Reducing the sound exposure level in an orchestra pit by a set of tailored measures

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Abstract

To reduce the risk of a noise-induced hearing loss in workplaces, the EU directive 2003/10/EC sets certain exposure action values and an exposure limit with respect to the daily or weekly sound exposure as well as the peak sound pressure. Hearing protection, which is one of the most efficient means to reduce the risk of hearing loss in the majority of work places, is generally considered inadequate as the sole solution for orchestra musicians. Technical and organizational measures should therefore precede or accompany individual hearing protection. Moreover, their pertinent execution requires deliberate solutions, which need to be in agreement with the conditions of performance practice and architecture.

This contribution presents an attempt to reduce the sound exposure level in the orchestra pit of the Deutsche Oper Berlin by a set of constructional measures. The current conditions and the requirements of the musicians were assessed with acoustical measurements and with a questionnaire, respectively. A hybrid simulation method was subsequently employed to simulate and optimize the sound field. Optimization focussed on an improvement of audibility between musicians and the equalization of the areal pattern of room modes. While the former objective is well-know for improving the ensemble play, the latter reduces the exposure as well as the masking of the fundamental frequencies of singers and instruments. The paper finally presents a set of constructional measures, which are considered viable approaches for reducing the risk of noise-induced hearing loss in the orchestra pit.

Keywords: Orchestra pit, health and safety

1 INTRODUCTION

The Deutsche Oper Berlin (DOB) is one of the three opera houses in Berlin. The building was designed by the architect Fritz Bornemann. It features the popular language of many post-war buildings. The opera is known for a modern and successful room acoustic design by the consultants L. Cremer, J. Nutsch and H. J. Zemke [1].

The repertoire of the opera consists mostly of grand operas of the 19th century, in particular Richard Wagner, but features also modern plays. During productions with greater assemblies of the orchestra, the floor of the orchestra pit is at the lowest level in order to increase the floor space. To assess the average floor space per musician, two plays are considered. The assembly plan for Tannhäuser comprises 75 musicians, which results into an estimated average space of 1.4 m^2 per musician. The assembly plan of Turandot comprises 86 musicians, which leaves an estimated average space of only 1.2 m^2 for each musician. With these ratios, the conditions of the orchestra pit of the DOB are not different from many other orchestra pits. Based on a survey at 46 opera houses, the floor space was identified as a primary factor for problems with excessive loudness and difficulties with ensemble play [2]. A threshold of 1.5 m^2 was identified as the area per musician below which problems are often reported. Solutions as curtains in front of the walls or extensive broad band absorption lead either to discoloration, or reduce the room acoustic support as well as the loudness of the orchestra in the auditorium. Sound screens are regarded as obstructive as well as impractical in the orchestra pit, and are advised only in

front of the loudest instruments, and therefore represent no general solution to the problem [3].
As part of the noise exposure reduction program (2003/10/EC, section 5 part 2, [4]), the management of the opera initiated the university project "Simulation and optimization of room acoustical fields at the example of the Deutsche Oper Berlin" (SIMOPERA) with two universities and an industry partner. The distinctive feature of the two year project was a hybrid simulation approach, consisting of wave based simulation for modelling wave phenomena at low to mid frequencies below the diffraction limit and geometrical acoustic simulation for modelling mid to high frequencies. Using this approach it was possible to account for the low frequency sound field in the orchestra pit, which is mostly excluded from simulation and handled by general experience. Yet eigenfrequencies and room modes are often accountable for increased reverberation times and the occultation of sounds at mid frequencies as a consequence of the masking effect. Raising the accuracy of room acoustical designs in the low frequency regime is therefore important. Typical design requirements are a homogeneous and proportionate sound pressure distribution. However, because of the non-homogeneous distribution of modes, these requirements are difficult to attain. Decomposing the complex modal structure with wave based simulation facilitates the development as well as the verification of acoustical concepts in this frequency regime.
Simulation based on geometric acoustics was complementary used in the mid to high frequency range. Both simulation methods were ultimately employed to develop constructional measures for reducing the sound exposure level in the orchestra pit, on the one hand directly by means of diffusion and selective absorption, on the other hand indirectly by way of enhancing audibility and transparency.
This paper summarizes the results and collects the experiences made within this project. First, a summary of the current situation at the DOB is given. Subsequently the simulation methods are further introduced and finally concepts of constructional measures for reducing the sound exposure level in the orchestra pit are presented.

