ACOUSTICAL CHALLENGES IN HORSE SHOE SHAPED OPERA HOUSES

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1 INTRODUCTION

In spite of its intrinsic acoustic challenges, the horse shoe shaped Italian Baroque theatre is still the most common model when new opera halls are designed. Based on the author's experiences in research and consultancy regarding such halls, the following topics will be touched upon in this paper: 1) singer-orchestra balance and how it can be influenced by the stage sets and of the design of the proscenium zone, 2) the effects of pit floor size, pit floor construction, overhangs, sound absorbing surfaces, pit floor height and screens on the musicians' acoustic environment, 3) sound exposure levels in opera orchestras, and finally 4) the application of electroacoustic enhancement either to increase reverberance for both audience and performers (particularly relevant in older opera halls) or as a possible way to improve mutual hearing between singers and orchestra.

2 THE BALANCE BETWEEN SINGERS AND ORCHESTRA

When the new opera in Copenhagen opened in 2005, it was soon clear to the Royal Opera company which had a history of more than 100 years of performing in the smaller "Old Stage", that the new hall was much more challenging. The dimensions of both stage, proscenium and orchestra pit in Operaen is much larger than in the "Old Stage" as shown below.

Comparison	Volume	# of seats	Width of Prosc.	Dist. Stage to 1st row
Operaen	10,300 m^3	1700	17 m	8 m
"Old Stage"	6,500 m^3	1400	12 m	6 m

The auditorium volume in Operaen is about 50 % larger than in the Old Stage, and in contrast to the Old Stage, Operaen has large side stages and rear stages. Consequently, in Operaen the singers easily felt "lost" (lacking support to their own voices) and in combination with the larger visual distance to the audience they felt that they did not reach the audience.
The orchestra also complained. They felt the sound in the pit was too loud, likely because the conductors asked them to play louder in order to fill the larger space.
In the year following the opening this author was asked to help unveiling – or perhaps solving - the stage-pit-balance and the loudness-in-the pit issues. Investigations on ways to improve the level of the singers as heard in the auditorium are described below while the problems of high levels in the pit are described in the following chapter.

2.1 Guide lines for stage set design

The first attempt to improve the balance issue was to define a set of guidelines for the design of stage sets in the new opera, since it is obvious that the stage set surfaces can have a significant influence on how well the singers' voices are projected into the auditorium. The guide lines addressed four factors of importance:

- <u>The size of the active acoustic space</u> behind the proscenium as defined by the stage set dimensions. The smaller this space the closer the singer will be to potentially reflecting surfaces. However, the stage set should not be so narrow or low that the singers experience the surroundings as a local, small space decoupled from the main hall volume. Rather the stage set should form a natural continuation of the surfaces in the auditorium so that singers, orchestra and audience feel that they are in the same acoustic space. In particular, a reflecting wall too far upstage should be avoided, as this could even create echoes back into the auditorium if singers are placed close to the stage front and turning their back to the audience.

- The total surface area of the stage set. In order to reflect as much as possible of the sound emitted by the singers it is advantageous if the stage set includes not only a rear wall but also closed sides and a ceiling surface. This also minimizes the amount of sound energy being lost in the large stage and fly tower volume. Minimizing the area of openings between the stage and the fly tower will also maximize the reverberance in the auditorium (which has a reverberation time around 1.4 Sec. [1]).
- The orientation of the set surfaces. The geometry of the surfaces will define whether the sound is reflected towards the auditorium or back to the singers on stage - or somewhere else. In particular, the angles of the side walls relative to the long axis is important. When the singers turn their side to the audience the reflections off the side walls may even be louder than the direct sound reaching the listeners. Subdivision of the side walls in narrow “legs” parallel to the stage front (as often seen as a way to ensure stage access without the audience being able to see the side and back stage areas) is not helpful.
- The choice of materials for the stage set will determine the efficiency of the reflection. Large areas of absorptive materials like (folded) drapes or sound transparent canvas are not suitable whereas hard, nonporous materials like Plywood, Acrylic, steel and even heavily painted canvas may be applied. For reflecting materials, also the mass per square unit matters. It should be high enough (no less than say 3 kg/m^2) for most of the vocal frequency range to be reflected.

In the guide lines it was also pointed out that the director should place the singers as far down stage as feasible so that they see most of the wall and ceiling surfaces in the auditorium and have maximum contact with its acoustics.

