Controlling multiple acoustic objectives during the implementation of the European directive 2003/10/EC at an opera house

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Summary
The European directive 2003/10/EC poses a challenge to opera houses. The directive stresses the reduction of noise related risks at their point of origin, which for the opera is the orchestra pit. The execution of classical means of noise reduction is impossible without compromising the opera as a cultural heritage and the artistic freedom of the art form.
The approach given here is to gather room acoustical as well as general requirements and use them as an input for wave based and geometry based room acoustical simulation models. With these models a set of constructional changes that improve the situation in the orchestra pit without impairing the room acoustics of the auditorium shall be developed. The project was initiated by the Deutsche Oper Berlin. This contribution gives a report on the work that has been done to consult this venue on the implementation of the directive. First results allow for the tentative definition of solutions.

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1. Introduction

With the European directive 2003/10/EC being effective for the entertainment branch, opera houses need to control the exposure level of musicians in the orchestra pit. To give an example of significance, a court in the UK recently decided in favor of a viola player who incurred a hearing loss from a rehearsal of Wagner's Valkyrie and ordered the responsible opera house to compensate him financially [1].
However lowering the sound pressure level in the orchestra pit is not a simple task. Opera houses are big and established enterprises with a dense schedule and a fixed manner of performance practice. Moreover, opera houses are often not profitable, depend of public funding and do not have the means for constructional changes, such as increasing the size of the orchestra pit while loosing the best paying parquet seats. Secondly, the room acoustics of an opera house represent the design of its time. Usually, a carefully negotiated compromise between architect, the performance practice and the requirements of the facilities, e. g. the lighting system and room acoustics. All together this forms the character of the house. It is passed on and maintained from generation to generation and generally heritage protected. Third, entering the domain of the acoustics of an opera house, several primary aims are balanced. Those are the projection of the acoustic performance of singers and the orchestra into the hall, the balance between the stage performers and the orchestra across the hall, the right amount of reverberation (for opera and music performance) and the individual and mutual audibility between stage performers and orchestra members. Secondary objectives relate to further acoustical attributes, such as the musical quality of timbre, intelligibility, dynamic range, loudness, spaciousness, envelopment and intimacy. Therefore, any constructional intervention for lowering the exposure level in the orchestra may directly affect multiple other objectives. Hence, the approach presented aims at lowering the sound pressure level in the orchestra pit, while obeying the restrictions of the original design as well as the complex interplay of objectives of an opera house.
With respect to the exposure levels in orchestras, Brockt gave an overview on several studies on sound exposure levels for musicians [3]. He outlines a weekly and annual exposure level of 85 to 95 dB (A). For musicians that usually perform in orchestra pits, this level will be even higher [3]. It is widely known that simple measure of absorption will have a negative ef-

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fect on room acoustic support and the overall loudness perception in the auditorium. A recent study with a validated prediction model of sound pressure level in open stages found that even extreme measures for sound level reduction on stage in terms of risers, absorption, volume per musician and screens, are each not capable of reducing the exposure level sufficiently [2]. Nevertheless, both researcher conclude that a mixture of constructional measures, along with an improvement of audibility among musicians can lead to a significant reduction of the exposure level. The approach that will be pursued in this project is based on a close description of the requirements and the acoustic situation of the opera house on the one hand and on the validation and optimization with a hybrid simulation model on the other.

With this publication, the authors present the current state of a two year project, named SIMOPERA (simulation and optimization of room acoustical field at the example of the Deutsche Oper Berlin). The paper covers in the first part initial room acoustic measurements and in the second part the setup of room acoustic simulation models. Finally, a discussion on further steps and initial conclusions is given.

2. Room Acoustics

2.1. Measurement setup and equipment

The standard 3382-1:2009 was followed to describe the present acoustical situation of the opera [6]. The analysis that is presented here describes the situation without audience. The volume of the auditorium is 11400 m^3, the volume of the fly tower is 17400 m^3 and the orchestra pit has volume of about 400 m^3. The auditorium comprises almost 1900 seats. Acoustically active are mainly the upholstered chairs with a porous covering, the wooden paneling from mahogany that covers the side walls almost entirely and the suspended Rabitz ceiling, which is designed as a staggered reflector.