2 ANALYSIS OF THE CURRENT SITUATION

The project started with Sound Pressure Levels (SPL) measurements within the orchestra pit and the auditorium during several plays. As regards the pit, SPLs comparable to the ones reported by Brockt [5] were obtained.
In a second step, a questionnaire was developed together with the orchestra department. With regard to the instrument groups viola, violin and wind instruments, the number of observations (i. e. returned questionnaires) allowed for a statistical analysis. Therein the viola and the violins form an interesting pair of instrument groups. The violas are situated in front of the wind instruments, while the violins are symmetrically flipped to the other side of the orchestra pit and reside in a quieter environment. Because the analysis of ratings allowed merely for a comparison of mean values and the observation of the string instruments where most consistent across different assemblies, these two groups are analysed in the following. The results are: (1) Viola players consider playing much less comfortable in the orchestra pit than violin players. (2) Viola players find it hard to distinguish between the sound of their own instrument and instruments of others. (3) Viola players have more difficulties to distinguish between instruments, while violin players find it much easier. (4) Viola players rated the intelligibility of instruments that need to be heard during ensemble play lower than violin players. (5) Viola players perceived the orchestra less balanced than violin players. (6) Violin players evaluated the room acoustics of the auditorium higher than viola players.
There was no question on the perception of excessive loudness. Nevertheless, the distinct difference in ratings is likely a consequence of the increase exposure levels in the proximity of wind instruments. This finding is not peculiar to the DOB and reflects a common observation in orchester pits [3].

2.1 Room acoustic measurements

Standard room acoustic measurements were executed in the entire performance space, comprising the stage house, the auditorium and the orchestra pit (ISO 3382-1, [6]). If the stage house was coupled to the auditorium as well as to the orchestra pit, a defined configuration of the stage was used, namely closed stage gates to sides and backstage as well as theatre curtains on stage level in front of the stage walls and gates with about one fifth of covering in order to omit flutter echoes. There was no audience present. The orchestra pit was positioned at

2.9 m below stage level, which in generally the configuration during grand operas. Ten measurement positions in the stalls, balconies and lodges were chosen. Using a logarithmic sweep as the probe signal, impulse responses for three source positions on stage and three source positions on the orchestra pit were measured. The measurement equipment fulfilled the requirements of the standard ISO 3382-1 [6].

The reverberation times are a $T_{\text{mid},30}$ of 1.5 s in the orchestra pit with the iron curtain closed, a $T_{\text{mid},30}$ of 1.5 s in the auditorium with the iron curtain closed and a $T_{\text{mid},30}$ of 1.75 s in the auditorium if the iron curtain is open. There is an enhancement of reverberant energy at low frequencies in the auditorium, with reverberation times of up to 2.9 s in the 1/3rd octave band centered at 100 Hz with the iron curtain opened.

Due to the reduced volume of the orchestra pit, the modal field extends into the mid frequency range, exceeding the theoretical value of the Schroeder frequency, which lies at about 100 Hz for the orchestra pit alone. At low frequencies, the mean reverberation time is less enhanced in the orchestra pit as compared to the stage house and the auditorium.

Looking at the situation of a typical scenery ('Les Contes d'Hoffmann' by Jacques Offenbach in 2018 at DOB), the reverberation time of the entire performance space decreases to a $T_{\text{mid},30}$ of 1.5 s. In addition, at low frequencies, the reverberation time is at about 2 s at frequencies below 125 Hz. Hence, the elevated reverberation times measured at low frequencies at an empty stage are generally not representative.

