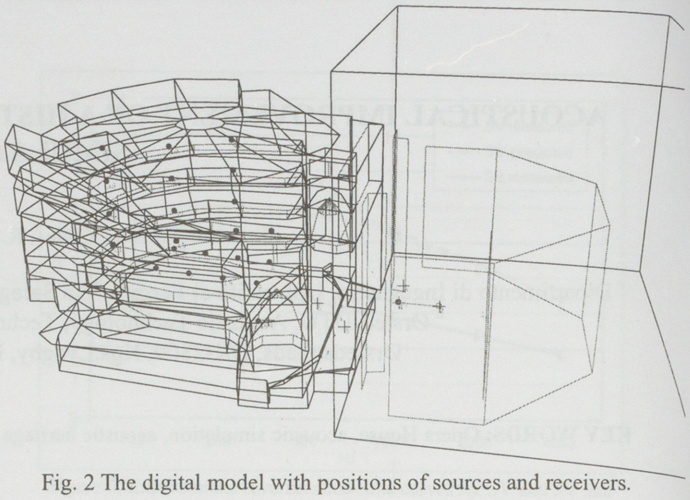

Fig. 2 The digital model with positions of sources and receivers.

2.3 Acoustical design elements

Different changes were carried out based on geometries and materials. The first attempt was to investigate the pit. This element is historically important, but can be modified without changing the identity of the theatre.

The pit depth was changed in order to see its influence on the balance. Firstly a simulation was performed with a pit floor depth level of 1.5 m from the edge of the barrier which separates the pit and the stalls. In the results this change is referred to as "1.5 m". The second attempt was simulated with a pit floor depth level of 2 m from the edge of the barrier. In the results this change is referred to as "2 m". The pit floor was fixed at 2 m from the edge of the barrier in all the following changes.

Subsequently the influence of changing the materials of the pit walls was evaluated. Changes of the absorption coefficient of the wall in the back of the pit, were tested. The new material chosen was more absorbent than the previous one. The purpose was not to look for a particular kind of material, but to search for elements which could influence the balance. In the results this change is referred to as "Pit back wall". This material was fixed for following simulations.

The covering of the pit fence facing the musicians was changed too. A more absorbent material was chosen. In the results this change is referred to as "Barrier".

Other elements were tested. The barrier's height and the stage's slope at 5%, 8% and 10%, but no significant aspect on the balance were detected. Because of this these results are not shown.

2.4 Results

The frequencies of main interest in this study are the octave bands 2000 and 4000 Hz, where the formant of the singer's voice is located and where the emission spectrum of the voice can be compared with that of the orchestra (Sundberg, 1977; Meyer, 1986). In order to have a more complete overview, 500 and 1000 Hz have been considered too.

It seems that two different balances exist in an opera house: one for the stalls and another for the balconies. That's the reason why the results have been divided by stall and balconies: two completely different behaviours are observed. The results are shown based on the distance between source and receiver positions.

Figure 3 shows the calculated balance, obtained from the simulations. Changing the pit level from 1.5 m to 2 m the influence is noted in the stalls but nothing changes in the balconies, for both the average frequencies considered. Keeping the level at 2 m and changing the pit back wall results in an increase in favour of the singer throughout the hall. The last change was the barrier's material with the pit floor at 2 m and the pit back wall material fixed. In the results the behaviour for both cases is the same.

