STAATSOPER UNTER DEN LINDEN BERLIN

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1 INTRODUCTION

The State opera Unter den Linden was built as the first detached court opera building in Europe in 1742. The building was severely damaged several times in history (1842, 1942,1945) and also restored or renovated several times (1788,1910,1928,1986). The in 2009 existing situation was created after the war, in 1955. In the period from 2010 to 2017 the building was fully renovated and all technical equipment renewed. A new rehearsal building was realised with 7 rehearsal halls, including a choir rehearsal hall and an orchestra rehearsal hall. The historic opera hall has 1350 seats and a small hall with a flat floor: the beautiful Apollosaal. This paper concentrates on the acoustical aspects of the renovation of the opera hall.
Starting points of the renovation are a substantial improvements of the room acoustic of the hall , at the same time preserving the architectural design and monumental status of the hall. Since the acoustic of the hall results from the geometry and the architecture, this is a contradiction in requirements.
In this paper we describe the steps in the acoustical design and the results after realisation.

2 ACOUSTIC OBJECTIVES FOR THE OPERA HALL

The opera hall in 2009 had 1350 seats and a volume of about 6500 m^3, this was a rather small opera, as most 18th century opera halls were small. The size didn't change over history[1]. Figure 1 and 2 compare this hall to other main opera halls in the world[2]. These show that the hall had a short reverberation time (RT) and a low specific volume. From Sabine's formula it is clear that, given an amount of absorption by each audience member, a minimum volume per person is required to obtain a certain reverberation time. The grey area in figure 1 shows that there is a maximum reverberation time related to the volume per person, above that there are no data points. Including all other sound absorption in addition to the absorption of the audience, the effective minimum absorption seems to be around 0,7 m^2 per person.

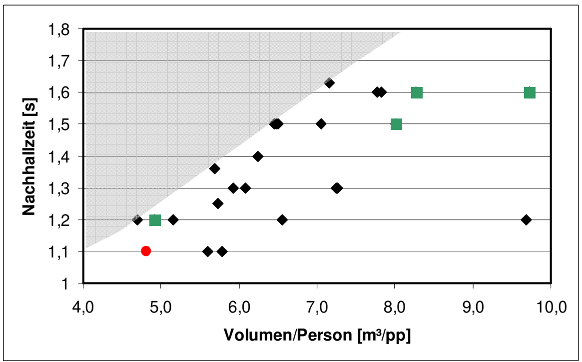

Figure 1. Measure reverberation times (1 kHz, occupied) related to the specific volume for 32 opera halls[2] .The green squares are opera halls that were judged to be very good[2]. Red: State opera Berlin.

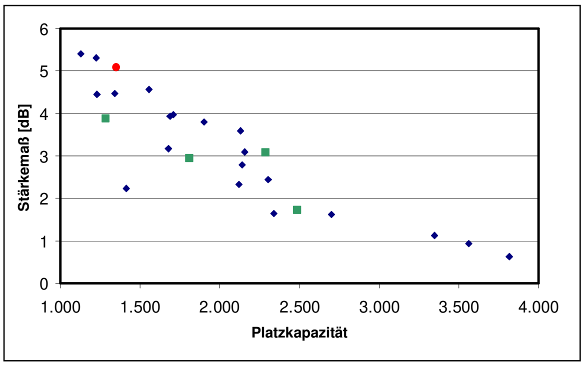

Figure 2. Strength G (1 kHz, occupied) related to the number of audience for 32 opera halls. The green squares are opera halls that were judge to be very good[2]. Red: State opera Berlin

The strength is mainly depending on the number of audience and is shown in figure 2. Here the strength is calculated theoretically from volume and reverberation time. Reason for that is that published strength data is not sufficiently available and not always sufficiently reliable, since it is quite a difficult measurement regarding the calibration of the source. Based on several measurements we did in opera houses, a loss of 2 dB for energy towards the stage house is included: $G = 31 - 2 - 10\log(V/24T)$ [dB]

The data show that the Berlin opera hall is relatively loud and this corresponds to the subjective impression of the authors. On the other hand, it may be so that many opera halls are not very loud, the strength is clearly below 4 dB. From an economic point of view it might be interesting to build a large opera hall, but the acoustical draw back is that it will not be loud enough. The limit seems to be around 2000 people audience.
The acoustic objective we formulated for this hall is that the reverberation time should be increased to 1.6 s. (occupied, safety curtain closed) but without increasing the loudness.
A specific volume of 7 m^3 per person would be necessaryto achieve this RT in combination with a strength G of about 5 dB (figure 1), corresponding to the existing situation (figure 2).
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With 1350 people audience and 7 m^3 per person, a volume would be required of 9500 m^3, this is an increase of 3000 m^3 compared to the existing hall.