2.2 Enlarging the reflective area in the proscenium zone

Besides the stage set itself, also the proscenium zone and the walls next to the proscenium in the auditorium are important reflecting areas for the singers’ voices. In the new Operaen in Copenhagen (and other newer operas), a technical proscenium is placed on the stage a couple of meters behind the architectural (visible) proscenium. This installation holds theatre lights and other equipment but it also hinders the stage set being placed close to the architectural proscenium and so form a smooth connection to the reflecting side wall surfaces in the auditorium. This discontinuity causes a lack of reflecting area in a zone otherwise well suited to support the singers’ voices. In the design of the NNT Tokyo Opera City hall, Leo Beranek et al. [2] strongly emphasized the importance of this surface as a

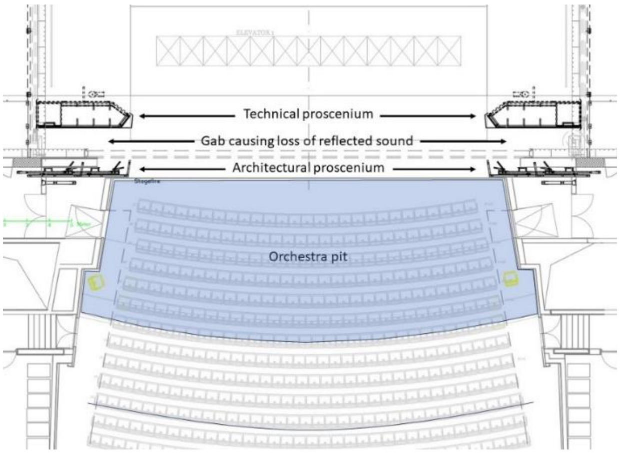

Fig. 1: Plan of the proscenium zone in Operaen, Copenhagen with technical and architectual proscenia

tool to promote better singer-orchestra balance. Figure 1 shows a plan sketch of the proscenium zone in Operaen with the two (moveable) proscenia. In order to test the importance of the missing sound reflecting area, a 1 m wide and about 4 m high reflecting surface was attached to the technical proscenium with hinges, so that during the performance it could be turned and partially close the opening.

2.3 Measured/perceived effects of stage set and proscenium zone reflections

The effects of these reflectors and of the stage set design for singers as well as for listeners in the auditorium were subsequently tested in connection with two performances of La Bohème, for which the stage sets in the four acts were quite different. In Acts 1 and 4, the set indicated a living room as shown in Fig. 2, while in Act 2 the set depicts a market place in front of a large façade including a high terrace. Act 3 is also in the open in front of a small inn.

Fig. 2: Photos of the stage sets used in the performances of La Bohème at Operaen 2006. Left to right: Acts 1 and 4 (living room), Act 2 (in the street), Act 3 (In front of an inn in the countryside).

During both performances of La Bohème, a reverberation enhancement system simulating response from the hall back to the stage [3] was on. Subjective responses were collected from questionnaires filled out by seven singers (members of the cast) and three members of the audience (representing the singers, the management and the author). The singers evaluated the feeling of reaching the audience (filling the auditorium) as well as the degree of support provided by the "room", while the listeners evaluated the level of the singers' voices and the balance between them and the orchestra. The listeners and singers were identical at the two performances and the listeners had the same seats (in the first balcony) during both performances. Still, the results were not very convincing – and perhaps even biased by the fact that the subjects could see the measures (stage sets and reflectors) being tested.
With a time span between the two performances of three days, the listeners (in the first balcony) could not detect any effect of the proscenium reflectors; but it was clear that during both performances the sound level from the singers was weaker during Act 2 (in particular when they stood elevated on the high terrace) compared to the levels during the other three acts. The balance with the orchestra was better when the smaller, more intimate "living room" stage set was used (in acts 1 and 4). With this stage set, the average of the singers' responses also indicated better support and improved contact with the audience, and that the reflectors had a positive influence.