Aside from the reverberation time assessment, the parameter strength (G) was calculated from the impulse responses. It is a measure of the perceived loudness. Throughout future acoustical changes of the opera, G could serve as an important quality criterion for the loudness percepiton in the auditorium and the balance between performers on stage and in the orchestra pit.

The stage metrics of the ISO 3382-1 are early and late support, ST_{early} and ST_{late}, respectively [6]. The former describes the perceived conditions of the ensemble play and the latter describes the perceived reverberation time on stage. Following the proposal of Vercammen and Lautenbach, the parameter early strength (G_{80}) was employed to evaluate the degree of transmission between the performers on stage and in the orchestra pit [7]. The results of the stage parameters in the DOB show close agreement with a series of opera houses in Germany [7, 8]. In view of the objective of this project, i. e. reducing the sound exposure level in the orchestra pit, parameters of stage acoustics are of prime importance and need to be controlled throughout the optimization process. Further information on the measurement methods and the results of this project were published [8].

3 Room acoustic simulation

Selective constructional measures which guarantee good audibility within the orchestra pit and which lower sound exposure levels for musicians were developed and evaluated in acoustic simulation. Due to the coupling of three large and partly non-diffuse rooms and the frequency dependent phenomena of sound waves, two simulation methods were applied, namely the Finite Element Method (FEM) and ray tracing.

3.1 Finite element method

A model of the opera was developed within the FEM framework of the software COMSOL Multiphysics 5.3a. The wave based method allows for an exact calculation of the wave field in complex shaped rooms where no analytic solution exists. It is however computationally expensive and therefore limited to lower frequencies. The limiting criterion results from the fact that each wave element (one wave length) has to be discretized with at least six elements in order to avoid numerical dispersion. For a cube with a volume of 12000 m3 (about the volume of the auditorium of the DOB including the orchestra pit) this leads to at least 6e4 hexahedral cells at 100 Hz, 6e7 cells at 1 kHz and 6e10 cells at 10 kHz. Computing the soundfield in such a volume up to a frequency of 1 kHz may last several days on a mid-size cluster computer.

In this project, FEM simulation was employed and evaluated (1) in the calculation of room modes and eigenfrequencies in the decoupled orchestra pit as well as the entire performance space, (2) in the comparison with other simulation methods, basically the ray tracing and the boundary element method, (3) in the study of boundary conditions, in particular at interfaces between room sections and (4) in the simulation of Helmholtz resonators.

Isolating the orchestra pit from the auditorium allowed for faster simulation, which was needed throughout the design and optimization process. As an approximation, the interface to the auditorium was set to the impedance of air. The comparison between the eigenfrequencies of the auditorium including the orchestra pit and the pit alone showed that the specific eigenfrequencies of the pit maintain with this boundary condition. On the contrary, assigning the impedance of infinity (sonically hard cap) at the interface to the auditorium altered the modal field considerably. Owned to the computational effort and the difficulty of obtaining actual boundary conditions in FEM models, there often exists a "missing frequency gap" between the realms of wave based modelling and methods of geometric acoustics. In this work an attempt for bridging this gap was undertaken by increasing the respective frequency ranges. Despite simplified assumptions of the boundary conditions in the FEM model and the methodological shortcomings of ray tracing at low frequencies, simulated SPLs within the orchestra pit deviated only by 1.2 dB in the octave bands from 125 to 500 Hz between both models [9].