3 DESIGN OF THE OPERA HALL

3.1 Coupled spaces

From the heritage perspective it was not possible to change outer walls, roof height or interior design, so enlarging the floor plan was impossible. Lowering the floor would cause large problems in the under stage areas. So the only possibility to increase the volume was to raise the ceiling and use the attic space. This space was sufficiently large to achieve the additional 3000 m^3. However another solution had to be found for the trusses that bear the roof. Smaller trusses were made and a large horizontal truss construction was added to take up the horizontal forces from the saddle roof.
From an acoustical point of view the question was how much this additional space should be coupled to the main volume of the hall. Based on theory of diffuse sound fields[3] a calculation model was made. From this theory it can be derived that with a source in room 1, the sound level in room 2 will be lower in steady state, the difference being:

$$L_{P_1} - L_{P_2} = 10\lg\left(1 + \frac{A_2}{S}\right)$$

Where A_2 is the absorption in the coupled room 2 and S is the open area connecting the two rooms.
When the sound level in room 1 drops, it is fed by the sound from room 2. But there is a delay due to the level difference and this causes a curved, sagging decay. For impulsive sounds, like music, room 2 has to be filled with sound energy first, before it can contribute to the decay of room 1, this causes an additional delay.For the subjectively important first part of the decay the additional space acts as a sound absorber.

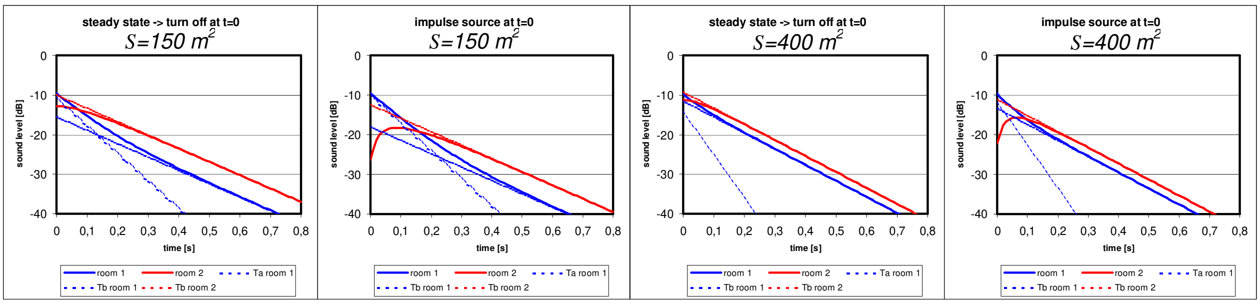

Figure 3. Diffuse field sound decay after switching off a steady state signal or after an impulse signal, room 1: 6500 m^3, room 2: 3000 m^3, coupling surface S: 150 m^2 (left) or 400 m^2 (right).

Figure 3 shows the decay of the diffuse field for a low and a strongly coupled secondary space, both for turning off the steady state signal as for an impulsive signal. From this study it was decided that the new volume should not be decoupled from the main hall, and therefore it was decided that the coupling surface should be maximised, the additional volume should be part of the main space.

3.2 Calculations with ray tracing

Due to monumental protection reasons, the existing ceiling should be preserved. It was decided to raise the existing ceiling by 5 m. It was possible to enlarge the hall above the corridors of the 3rd floor. Like a mushroom the hall is enlarged to the outer walls, creating a "reverberation gallery". From this space (and many intermediate designs) a 3D model was made and used with ray tracing for calculating reverberance and strength.
Figure 4 shows the 3D models of the existing hall and the final design in the longitudinal section of the building. It was possible to achieve 9300 m^3. With closed fire curtain (FC) an average RT of 1,6 s. was calculated. With open curtain it depends on the stage set being used. With the set that was on stage during the measurements in the existing situation, the resulting RT's are a bit lower (fig. 5).