However, although the tendencies in these results made sense, the statistical significance behind was poor. Therefore, a new test of the proscenium reflectors was organized, however without the possibility to have the stage sets present on the stage. The advantage of this test separated from the scheduled performances was that the large time span between the situations to be compared could be avoided. Besides, for this test also the reverberation system was introduced as a variable. In this test, the listeners – mainly when listening from seats in the stalls - perceived an effect of the reflectors, when the singers stood close to them - and somehow the effect seemed to be more pronounced with the reverberation system in use (although this is not intended for the auditorium). With the reverberation system on, the singers experienced a difference between the “true” acoustics in the hall when placed close to the stage front and the “artificial” reverberation when placed further back on the stage. With the system off, they felt less difference between upstage and downstage.
Objective measurements confirmed the effect of the reflectors (for the singers): With a loudspeaker source with human voice directivity placed 2 m from and directed towards the reflector and a microphone placed behind the source (on stage) and 8 m from the reflector, the level from the singer was increased about 2 dB (in the 1 and 2 kHz octave bands) when the reflector was in place.
Overall, it was difficult to obtain clear and unanimous results regarding the influence of the proscenium reflectors – seen as an isolated measure. These reflectors seemed to interact with the stage set and the reverberation system in a way which meant that a combination of these tools was necessary in order to achieve a significant improvement in the singer-orchestra balance.
In spite of our difficulties in documenting through subjective testing the effects of reflecting stage sets and proscenium surfaces on singer-orchestra balance, it is clear that these effects exist. For example, computer simulations that we have carried out during our design of the Royal Drama theatre [4] showed a 3 dB increase on level of a singer facing the audience when an absorptive stage set was changed to a reflective one [5]. However, as indicated by the experiences described above, it can be difficult to document these effects through subjective testing in practical cases with limited reflector sizes and limited freedom to design the experiment.

3 ORCHESTRA PIT PROBLEMS

3.1 Improving the singer/orchestra balance by means of changes in the pit

In the “Old stage” in the Royal Opera Theatre in Copenhagen (build 1874), the singer orchestra balance became an issue after a renovation of the forestage and pit in 1984. Dealing with this problem has been described in a previous paper [6], so here only the main conclusions are repeated.
In the 1984 renovation, the former fully open orchestra pit was partly covered by a new, larger forestage, but the pit could also be extended into the stalls area by removing the first two seat rows as shown in the second and third drawing from the left in Fig. 3. The moveable seating section and the open pit floor area were placed on elevators so that the floor height in these areas could be adjusted. However, most of the musicians immediately complaining about being placed low and partly under the new forestage. On the other hand, the singers were afraid of being overpowered by the orchestra. After long, heated discussions it was decided to carry out experiments to illuminate the acoustic facts. Three configurations with medium pit floor area were tested: a high, uncovered pit (about 1.5 m below stage level) and a 2.0 m deep open pit in front of the forestage or the 2 m low pit partly covered under the forestage. The results were that musicians strongly preferred the high, uncovered pit and that a panel of listeners could not agree on any negative change in the singer – orchestra balance with this setting. (At least, any differences in balance were much smaller than the differences noticed between different seating positions in the hall.) This was confirmed by objective measurements in the seating areas. Changes in G and EDT between the different settings were less than 0.5 dB and less than 0.1 Sec. respectively.

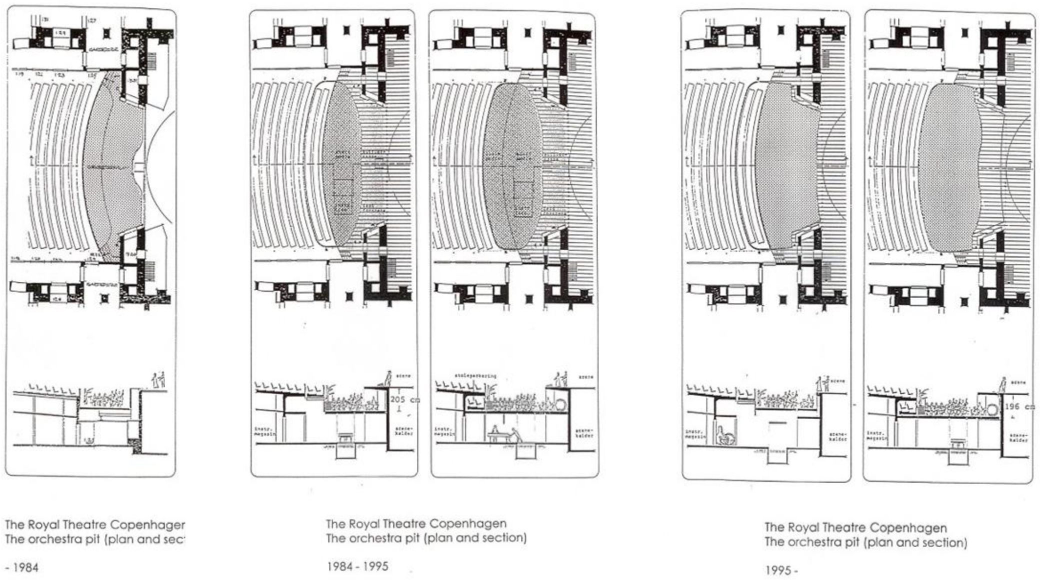

Fig. 3: Plans and sections of orchestra pit configurations in the Old Stage from 1984 to 1995.