The fly tower was empty, the scenery curtains pulled in upper position and there was no scenery on stage. The side walls were covered by about one fifth of the surface area with thick, slightly ruffled theater curtains in order to prevent flutter echos between the parallel walls.

The orchestra pit was positioned in its standard position for opera performances at -2.9 m below stage level. The instruments were removed. Only the music stands and thinly padded seats remained.

The orchestra pit as well as the fly tower form each a coupled volume in accordance with the definition given in ISO 3382-1 [6]. Therefore, measurements were executed with and without the safety curtain between the auditorium and the fly tower closed. The reverberation time of the orchestra pit was accordingly assessed separately. Another reason for executing measurements without the fly tower open, is given by the need to adapt the simulation models to the measurements. This task is simplified for detached sections of the total room. An inhomogeneity exists for the distribution of the acoustic properties of surfaces across the room. This is typical for an opera and reverberation times therefore depend on the location of the measurement.

Around the turn of the year 2017/2018, a horizontal reflector at the ceiling was opened due to maintenance work. This may influence the room acoustic parameters given in this report. The measurement positions are depicted in Fig. 1. As can be seen, the selected positions make use of the symmetry of the room and were place at representative listener positions.

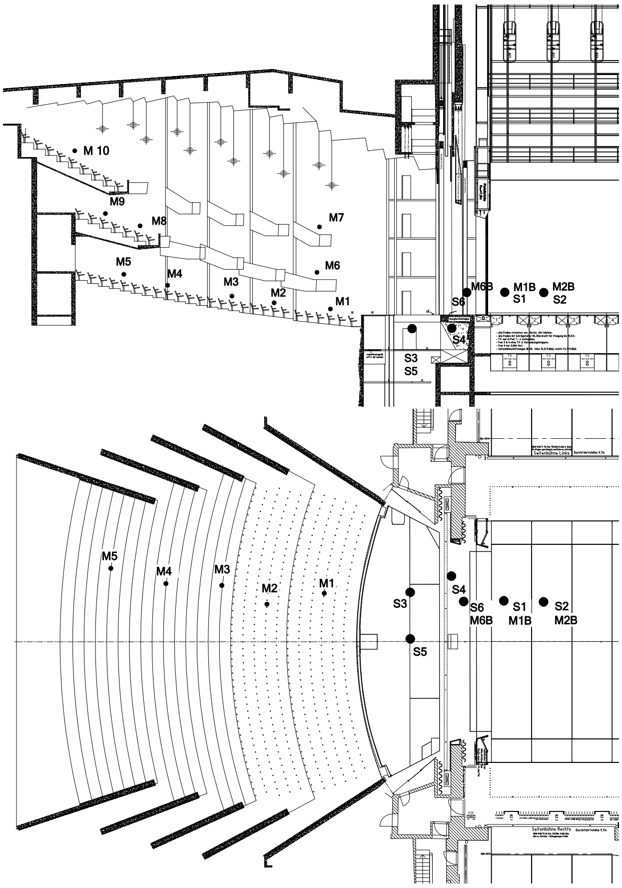

Figure 1. Source- (S) und measurement positions (M) of the room acoustical analysis presented in this article at the Deutschen Oper Berlin in sectional view (upper plot) and the floor plan (lower plot).

2.2. Measurement method

The logarithmic sweep was applied as the measurement signal. This excitation signal for measuring the impulse response is characterized by a high and frequency independent signal-to-noise ratio (SNR) and removes harmonic distortion of the signal chain [7]. In compliance with the ISO 3382-1, the reverberation time and energy criteria were calculated by backward integration of the impulse response. The measurement signal had a spectrum broader than the analyzed frequency range. It had a duration of 15 s, thereby being considerably longer than the reverberation time of the DOB. The stimulus was recorded three times for each source-receiver combination to improve SNR further. Nevertheless, it was not possible to tap the full power from the omni-directional source and therefore in the one third octave bands below 160 Hz, the SNR was below 45 dB, which is too little for executing the T30 method. In some bands, the SNR was even below 35 dB, which means that also the T20 method, as described as an alternative in the ISO 3382-1, is not applicable. Those impulse responses were therefore discarded from the analysis. The required reference measurements for measuring the parameter strength, a measure of loudness in the auditorium (without the influence of the power level of the source), was executed in the anechoic chamber of the Beuth University of Applied Sciences in Berlin.