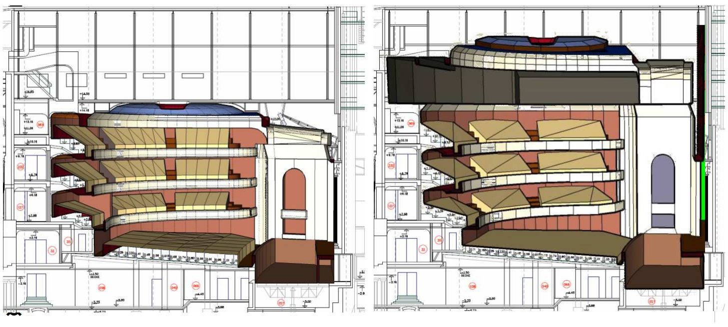

Figure 4. acoustic calculation model overlaying the longitudinal section of the hall. Left: existing before 2010, right: final design.

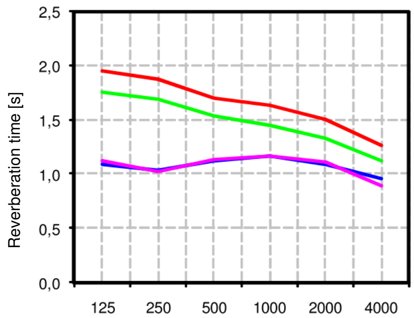

Figure 5. measured and calculated RT with audience (simulation). Violet: exiting measured FC closed, Blue: existing calculated, Red: new with FC closed, Green: new with FC open.

3.3 Scale model research

In order to incorporate the wave character of sound, the initial research through calculations was extended with a scale model. A scale model 1:10 was made, details with size 10 cm, in many cases also smaller, were taken into account. Reflecting surfaces are wood with varnish, audience by pyramid foam, simulating an occupied hall, see figure 6.

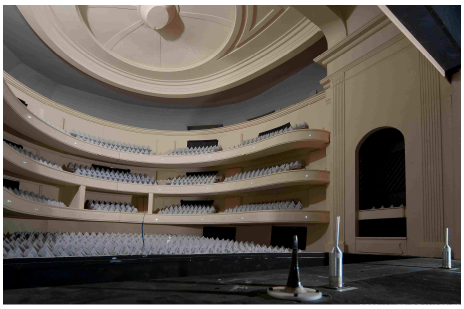

Figure 6. Scale model 1:10 with the raised ceiling and reverberation gallery. High frequency source and microphone with pre-amplifier in foreground.

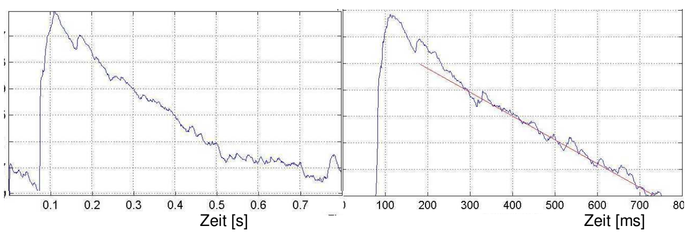

Figure 7. Measured and smoothed (20 ms) impulse response ETC from fore stage to middle of 3rd balcony of existing hall (before 2010). Left: 1:1, right: 1:10. 6 dB/div.

As with the calculations, first the existing situation was examined and fitted to the measurement data and after that the new situation. Frequencies are raised according to the scale factor. Omnidirectional sources and microphones are adapted to the adapted frequency range. Contrary to the frequency the air absorption can not be scaled linear. This is compensated by a calculation algorithm. To obtain maximum stability in the impulse response (IR) the air in the model was air conditioned. Measurements were done with a MLS signal and Energy-Time Curves (ETC) were calculated. From these data parameters like clarity were calculated. Reverberation time was only considered roughly, since sound absorption data of the scale model materials is not exactly corresponding the real scale materials. Nevertheless the model showed an RT increase from 1.1 to 1.6 s. (occupied, FC closed). Figure 7 shows a comparison of the measurement in reality and in scale model. Although not completely identical, the trend is very similar.
In the further process of investigations and design, many alterations and improvements were investigated. Two of them are discussed here.
At first instance the wall of the reverberation gallery follows the elliptical shape of the hall. Figure 8 shows that an group echo occurs at the front seats at the stalls. By introducing a folded, sound scattering structure the problem was solved.