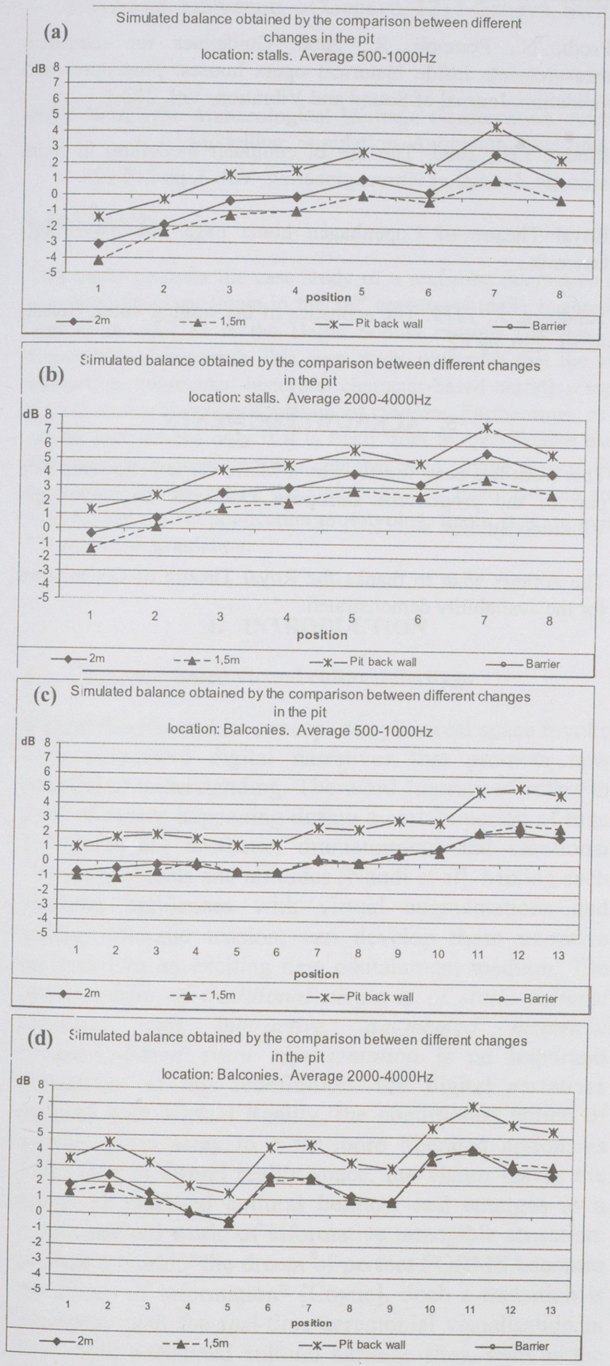

Fig.3 The balance is shown: (a, b) the balance in the stalls at 500-1000 Hz and 2000-4000 Hz; (c, d) the balance in the balconies at 500-1000 Hz and 2000-4000 Hz.

Figure 4 shows the equilibrium between singer-conductor-orchestra. Previous studies suggested that the sound pressure level produced by the orchestra at the singer's ear has to be 10 to 20 dB lower than the sound power level of his voice.

Considering the existing equilibrium between singer-conductor-orchestra no remarkable changes are noted except when the pit floor is at 1.5 m. In this case the conductor has no significant changes in the way he hears the orchestra and the singer. On the other hand the singer hears the orchestra 3 dB stronger than in other conditions.

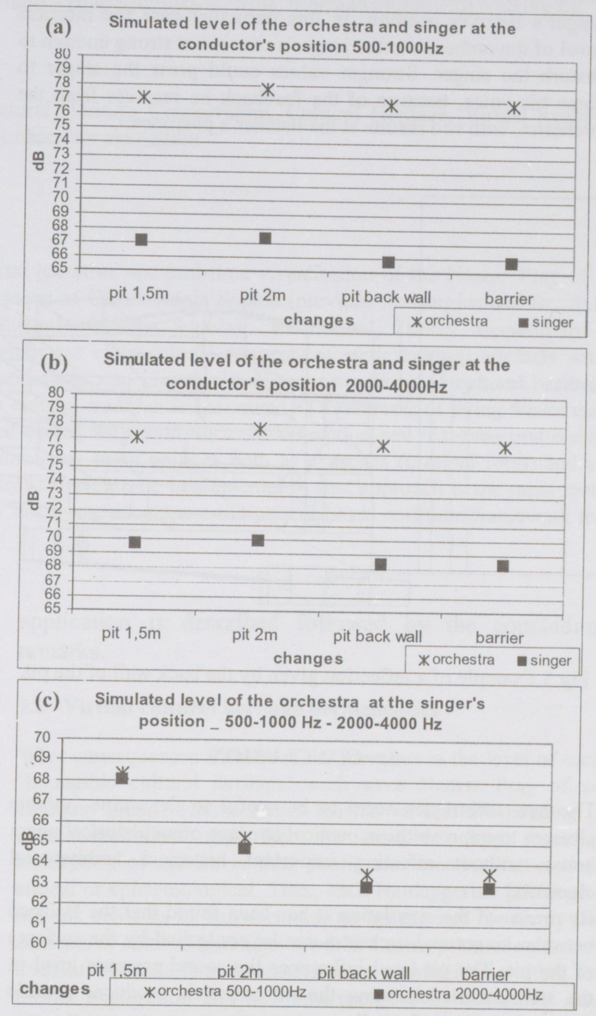

Fig.4 a) and b) show the way in which the conductor can hear the orchestra and the singer a) at 500-1000 Hz and b) at 2000-4000 Hz; c) show the way in which the singer can hear the orchestra at 500-1000 Hz and at 2000-4000 Hz.