It should be mentioned that Parati et al. [7] have carried out computer simulations to study singer – orchestra balance in operas as a function of changing the pit floor height and adding absorption in the pit. Assuming that the level of the playing is unaffected by these changes they found that in a model of the Old Stage the level of the orchestra sound measured in the stalls was reduced by 1 dB by lowering the pit floor from 1.5 m to 2.0 m; but no changes were found in the balcony seats. Adding absorption to the back wall under the stage front reduced the level in all seating areas by about 2 dB. Adding a thin layer of absorption to the wall between pit and stalls seating did not change the orchestra level in the audience area but may reduce the communication between orchestra and singers! (In Parati's paper similar experiments in two other opera hall models are described; but in those cases the effects of the changes were smaller or ambiguous.)

3.2 Consequences for the orchestra in the pit

Measurements in the pit, however, showed dramatical differences for the musicians: ST_{early} [8] increased by 3 dB to a value far above the optimal range (roughly -11 to -13 dB according to own experience), and EDT dropped by 30 % to 0.6 Sec. in the low, covered situation - far below the value in the hall. In other words, it was documented that the musicians in the pit would be deprived of contact with the acoustic conditions in the auditorium if placed in the low pit. As a consequence, in 1995, the new, fixed forestage was torn down and changed into a forestage/pit-elevator, so that the orchestra could sit in the open pit with a free choice of pit height - even when the pit floor area was at its maximum (the two rightmost drawings in Fig. 3). The management was also happy to be able, again, to sell tickets for the first two seat rows whenever only the medium sized pit was required.
About the same time, concern was raised about the sound exposure levels at the musicians' ears and the working environment authority demanded that sound absorption should be installed in the orchestra pit (as is customary near "noise" sources in work places). The acoustic effects of introducing absorption on the pit walls were therefore tested by measuring sound Strength, G, as a function of distance and ST_{early} and EDT versus frequency in the pit both with and without absorption. In the two sets of measurements the floor area and pit floor height in the empty but furnished pit were identical. The results of the ST_{early} and G(distance) measurements are shown in Fig. 4. It is seen that while ST_{early} drops by 1 – 2 dB, G remains almost unaltered. Also EDT showed practically no difference between the two configurations.

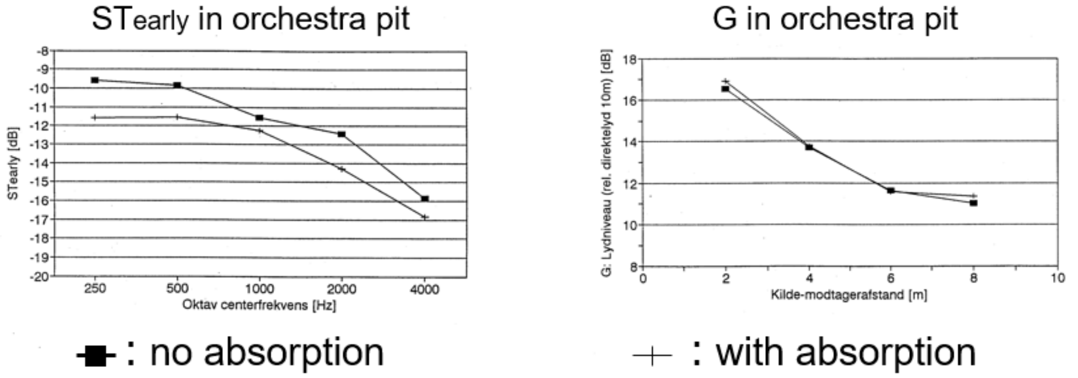

Fig. 4: Measured STearly versus frequency and G versus distance in orchestra pit with and without absorbing walls.

These results demonstrated that absorption does not reduce the exposure levels. This is in line with the findings of Wenmaerkers who also found that the sound levels reaching the musicians' ears (except for cello and bass players) are primarily determined by the direct sound from their own instruments [9]. On the other hand, the early reflections which should help the musicians hearing of more distant colleagues' instruments are attenuated. Therefore, the most likely result of adding absorption is that ensemble playing becomes more difficult which in turn may cause the musicians to play even louder because they cannot judge how to balance with the other musicians - and with the singers for that matter. (Important work on how level differences affect hearing one self and hearing others has been carried out by Naylor [10]). Therefore, introducing absorption in the pit might result in both higher exposure levels and poor singer-orchestra balance. If this hypothesis is true, "noise problems" in musicians' work places cannot be treated in the same way as in other professions. Adding absorption on surfaces around the orchestra could be counterproductive. However, small areas of absorption placed locally on walls or on screens near very loud instruments has proven useful for reducing radiation of specific, loud instruments.