Also visible is a gap in the IR at this position, due to lacking early reflections from the stage. This is typically something to solve with proper reflection stage sets.
The architect that renewed the hall after the fire of 1843 made an article in 1810 about sound focussing due to elliptical ground plans in theatres[4]. Also the existing situation from 1955 has walls that follow the form of an elliptical cylinder. Calculations based on the Kirchhoff integral[5] show the first reflection with focussing areas, fig. 9. Compared to direct sound the calculated increase is 7 dB.

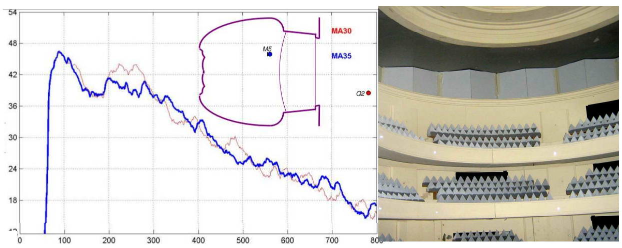

Figure 8. Measured and smoothed (20 ms) impulse response ETC from the stage to front of stalls. Left: red is with elliptical wall, blue is with folded walls.

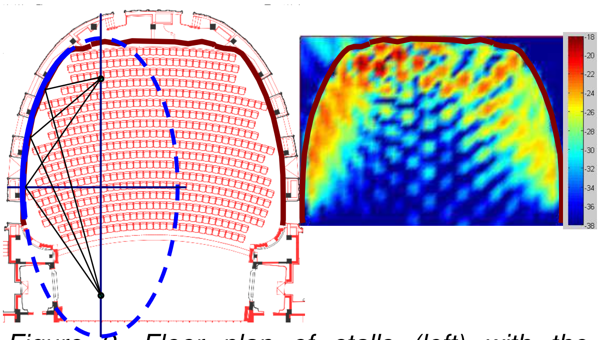

Figure 9. Floor plan of stalls (left) with the segment of an ellipse (blue) and sources and receiver points that result in focussing. Right: calculation[5] of the first reflection (125 Hz).

A practical comparison with the existing situation was hardly possible: In the existing situation these walls were partly sound absorptive, which should be replaced by reflective walls to obtain the required reverberation time (see chapter 3.4). A possible solution would be to introduce scattering on the walls, that would be contradicting the need to preserve the monumental interior. This topic was investigated in the scale model. With curved mirrors on the walls and a light source, the exact position of the focussing was located and at this spot the impulse response was measured. Figure 10 shows that the first reflection is indeed higher than the direct sound, but the increase is limited and since also the time delay is limited, this will not be perceived as an echo. Based on the scale model results it was decided not to implement scattering on the walls.
Other topics that were investigated during design phase were for example the raise of the fore stage ceiling, orientation of the windows of the control room, lowering the orchestra pit, diffusors in the pit, orchestra reflectors and reflectors in the fore stage boxes.
When the hall is being used for symphonic music, the orchestra plays on stage and the raised floor of the orchestra pit. Early 2017 a new orchestra shell was designed and built, based on ray tracing calculations and scale model research. Important issue was to realize early reflections and at the same time open up the shell towards stage house, to control loudness on stage and in the hall.

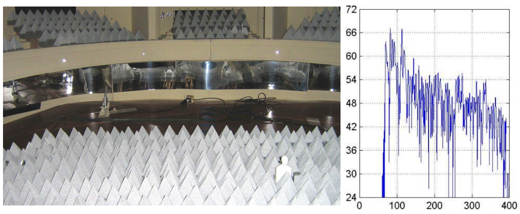

Figure 10. Left: scale model with curved mirrors on the walls, right: measured ETC in the focal point.