3.2 Ray tracing

Appropriate for simulating sound fields above the diffraction limit, models geometric acoustics have been established as today's standard simulation procedure in acoustic consultancy. A computational efficient realization is the energy based ray tracing algorithm. In this project a model of the DOB was developed with the ray tracing software CATT-Acoustic (v9.1c and TUCTv2). In order to adapt the model to the acoustics of the opera, the sound absorption data published by Cremer and colleagues was first assigned to the surfaces of the opera [1]. Subsequently, the absorption coefficients were adjusted in order to match the simulated with the measured reverberation times. During this process, the auditorium (including the orchestra pit) was separated from the stage house and each room was adapted individually. Finally, the performance space, consisting of three coupled rooms, was adjusted as a whole. It turned out difficult to achieve a frequency dependent match of reverberation time for all three compartments, i.e. the auditorium, the orchestra pit and the stage house, primarily in the low frequency range. Therefore, the adaptation focussed eventually on a close match in the orchestra pit and in the auditorium.

4 Proposals of constructional measures

4.1 Helmholtz resonators in the orchestra pit

Due to the capacity of a high absorption area, Helmholtz resonators are an efficient means for damping the specific modes and eigenfrequencies of a particular room by adjusting their resonance frequency accordingly. The frequency range in which they operate can be broadened to the neighbouring octave bands by increasing the air flow resistance of the opening. A good trade-off with the quality factor can be achieved. These features as well as the freedom of arbitrarily shaping the resonator's volume result in a highly customizable absorber.

FEM models of Helmholtz resonators were developed and validated in the simulaiton of an impedance tube in accordance with the transfer function method described in the standard DIN 10534-2 [10]. The model was compared to the measurements of specific designs and showed good agreement. This development led to the valuable tool of designing and evaluating Helmholtz resonators within FEM models of room acoustics.

Based on a grid measurement in the orchestra pit, the sound field was spatially sampled and locations of raised sound pressure in the low frequencies regime were identified. In order to equalize the frequency response across the orchestra pit, Helmholtz resonators were distributed and adjusted to the sound field. Because of a tentative description of wall impedances, the results of this implementation are not presented here (see also discussion). The description of Helmholtz resonators as a FEM model as well as the proof of concept was published by the authors [11].

4.2 Proscenium reflectors

The objective of this constructional measure is the improvement of the mutual audibility by means of intensified early reflections. The proposal draws upon the well studied insight that insufficient audibility among musicians

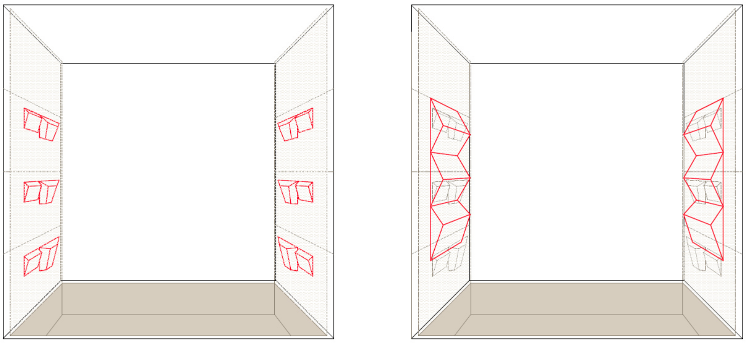

Figure 1. Conceptual drawing of the proscenium and the orchestra pit of the Deutsche Oper Berlin. (Left) The current reflectors in the proscenium behind an acoustically open mesh. (Right) Proposal of large reflector arrays for improving audibility between distant positions within the orchestra pit. Each reflector of the array has a size of 1.5 x 4 m

often results in a louder and less accentuated playing style. The musician is inclined to play louder in order to hear oneself as well as to be heard. Consequently, if the ensemble play is hampered by poor audibility and elevated exposure levels, disintegration and dissatisfaction can emerge among musicians and consequently further amplify the described effect. This observation can be regarded as the musical analogue of the well known Lombard effect. As a countermeasure, arrays of reflectors were designed at sides of the proscenium above the pit. Figure 1 depicts the current situation and the proposed reflector arrays. The enlarged reflectors facing the orchestra pit are aligned such that audibility across distant locations within the orchestra pit is enhanced. The performance of the reflectors was assessed with the parameter early strength (G_{80}) within the ray tracing model. The results show an increase of up to 2 dB between distant positions.