Please note that in Parati's simulations the powers radiated from the pit and from the stage sources were held constant across the configurations – i.e. assuming no effect of the changed acoustic environment on the power generated by the musicians in the pit! The authors' hypothesis is that the playing level may well depend on the acoustic surroundings experienced by the players: such an increase in playing level could perhaps be larger than the 1 dB reduction measured, when the pit is lowered by 0.5 m. Likewise, the loss of Support - when the pit rear wall is made absorptive - may also well cause the played level to increase by more than the 2 dB reduction found in the simulations. Anyway, the reduced acoustic quality experienced by the musicians is a high price to pay for the dubious effect on the balance.

3.3 Influence of the pit floor construction

For reasons of fire protection, the new pit floor built during the 1984 renovation of the Old Stage was made as a double layer of wood on gypsum board. Cello and double bass players strongly disliked this new “dead” floor. Therefore, before the 1995 renovation a number of other floor constructions were tested by building floor samples which were tested both by cello/bass players and by objective measurement of the radiated sound after broad band excitation with a vibration exciter. Players testing the samples (placed on the existing dead pit floor) are seen in Fig. 5, while the three graphs in Fig. 6 show the 1/3 octave band values of the sound radiation from the existing layered floor as well as from two alternatives of either 20.5 mm Honduras Pitch Pine or 25 mm Swedish Pine both build as massive planks on laths over air space. As can be seen, the massive wooden floors radiate between 5 and 10 dB more sound in the 125 to 630 Hz region compared to the wood/gypsum layered floor. As could be imagined this was much preferred by the players and was said to bring back the warm string sound of the orchestra which they had also had before the 1984 renovation. (In Operaen, the floor is made of 45 mm plywood.)

Fig. 5: Testing different floor samples in the Old Stage pit by cello and bass players

Increasing the level of the sound from the orchestra could seem to be “dangerous” for the delicate singer – orchestra balance; but it is not the sound power from the strings which dominates in the total output of the orchestra, and it is likely that the bass and celli are less likely to force their instruments when they experience a full-bodied response from the floor. Besides, it is not the very low frequencies which masks the singers’ voices (if these contain a suitable “singers’ formant” [11]) and the propagation of low frequency vibrations in the floor are often considered to help the communication within the orchestra. So, again, allowing the orchestra to bloom may well be positive for the singer-orchestra balance.

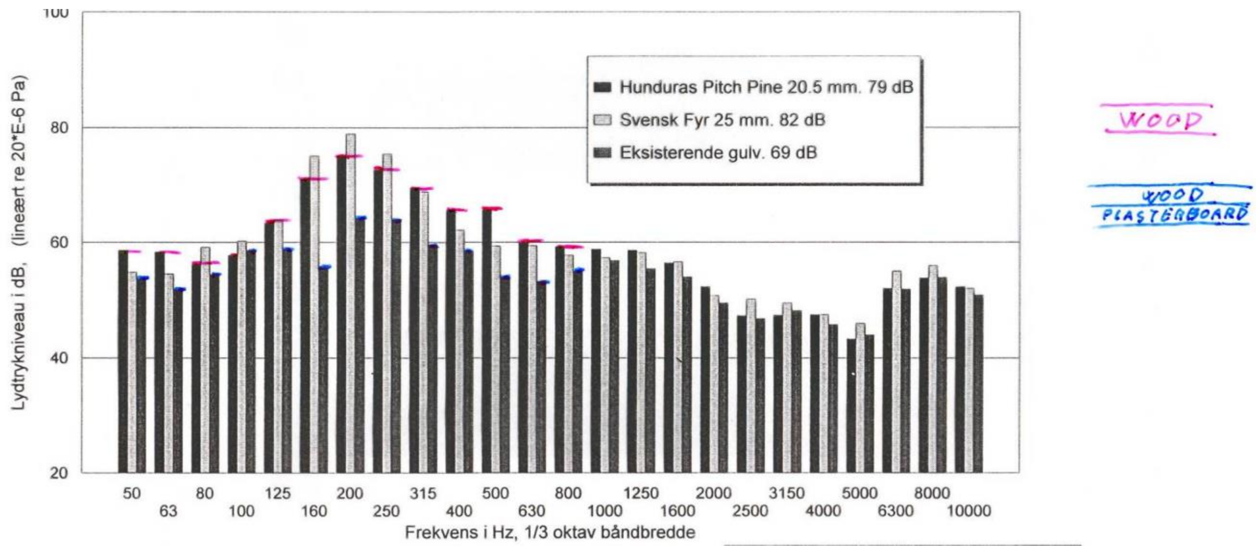

Fig. 6: measured levels of radiated sound from floor samples. For each 1/3 octave, the bars from left to right represent 20.5 mm Honduras pitch pine, Swedish pine, existing floor (wood on gypsum board).