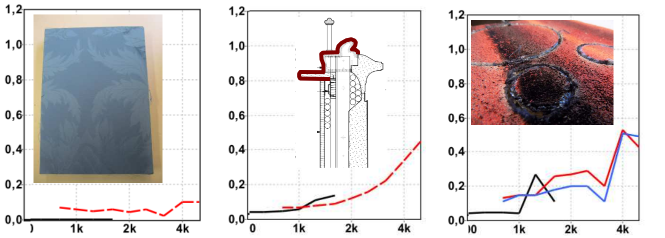

Figure 11. Measured sound absorption in the interferometer, after optimisation. Left: wall finishing (glued woven textile), middle: railings (glued velvet), right: wall above stage opening (glued velours).

3.4 Control of sound absorption

The increase in reverberation time could not be obtained solely from the volume increase, since this will also increase absorbing surfaces. So the absorption of other surfaces needed to be decreased. The panels of the timber walls were replaced by heavy panels (40 kg/m^2) with new textile glued to the panels. Also other textiles like velvet covering of the railings and the wall segment above stage opening were optimised with sound absorption measurements on small samples (figure 11).
In the exisiting situation there were cavities acting as Helmholz-absorber[6]. These were closed.
The most important sound absorbing surface however is the seating. The existing seating had a very low absorption. Acoustic objective was not to increase the sound absorption of the seats.

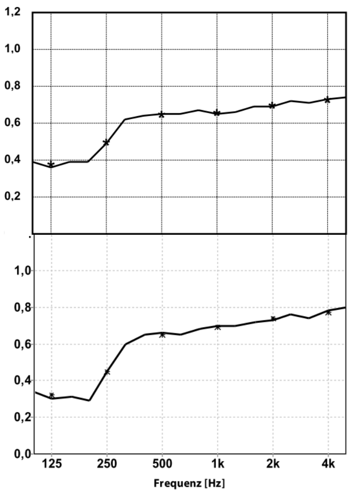

Figure 12. Sound absorption of 16 seats, measured in occupied situation. Top: existing seats, bottom: new seats.

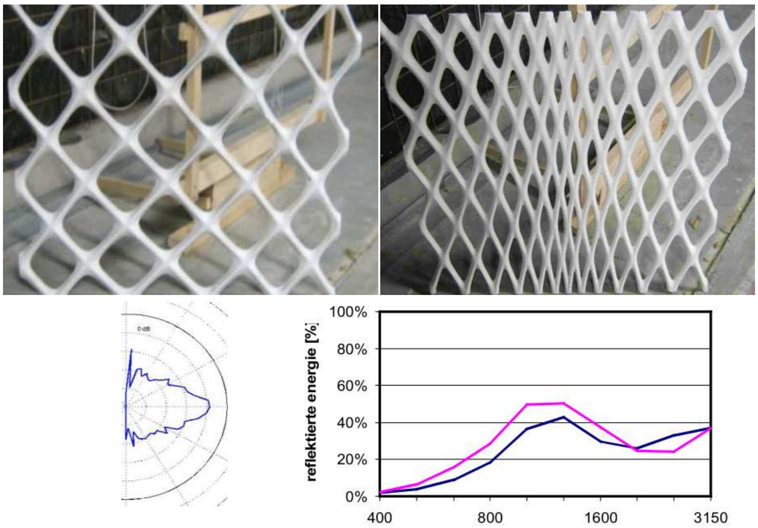

Figure 13. Measurements of the grid structure scale 1:2. Top: both samples, bottom left: directional reflection (6dB/div). Bottom right: total reflected energy [%], blue: left sample, violet: right sample.

At the same time the seating comfort should be improved, also increasing the height of the backrest with 10 cm. The improvement in seating comfort was realised with ergonomic design and a thin padding of the backrest. The increased absorption of this padding was compensated by an airtight layer in the seat. Figure 12 shows the absorption data of the old and the new seat in our acoustics laboratory: A very slight increase at high frequencies and a slight decrease at low frequencies.

3.5 Acoustical transparency of the grid

The architect H.G.Merz has connected the original hall to the raised ceiling with a grid structure, as a reference to the original architecture with gratings and diamond motives from architect Knobelsdorff (fig. 14). This grid should be sound transparent, it should not close off the newly designed reverberation gallery. Two samples scale 1:2 of different parts of the grid were built and the directional reflection behaviour[7] was measured in our anechoic chamber, see figure 13. From these measurements the structure was futher optimized and it was decided to fully close the upper, half open, part of the grid.