2.5 Discussion

The significant difference, based on the pit floor level, between stalls and balconies is based on the fact that independently to the pit level, all the positions in the balconies can see the sources in the pit. This means that the direct sound can reach all the balconies. On the other hand no direct sound can reach the stalls. This part of the theatre is reached by reflections coming from the ceiling. Moving up the pit floor the reflection path is reduced and the sound pressure level increased. The pit back wall contributes to reflect the sound throughout the hall. Changing this material has an influence on the reflections in the stalls and in the balconies. Figure 5 illustrates this.
In all this study the equilibrium between singer-conductor-orchestra was considered too. The pit side material of the barrier

has no influence in the auditorium or on the balance. The influence of it is reflected on the equilibrium between singer-conductor-orchestra. This side of the barrier is responsible for the early reflections reaching the singer from the orchestra and to the conductor from the singer. The tested materials combined with different pit levels showed their influence. In the results the difference can clearly be seen with a pit level of 1.5 m at the singer's receiver position. In this particular case the increasd level of the orchestra at the singer's ears is not strong enough to disturb the singer. Stronger values could press the singer to force his voice, because of the feedback he receives from the orchestra, with bad results at the listener's positions.

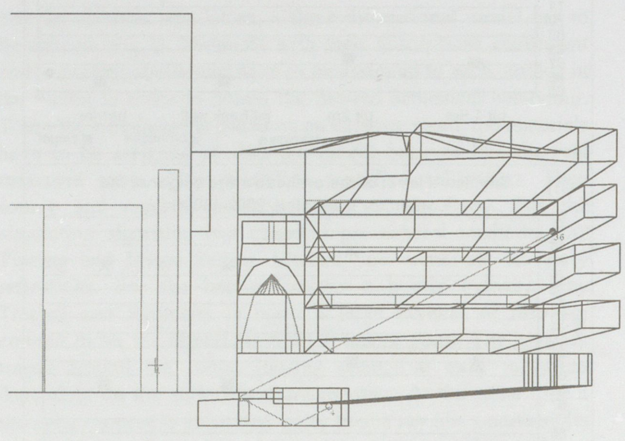

Fig 5 Example of a reflection given by the back wall of the pit.

3. CONCLUSION

The new techniques seem to be useful to determine suitable changes to improve the acoustical heritage of an historical opera house without affecting important historical architectural elements.
By means of the simulation it has been found that the Balance between singer and orchestra can be controlled by the surfaces of the pit. The pit level influences the sound pressure level in the stalls, while changing the pit materials produces notable effects throughout the hall.
The pit fence and the pit level can affect the equilibrium between singer-conductor-orchestra and not the balance.
The stage's slope has minor influence on the balance.
To date, the results presented in this study have been for one model. Future work will include testing in additional models to investigate the general validity of the techniques suggested in this paper.

4. REFERENCES

ISO3382: 1997, Acoustic – Measurement of the reverberation time of rooms with reference to other acoustical parameters.

Lynge Christensen, C., 2001. Odeon – a design tool for auditorium acoustics, noise control and loudspeaker system. Proceedings of the Institute of Acoustics, Vol. 23, pp. 137-144.

Meyer, J., 1986. Some problems of opera house acoustics. In: Proceedings of 12th ICA, Vancouver.

Odeon home page. http://www.odeon.dk

Parati, L. Otondo, F., 2003. Comparison of directional sources in simulating a soprano voice. In: Proceedings of SMAC03, Stockholm.

Prodi, N., Pompoli, R., 1999. Acoustics of opera houses: a cultural heritage. In: Proceeding of Forum Acoustic, Berlin.

Prodi, N., Pompoli, R., 2000. Guidelines for acoustical measurements inside historical opera houses: procedures and validation. Journal of Sound and Vibration, Vol. 232-1.

Rindel, J.H., 2000. The use of computer modelling in room acoustic. Journal of vibroengineering, Vol. 3, pp 219-224.

Royal Theatre of Copenhagen home page. http://www.kgl-teater.dk .

Sundberg, J., 1977. The acoustics of the singing voice. Scient. Amer. 236, pp 82.

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