4.3 Diffusion and projection of sound energy within the pit

While reflector arrays in the proscenium are meant to enhance audibility, strong reflections from hard walls in the proximity of players may result into a strong enhancement of sound pressure. In order to mitigate this effect without loosing stage support, intensified diffusion and projection of the sound energy into the auditorium are proposed. Diffusion can be achieved through geometric structures and pattern of local impedance variations. The advantages of a impedance pattern are simplicity (including reduced costs) and a minimum installation depth. They can be realized in stripes of porous absorbers or by means of phase grates. Ballestero and colleagues presented an example of such a solution with metadiffusers in the orchestra pit [12].

The simulation of increased diffusion (as compared to the current situation in the pit) did not result in the reduction of the SPL. This might be a consequence of the oversimplified calculation method of energy based ray tracing, the conservation of the energy decay within a room when not changing the absorption characteristics and ultimately the ignorance of the playing style, which presumably will change in response to increased diffusion.

Alternatively, by cladding the wall of the orchestra pit towards the stalls area with reflectors of triangular shape with an edge length of 1 m, and aligning these (as far as possile) to the sides of the stage opening, a portion of early sound energy is projected into the hall. The backside of the reflectors is designed as highly absorptive and the pit's wall behind these remains sonically hard. The setup shall balance stage support with increased diffusion at mid frequencies. The repetitive pattern of reflectors results into a theoretical maximum of diffusion in the range of 250 to 500 Hz. In addition a considerable portion of sound energy is absorbed by the absorptive backside. This reduction was assessed in simulation. It led to an average decrease of the A-weighted SPL in the time span from 500 to 3000 ms after direct sound of 1 dB and a decrease of the SPL in the 1 kHz octave band within the same time span of 2 dB.

Moreover, both, the diffuser and the projection solution reduce the focusing effect of the concave wall of the orchestra pit. The analysis of early reflections in the geometrical model (based on the well known mirror image source method) of the untreated pit readily illustrate this focussing effect in the two centre points of the elliptical curvature.

5 Discussion

The presented project comprised many tasks that are part of a room acoustic consultancy assignment and thereby identified current challenges. In the following a set of experiences are given:
(1) The development of simulation models is still a laborious task. Today's availability of laser scanners allows for an efficient measurement of room dimensions. However, the conversion of so called point clouds of centrally recordes solid measures into simulaiton models of proprietary file formats is difficult. Therefore the authors created the simulation models per code or per CAD software and commercially available conversion tools. Also this conversion did not work flawlessly and resulted in error correction within algorithm generated code.
(2) The assessment of wall impedances in the low frequency range remains a challenge. Much work has been put into wave based algorithms. Recent developments include the time-frequency processing and therefore enable the assessment of the simulated sound field with standard room acoustic tools. As regards the boundary conditions there are conversion formulae that transform wall impedances from standard absorption data (alpha) in the mid to high frequencies regime [13]. However, at low frequencies, where wave based algorithms are especially useful, impedance values are difficult to acquire. Leaving plate absorbers with their descriptors aside, the locally reacting surface of a room represents a manifold which is hardly measurable at the surface itself with today's acquisition tools and manageable effort. There are however approaches that calculate impedances across wall zones inversely from the sampled sound field [14]. In this project the authors developed an optimization framework for searching the wall impedances using the least square error criterion for the match between the measurement and the FEM simulation of a spatial grid of microphone signals. Although the experimental setup was simple, the results remained behind expectations.
(3) Standard room acoustic measurement loudspeakers lack sound power at low frequencies in larger rooms. During acoustic measurement in rooms as large as the Deutsche Oper Berlin, it turned out difficult to excite the room below 100 Hz with sufficient signal-to-noise ratio. In this project three omnidirectional loudspeakers, each at a time and all fulfilling the requirements of the ISO 3382-1, were tested. Only by employing an additional PA loudspeaker at low frequencies, the SNR could be sufficiently raised. Care is required for achieving omni-directionality of the sources in their respective spectra.
(4) The adaptation of a ray tracing model to a complex sound field of coupled rooms by means of the reverberation time is prone to error. Because the parameter describes the exponential decay in a diffuse sound field, it is neither a metric for typically undulating decays of coupled rooms nor a metric for non-diffuse sound fields. Therefore coupled rooms are best detached during measurement and during the subsequent adaptation of the simulation model, as it was done here. The adjustment remains however coarse and may not reflect the actual spatial distribution of surface characteristics. There are optimization algorithms that support the adaptation of simulation models to measurement, also on the basis of spatial parameters. These were however not available in this project.