4 SOUND LEVELS IN PITS AS AN OCCUPATIONAL HEALTH ISSUE

4.1 Influence of the pit floor area per musician

Excessive orchestra sound levels are not only a problem for the singer-orchestra balance. It is also a matter of occupational health for the orchestra musicians. In connection with consultancy for the Royal Opera in Stockholm, Sweden we received access to a huge amount of data regarding problems experienced by orchestras in opera houses throughout the world. Our analyses of these data based on questionnaire responses from the managements in 46 venues staging opera were reported in [12]. The main results were that problems with excessive sound levels and difficulties in achieving ensemble – largely related to insufficient floor areas in the pit - are experienced in 2 out of 3 opera houses. As shown in Fig. 7, The average floor area per musician in pits, from which no such problems were reported, was just about 2 m^2, whereas the average area in pits with problems was close to 1.5 m^2 per musician. With insufficient floor space, it is difficult to optimize the orchestra lay out for proper mutual hearing including obtaining sufficient distances to the loudest instruments (brass and percussion) and space for placing sound attenuating barriers or screens if needed.

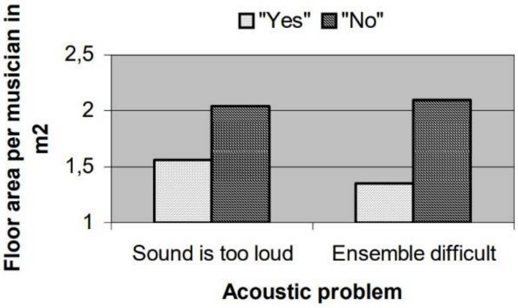

Fig. 7: Average floor area per musician in opera houses answering “yes” and “no” respectively to questions about problems of loudness and ease of ensemble. Results based on data from 46 opera houses around the world.

4.2 Effects of introducing screens in the pit

Our own experiments in the pit in the new Opera in Copenhagen a few years later confirmed the importance of sufficient pit floor area. The experiments – which were initiated by the musicians’ impression of being asked to play louder in the new, larger hall - had the sole purpose of investigating how the levels in the pit could be reduced through rearranging the orchestra layout and introducing screens. Questionnaires were distributed to orchestra members during rehearsals of “Maskerade” (opera by Carl Nielsen) and “Elektra” (by Richard Strauss) and accompanied by measurements of the efficiency of different screens placed around the louder instrument groups [5]. The floor area in the pit is 130 m^2 plus 28 m^2 under the forestage; but this covered part is practically always closed off by mobile wall elements and only used for storage and access. When using only the uncovered area, the area per musician was 1.4 m^2 for Elektra with 92 musicians present whereas 2.0 m^2 was available for each of the 66 musicians required for Maskerade. It was obvious that problems with excessive levels and poor ensemble conditions existed mainly during Elektra. The musicians commented that these problems were primarily a result of certain loud instruments (normally French horns, brass and percussion) being too close for the musicians to hear other instruments (including their own) in proper balance. (Obviously, the different orchestrations in the works of Strauss and Nielsen will also be an important factor.)

The objective measurements on different screens placed in the furnished pit were carried out with a small, fairly directive sound source placed 1 m from the screen while an omni directional microphone was placed at half a meter distance on the other side. As seen in Fig. 8, the screens gave 5 – 10 dB of attenuation above a frequency related to their overall size. The screens which attenuated already from 500 Hz were about 100 cm wide and 80 cm high; but smaller screens attenuating from 1000 Hz and above might be equally appropriate, since the musicians did not like to be separated by "walls". It should be added that the brass players preferred the screens in front of them to have absorptive cladding facing their direction. Thus, the screens should be absorptive on both sides.