4 THE RESULTS

4.1 Measurement setup

In september 2017 the hall was almost finished, see fig. 14. Before the first rehearsal, acoustic measurements were performed. The hall was measured without and with audience simulation with special curtains, see fig. 15. Measurements were performed with fire curtain (FC) open and closed. Also the situation for symphonic concerts, with orchestra shell on stage, was measured.
Measurements of the RT were done with interupted noise and with a 9 mm pistol, mainly for the 63 Hz octav band. Impulse response measurements were done with an MLS signal and MLSSA computer, and with an omnidirectional sound source[8].

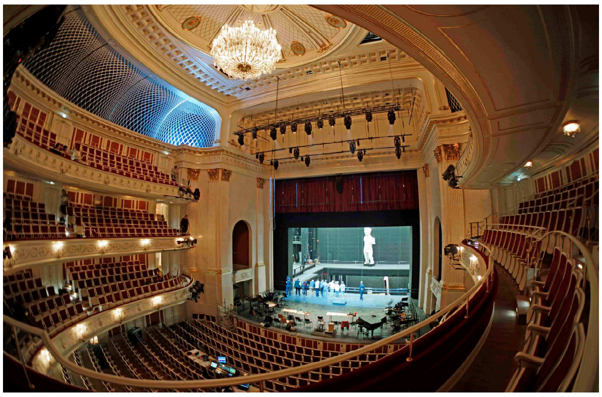

Figure 14. Photo of the renewed opera hall, september 2017

Figure 15. Stalls with audience simulation(curtains) and one of the authors with a sound level meter.

From these data the different parameters, such as clarity were derived. The 1 m positions were used to determine the strength. Figure 16 shows the source and receiver positions.

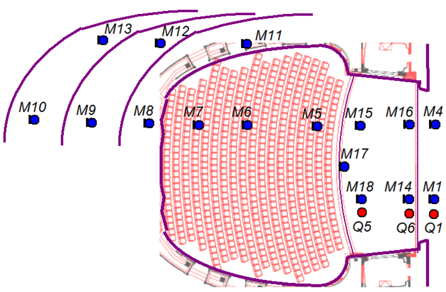

Figure 16. Sources (in red) and receivers (in blue). Balconies are schematic. Not shown: source position 7 in the pit (under Q1).

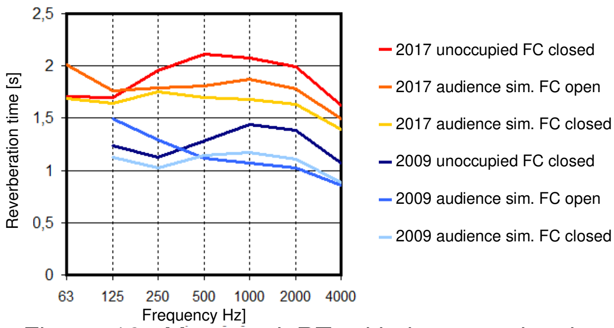

Figure 18. Measured RT with interupted noise and pistol(63 Hz) in 2009 and 2017. Opera situation.

4.2 Measurement results

Figure 17 shows some examples of IR's before (2009) and after renovation (2017). The IR's from 2009, typical for drama theatres, were changed into IR's with stronger late reflections, more like concert hall acoustics. The decay curve is smooth, without disturbing irregularities. Measured RT's are shown in fig. 18. Due to the low absorption in the unoccupied hall, the RT is over 2 s.
In the relevant situation, with FC closed and with audience, the measured RT(125-4kHz) is 1,6 s. and 1.7 s. at 1 kHz.