3. Analysis of room acoustics

The reverberation times were measured with the iron curtain (fire safety curtain) closed in the orchestra pit (CC), the auditorium with the iron curtain closed (CC) and the auditorium with the iron curtain open (CO). The measurement results of the reverberation time were averaged across the measurement positions in the orchestra pit and the auditorium. Figure 2 gives the results in one-third octave bands. For a better interpretation of the data, the distribution of reverberation times and the median value per band are plotted. Even though the Schroeder frequency is below 30 Hz for the entire room, already at 250 Hz the spread of results increases and testifies the aforementioned dependency of reverberation time on the location of measurement. If the data had not been pruned as described before, the spread at 100 Hz would be even higher due to undulating energy decays of the logarithmic representation in that band. A spread of results is also observed for the measurement in the auditorium with the curtain open (CO). It is well known that the logarithmic energy decline of room impulse responses in coupled rooms deviates from a straight line and therefore the regression with a straight line as instructed by the algorithm of ISO 3382-1 for calculating RT_{60} introduces uncertainty.
The reverberation times in the 500 Hz octave band are at 1.40 s, 1.53 s and 1.76 s for the orchestra pit (CC), the auditorium (CC) and the auditorium (CO), respectively. The increase of the reverberation times around 100 Hz in the auditorium (CC) deviates somewhat from the measurement results of Cremer et al. [4].

The sensation of reverberation is quantified with the parameter Early Decay Time (EDT) with the iron curtain open (CO). The parameter was first calculated in octave bands and then averaged across the bands with the center frequencies of 500 and 1000 Hz. Figure 3 shows the spread of EDTs for source positions S1 to S6 at each measurement position in the auditorium. A diminishing effect of the source position can be observed as a function of distance from the stage. Note that M6 and M7 are microphone position in the boxes close and high above the stage. Based on the mean EDTs, a fairly constant sensation of reverberation is observed close to the long axis of the auditorium.

The sensation of transparency was evaluated with the parameters Clarity (C80) in [dB], Definition (D50) and Center Time (TS) in [s] in the auditorium (CO). For C80, a mean of about 0 dB was found for the auditorium, with a slight increase for rear listening positions. Likewise, a small but unequivocal increase was observed for D50 towards rear listening positions (from about 0.31 to 0.37). Consequently, Ts decreased at the same time towards rear positions, however less pronounced (from about 0.135 s to 0.125 s). The behavior of these three parameters may point to the typical lack of early side reflections at listening positions close o the stage in a fan shaped auditorium [9]. Graphs of the three parameters can be found in Schlesinger et al. [17].

The parameter Strength allows for controlling the loudness sensation in the hall as well as the balance between stage and orchestra pit. Due to limited measurement time, only a few measurement positions were sampled at the moment of writing this article. Figure 4 gives the results at the measurement positions M1, M3, M5 (rear of parquet), M8 (first floor). The results show the expected decline of 1.2 to 3.3 dB per distance doubling from the source. Although a homogeneous loudness sensation is observed, the values are a little low in total. As it was mentioned before, the reason for low strength values might be to some extend caused by the absence of one horizontal ceiling reflector. Future measurements are planed to investigate the situation with the ceiling fully closed. When comparing the results with the measurements of the parameter Strength in the Opera of Cologne, the Festspielhaus Bayreuth, the Staatsoper unter den Linden and the Komische Oper in Berlin by Vercammen and Lautenbach [10] it is in evidence that the design of the architecturally modern houses (KÃűlner Oper and DOB) led to a high degree of balance, within the stage and the orchestra pit and between the stage and the pit. Although it is likely that those are two single observations, the authors are convinced that modern acoustic design and homogeneous surfaces allow for a high degree of balance.