The presented constructional measures in this contribution are at a conceptual stage. If the management of the opera decides to implement one of these, further preparatory steps are required. Inevitable will be the analysis of the requirements of each opera department regarding conflicts and practicability of the proposed measures.
The reflector array in the proscenium improves mutual audibility across distant positions in the orchestra pit. The measure therefore reponds to the requirements of many musicians of the DOB who consider communication within the pit as crucial. The design pursued a modest intervention into the current architecture of the stage opening, leaving space to performers behind the reflectors in the mesh covered balconies as well as enough space for lighting. Parameters of further optimization are size, alignment, location as well as the reflector's

edges to increase the frequency range of the reflector. In addition, a motor steering could adapt their angle to the level of the orchestra pit, thereby delivering acoustic support in other stage settings too.

The diffusers and reflectors as well as the Helmholtz resonators within the orchestra pit represent measures that have little interference with the conditions of architecture and performance practice. The wall mounted reflectors might be hinged and temporarily collapsed into the wall, such that their depth does not interfere with the floor of the orchestra pit while manoeuvred between different levels. As with the reflector arrays, parameters of size, alignment, the location as well as the edges need further development.

Given the fact that the sound pressure level decreases by 6 dB per distance doubling between receiver and source in free field conditions, the enlargement of the orchestra pit represents a reasonable but extensive solution. Literature shows that an average floor space of more that 1.5 m leads to acceptable loudness levels and good ensemble play [2]. The option of enlarging the orchestra pit was not analysed in this work. In order to demonstrate the effect of increased distances between musicians on individual exposure levels, it would need a model of a complete orchestra, as developed by Wenmaekers and colleagues [15].

The presented project SIMOPERA ended in March 2019. As of writing this paper, the decision on the execution of the constructional proposals in this project is pending. In parallel, the orchestra management pursues a number of activities in order to comply with the regulatory requirements, such as the sound pressure level monitoring of performances in front of the wind instruments, the rotation of musicians within groups, the arrangement of preventive occupational medical care, the supply of individual hearing protection as well as the execution of a noise reduction program, within which the here presented project forms a part.

6 Conclusion

In this contribution, constructional measures for reducing the sound exposure level of musicians in the orchestra pit are mapped out. These measures are part of a set of provisions, such as individual hearing protection, in order to mitigate the risk of gaining a hearing loss in the musician's workplace.

Without acoustical treatment, there are often ample sound pressure level differences at low frequencies within the pit. These may lead to discolouration and the masking of soft sounds in the mid frequency range. Additionally, hard surfaces and possible focussing effects within the concave shell may further result into an escalating intensity adaptation among musicians, involving hampered ensemble play and increased sound exposure levels.

At the example of the orchestra pit of the Deutsche Oper Berlin, a hybrid simulation approach was employed to simulate and optimize the sound field. A set of constructional measures for lowering the sound exposure levels of musicians was proposed. These proposals represent a balancing act between sound pressure abatement within the orchestra pit, improved audibility within the orchestra and the optimal projection of sound energy into the auditorium.

7 Acknowledgement

This project was funded by the Berlin Institute for Applied Research.

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