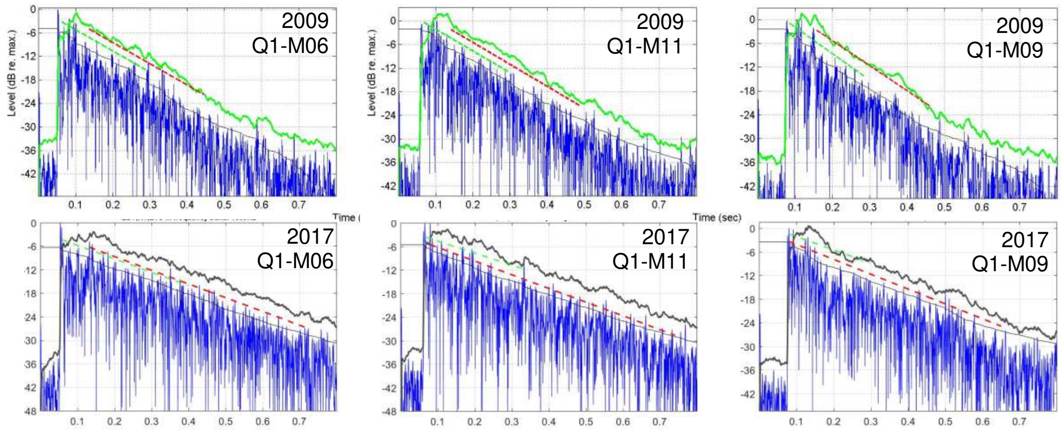

Figure 17. Some measured IR's from 2009 (top) and 2017 (bottom). Opera situation with closed FC and audience simulation.

At the time of these measurements there was only the building related sound absorption in the stage house and not any curtains of the user, resulting in a longer RT with FC open. The results in the concert situation are shown in fig. 19.

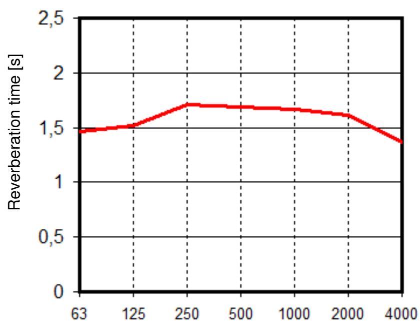

Figure 19. Measured RT with interupted noise and pistol(63 Hz) in 2017. Concert situation

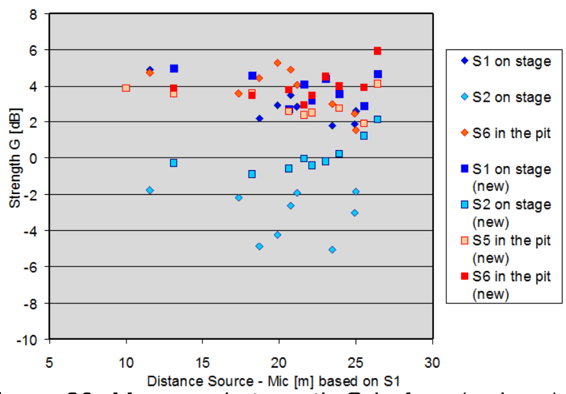

Figure 20. Measured strength G before (wybers) and after renovation (squares).

Figure 20 shows the strength in the hall. It shows the low loudness of sources on the middle of the stage (S2). The difference before and after renovation is related to the stage situation, not to the renovation. The strenght has slightly increased for the source at fore stage but is reduced for sources in the pit. This is a balance shift in favour of the singers. However this is not the case at 3rd balcony level, the level of both singers and orchestra is increased here, due to the reverberation gallery. On average a strength G is measured of around 4-5 dB, exept for the 3rd balcony where it is about 6 dB. So the acoustic objective, that the hall should not become louder, is realised, with exeption of the 3rd balcony level.
Figure 21 shows the early sound strength G_{80} until 80 ms in the orchestra pit, with sources in the pit. For comparison the decrease of direct sound under free field conditions is shown. The measurement results are about 7 dB above direct sound. The overal sound levels haven't changed much by the renovation, nevertheless the orchestra pit has totally changed, using convex panels to

decrease the strength of individual reflections, while increasing the number of reflections. The musicians indicate a remarkable improvement.
Figure 22 shows the early sound energy between pit and stage. At fore stage the audibility between singers and orchestra is excellent, but for the source 6 and positions further on stage, the direct line of sight is interupted and sound strength drops to low levels, even under the level of (uninterupted) direct sound. This however is typical for opera houses[9] and could be improved by the stage set. Also the staging can be changed, by bringing the singers more the front of the stage.