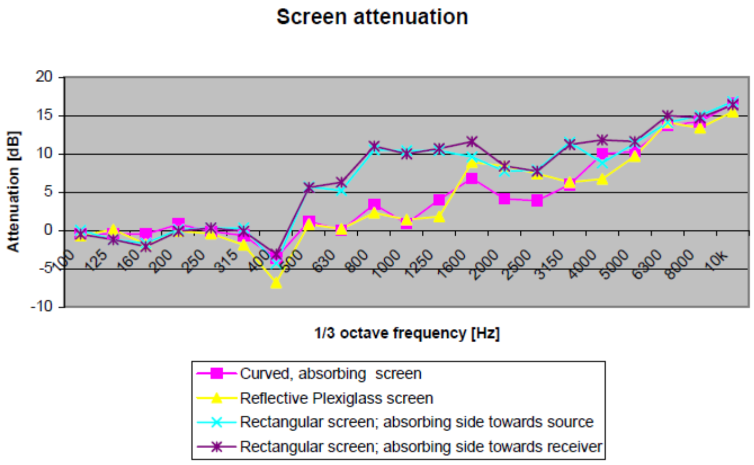

Fig. 8: measured attenuation of sound levels by different sound screens placed between musicians in orchestra pit. See text for details.

4.3 Pit musicians' exposure levels

In 2008, the EU Directive 2003/10/EC specifying a maximum eight-hour noise limit of 85 dB in work places was implemented also in the music industry. Soon after, we were asked by a couple of Danish orchestras – including the Royal Opera Orchestra – to investigate whether or not they complied with this requirement. In the process of estimating the exposure levels (according to the ISO 9612 standard) of members in the opera orchestra, we measured noise levels over entire rehearsal and performance sessions with dose meters attached to ten of the orchestra musicians. The measurements – typically lasting two to three hours (excluding larger breaks and other irrelevant events) – were carried out in both the Old Stage, the new Operaen and in a couple of orchestra rehearsal halls in Operaen. Unfortunately, it was not possible to compare the two opera halls with the same piece being performed, because after the opening of Operaen, most of the larger opera productions have been performed in Operaen while smaller classical operas and ballets are staged in the Old House. However, it was possible to measure on each of four works both during rehearsals in regular rehearsal halls as well as during performances in the two stages: the opera by W. A. Mozart "The Marriage of Figaro", the ballet by Sergei Prokofiev: "Romeo and Juliet", the operetta by Frans Lehár "The Merry Widow" and the opera by Bo Holten "The Visit of the Royal Physician". The volume and RT values in the two rehearsal halls were 4,400 m^3 and 1.2 Sec. (hall 1) and 2,300 m^3 and 0.8 Sec. (hall 2) respectively.
The $L_{A,eq}$ results from the rehearsals and performances averaged over ten dose meters (10 musicians playing different instruments) are shown in the table below along with their verbal comments:

Dose meter levels	Romeo (Ballet) Rehear.	Romeo (Ballet) Perform.	Figaro Rehear.	Figaro Perform.	Merry widow Rehear.	Merry widow Perform.	Livlægen Rehear.	Livlægen Perform.
Hall	Rehear. Hall 1	Old Stage	Rehear. Hall 1	Old Stage	Rehear. Hall 2	Operaen	Rehear. Hall 1	Operaen
$L_{A,eq}$ 2-3 hours	**85 dB**	**91 dB**	**86 dB**	**85 dB**	**86 dB**	**89 dB**	**86 dB**	**90 dB**
Verbal	Average	Very loud	Weak/aver.	Weak	Average	Average	Average	Loud

Regarding the final exposure levels, all instruments except celli and double basses were subject to levels above 85 dB. The levels ranged between 87 and 93 dB with trumpet and percussion being subject to the highest levels. Interesting, also violin and viola players were exposed to levels of 90 dB or above, likely because they have one ear placed very close to their own instrument. Variations in $L_{A,eq}$ between different performances of the same work on different evenings were smaller than 1 dB! Unfortunately, it was not possible to measure whether the playing level in Operaen was louder than in the Old Stage, because the works played in the two venues were different; but it looks as if the levels are higher during performances in the pit than in the rehearsal halls. However, most likely this is not a result of differences in the acoustic conditions but of the different situations. During the rehearsals there are often small periods without playing where the conductor and musicians talk and musicians make notes in their music sheets. Besides, the musicians (and the soloists as well) turn up the intensity and level during the performances compared to the rehearsals. It is seen that the increase from rehearsal to performance is particularly large in case of the ballet (Romeo and Juliet) – perhaps because there are no singers with whom the orchestra needs to balance its output.