Room acoustic support for the orchestra as well as for each musician is a crucial feature of the stage. It is defined as the frequency averaged parameter ST_{early} in the ISO 3382-1. The figures that were measured in the DOB resemble the results in the Cologne Opera,

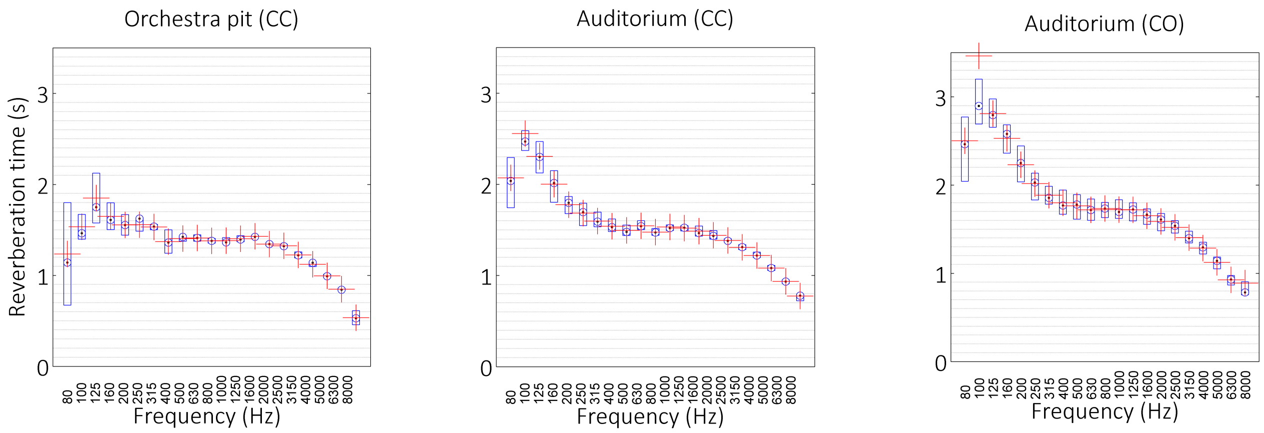

Figure 2. Comparison of the reverberation times per one-third octave band for the orchestra pit with the iron curtain closed (CC), the auditorium with the iron curtain closed (CC) and the auditorium with the iron curtain open (CO). The circle gives the median, the plus sign the mean and the boxes indicate with its lower edge the 25 and with its higher edge the 75 percentiles.

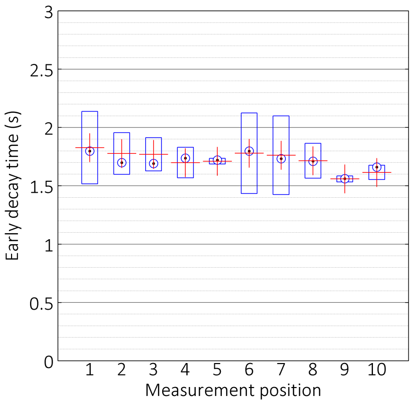

Figure 3. Parameter Early Decay Time (EDT) in the auditorium with the iron curtain open (CO) at the measurement positions 1 to 10, each evaluated for the source positions S1 to S6. The circle gives the median, the plus sign the mean and the boxes indicate with its lower edge the 25 and with its higher edge the 75 percentiles.

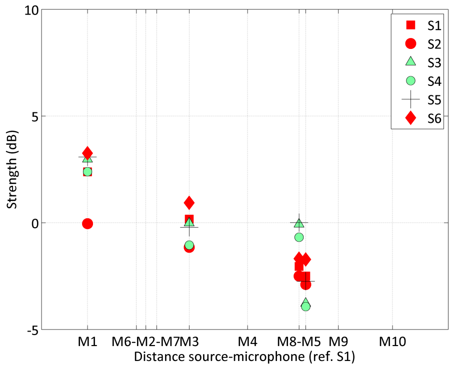

Figure 4. Parameter Strength G as a function of distance from the source position, and distance-averaged for all other source positions in the auditorium with the iron curtain open (CO). G is a parameter of loudness (independent of the sound pressure level of the source) and is preferably in the range between −2 to 10 dB (JND 1dB).

(with some exceptions) the Bayreuth Festspielhaus, the Berlin State Opera (Staatsoper unter den Linden) and the Komische Oper Berlin at similar positions [10]. From S1 to S6, ST_{early} is -17.5, -17.7, -9.3, -10.8,-7.3 and -14,8 dB. The highest value was measured below the stage, which is known to be a loud place and which is not liked by musicians of percussion instruments and double bass in the DOB. As we are going to see later in this article, standing wave build up at this location.