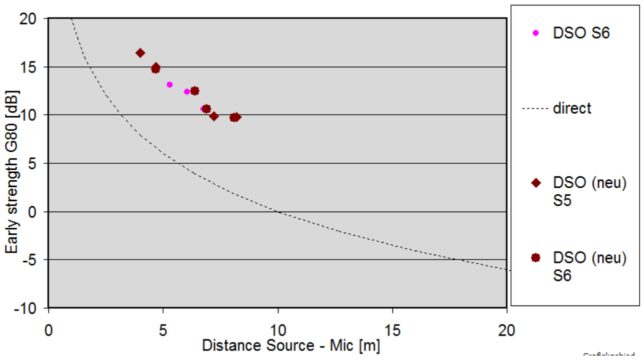

Figure 21. Measured Early Strength G_{80} before (violet) and after renovation (brown): sources and receivers in the pit

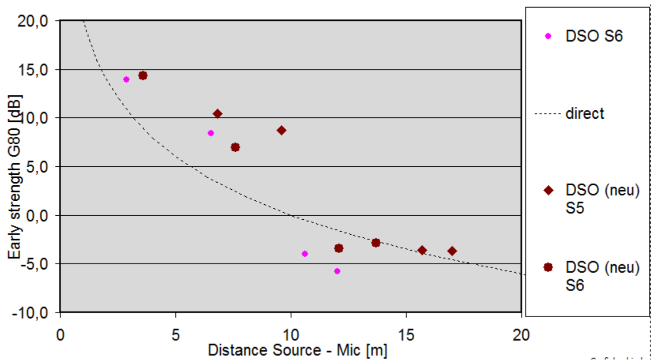

Figure 22. Measured Early Strength G_{80} before (violet) and after renovation (brown): sources in the pit and receivers on stage.

The measured clarity is indicated in the table 1. The distribution of the clarity over the audience areas is given in table 2 (FC open, with audience simulation).

Quelle	2009	2017
Q1	4,6	0,6
Q2	6,4	0
Q5		-2,8
Q6	4,4	-0,2

Table 1. Measured Clarity C_{80} [dB] in the hall, before and after renovation, average of all hall positions, 500-1kHz

Position	2017
Parkett (M5,M6,M7)	-2,4
1.und 2. Rang (M8,M9,M11, M12)	0,2
3. Rang (M10, M13)	-0,4

Table 2. Measured Clarity C_{80} [dB] in the hall, after renovation, average of sources 1,5 and 6, 500-1kHz

The measured clarity after renovation is much lower than before, indicating much beter balance and mixing of early and late sound. It should be noted that at the time of the measurements, the excess of reverberation from the stage tower could slightly influence these results. Source position 5 has lower clarity as position 6, because it is more towards the edge of the pit, so there is more shading of direct sound. The clarity at 1st and 2nd balcony are higher than at stalls, due to better lines of sight to the pit and more shading of reverberant sound, because of the balconies above. At 3rd balcony the proximity of the reverberation gallery reduces the clarity. The new clarity data is significantly better than the old situation. The 2009 results refer to a speech theatre acoustic, the new situation is more similar to concert hall acoustics.

5 CONCLUSION

By changing the geometry, raising the ceiling with 5 m, extending the hall over the 3rd level corridors and by reduction of absorption of the walls surrounding the audience, the acoustics of the Berlin

state opera has significantly improved. An increase of sound reflections, a significantly longer reverberation time and a lower clarity resulted in a totally different acoustic. A rich and warm sound has emerged. The strong side wall reflections cause a large apparent source width, especially for audience at the rear of stalls and at 1st and 2nd balcony.
At low frequencies the RT is about 0,1 s. lower as expected. However the strength and clarity of bass sound is judged to be very good.
For the concert situation it was expected that a longer reverberation as 1,7 s. would be needed. However the hall is assesed to be quite sufficiently reverberant, with a good balance between detail of the music and reverberance, so there is no need to increase RT in the concert situation.
All together the difficult combination of two objectives was achieved: a substantial improvement of the halls acoustic and at the same time preserving the architectural design and monumental status of the hall. Client, user and audience are very happy with the excellent new acoustic of the old Staatsoper Unter den Linden.

6 REFERENCES

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