5 ARE ELECTRO ACOUSTIC SYSTEMS THE ANSWER?

In several cases, electro acoustic systems have been used to reduce acoustic problems in classical opera houses. Around 2000, the author was involved in designing and implementing reverberation enhancement systems in a number of Danish halls, among them the Old Stage. In the Old Stage it was hoped that the system (consisting of 256 loudspeakers hidden in ceiling and in walls and on the stage) could provide more warmth and reverberance (a relevant desire in many Italian Baroque style operas) in the auditorium and under the deep balcony overhangs - and bring some of that room response back to the singers on stage as well. With separate microphones used to pick up of the sound from the pit and from the singers on stage it is also feasible to influence – to some degree - the singer/orchestra balance in the auditorium. The graphs in Fig. 9 show the reverberation times obtained (measured in the stalls seating area). It should be mentioned that the very high values at 125 Hz does not reflect the listening experience. The level of the artificial reverberation is quite modest so the increase in EDT – and hereby the experience of “fullness” and “warmth” – is more moderate. This system is still in use today, so apparently it has a positive effect.

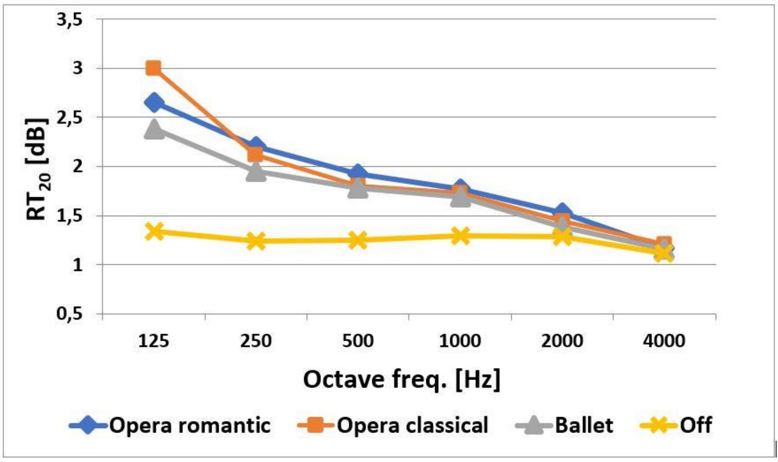

Fig. 9: Reverberation time values measured in the OLD Stage, Copenhagen with three different settings of the reverberation enhancement system and with the system off.

As already mentioned, a sound system was installed in the new Operaen already before the opening to simulate response from the hall back to the singers on stage, while another system also amplifies the sound from the orchestra to the singers on the stage.

Naylor [13] proposed a different system which emits a mix of sound from the auditorium and sound from the singers into the pit through small loudspeakers installed in the ceiling under the pit overhang.

About 25 years ago this author also developed an idea for a system assisting communication within the orchestra under a deep overhang; but (perhaps fortunately) installation was never attempted.

In the huge Bastille Opera in Paris (seating 2745!), the singers are amplified in some cases; but that can be regarded a consequence of ambitions towards audience sizes exceeding the limits of singers' voice levels in natural acoustic spaces. Fortunately, the general tendency is still for traditional western operas to be performed in moderate sized halls without amplification. Due to the proscenium stage and orchestra pit geometry in traditional opera settings, some electro acoustic assistance is sometimes needed in communication between the performers; but our goal is still to design for the natural acoustics to cater for as many of the acoustic needs as possible.

6 CONCLUSIONS

Although acoustic problems in Italian Baroque style theatres such as focusing from concave walls and ceilings, false localization of some instruments in the pit, too little reverberation and poor sound under balconies have been solved in modern versions of these theatres, a few problems remain: primarily poor balance between singers and orchestra and a need to better protect the hearing of the musicians.

It is possible to improve the balance between singers and orchestra in proscenium theatres by ensuring large reflecting areas in the proscenium zone and by careful design of the stage set. This author is more skeptical towards making changes in the pit such as adding absorption to surfaces around the musicians, introducing overhangs or lowering the pit floor. Not only were the results regarding balance experienced by listeners unclear, but the conditions for the musicians were found to be seriously worsened.

Pit orchestra members live risky lives with respect to damage of their hearing. Exposure levels are close to or above the EU regulations for noise levels in work places. Some physical measures can reduce the levels such as adequate pit size per musician and use of absorptive screens (and perhaps small areas of absorption near loud instruments); but this author is convinced that the best measures are to ensure proper listening conditions and to work towards a more suitable playing style. Unfortunately the authors hypothesis that poor hearing of others can lead to louder playing has not yet been scientifically tested; but it seems to be an idea which many musicians find realistic.

Electroacoustic systems can help solving problems of mutual hearing and reverberance in existing theatres: but hopefully the physical designs can be optimized so that opera performances in general will not turn into amplified events with musicians using in-ear monitors. Most opera performers and audiences still wish to hear opera in natural acoustic surroundings and not through a sound system.

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