4. Room acoustic simulations

Selective acoustic measures which guarantee good audibility within the orchestra as well as lower stress for the musicians caused by high sound pressure levels shall be developed within the project.

For computing sound fields in all three coupled rooms the use of several simulation methods is required. Methods based on Geometrical Acoustics as raytracing are suitable in the frequency range above the Schroeder frequency. However, inside the orchestra pit the sound field is strongly influenced by room modes which can only be modeled by wave-based methods like the Finite Element Method (FEM).

The simulation with FEM of the orchestra pit is presented in the following section.

4.1. Simulation of the sound field in the orchestra pit with the finite element method

Figure 5 shows the orchestra pit at Deutsche Oper Berlin. The floor space is about $150\,\mathrm{m}^2$ with $33\,\mathrm{m}^2$ lying under the stage which is referred to as the overhang area. The overhang area is divided by the prompter's box in two parts. The standard setting of the stage lift is at -2.9 m below stage. The side walls of the pit in perpendicular to the long axis of the opera are made up of wood while the smaller side walls are made from concrete. The pit wall directly under the stage and the ceiling of the overhang area are inclined towards the floor in order to avoid axial room modes.

Figure 5. The orchestra pit at Deutsche Oper Berlin with the overhang below the stage (left).

For computing SPLs in the orchestra pit with the FEM in the software package COMSOL (Multiphysics 5.3a) a monopole source which generates a SPL $L_p = 90\,\text{dB}$ at one meter distance in free field was defined. Each side wall and the floor are considered sonically hard, as an approximation. On the upper boundary surface the impedance boundary condition was set to $Z = \rho c$.

Computation in COMSOL was done in the frequency range 5 - 710 Hz with tetrahedral elements. In the range 5 - 500 Hz a minimum of six elements per wave length was used. From 500 - 710 Hz computation could only be done with four elements per wave length. Figure 6 depicts the SPL distribution on a section at 1.5 m above floor level. This heights was chosen as a compromise between ear heights of sitting and standing musicians.

Increasing SPLs at 25 Hz can be seen particularly in the overhang area, caused by axial modes between the parallel walls of the overhang.

SPL distributions at 55 Hz and 90 Hz in Figure 6 and at 55 Hz and 80 Hz in Figure 7 show high SPLs along edges and corners of the pit, which each indicate a complex pattern of standing waves.

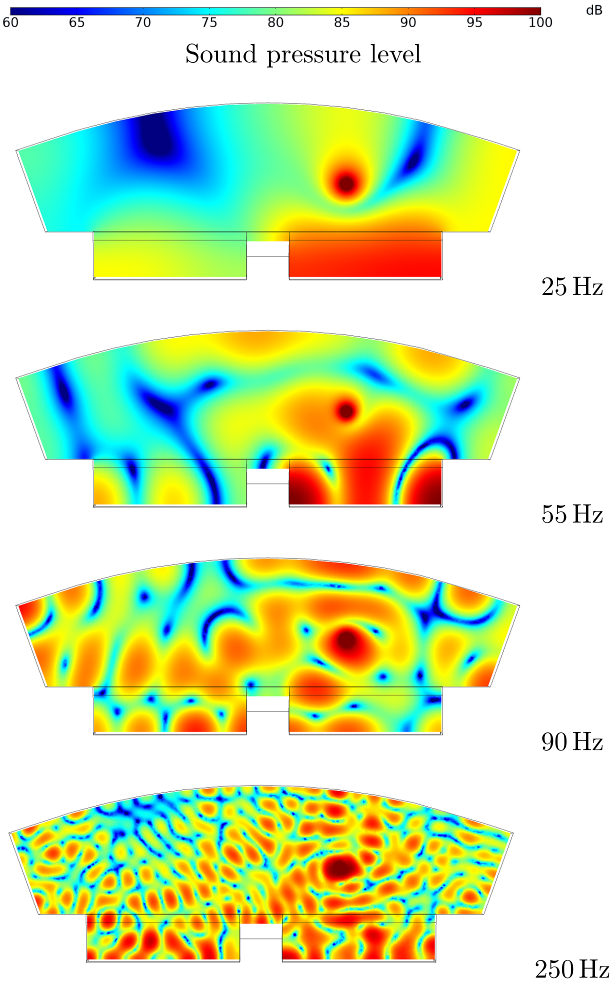

Figure 6. SPL distribution for 25, 55, 90 and 250 Hz top down. Distribution is plotted on a section at 1,5 m above the floor. Computing with COMSOL Multiphysics 5.3a.

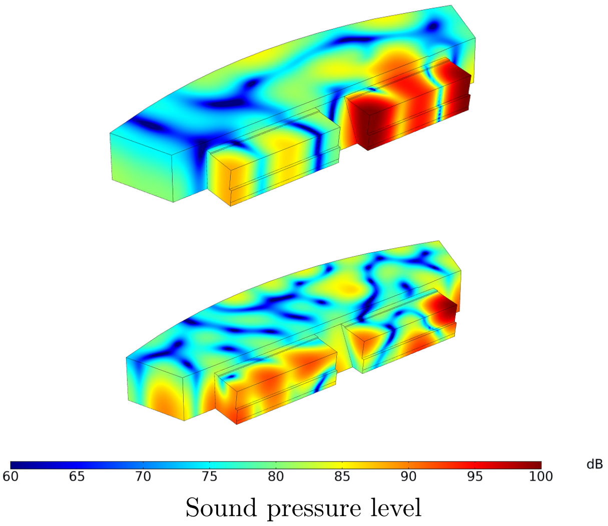

Figure 7. SPL distribution for 55 Hz top and 80 Hz drawn on the boundary of the orchestra pit, indicating the existence of complex room modes.

4.2. Simulation of the sound field in the auditorium based on Geometrical Acoustics

For evaluating the effect of constructional changes in the orchestra pit on the room acoustics in the auditorium a model using geometric acoustics was created with the software CATT-Acoustic. The absorption coefficients were estimated from the publication by Cremer et al. [4] and matched to the measured reverberation time RT_{60} with iron curtain closed, as given above. Figure 8 shows the resulting SPL distribution on the seating areas for an omnidirectional source in the orchestra pit.

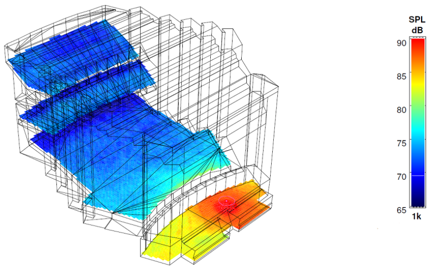

Figure 8. Computed SPL distribution at 1 kHz for a sound source inside the pit. Computing with CATT-Acoustic TUCT v2.0b:1.03, $4{,}28 \cdot 10^5$ rays, t=2 s.

5. Discussion

The analysis of the room acoustics in the DOB represent a part of the ISO 3382-1. Further parameters of that standard that describe the sensation of spaciousness need to be measured. There is also a chance that many of the energy based parameter are merely single observations at a point in space due to interferences [18]. By applying virtual arrays, one is able to sample a range of receiver positions that together allow for an improved analysis of energy based parameters.

The frequency averaging of many parameters as proposed in the ISO 3382-1 is certainly adequate for consultancy task, it might however hide important information, especially in the low frequency range. For example the ST_{early} without frequency averaging can be used as validation method or a supplement for in-situ measurements of the boundary conditions.

As written, the measurements in the auditorium were done while a small part (horizontal reflector) of the ceiling was open for maintenance work. For this reason, further measurements will be executed in order to validate the room acoustic results given here.

The simulation models shown here represent our preparation for a mapping of the current acoustic situation and for comprehensively analyzing constructional changes for lowering the exposure level in the orchestra pit. A central analysis task of our FEM will be the dependency of SPL distribution on source positions and boundary impedance conditions. By such means, it is the intention to investigate an increase of acoustic transparency by selective absorption in the low frequency range. Drotlett et al. suggested the use of low-frequency absorption for improving acoustic transparency and therefore more quiet playing of musicians [11]

The simulation presented here incorporated simple assumptions on impedance. For example, the walls of the orchestra pit were set as being sonically hard, which is not the case in reality. According to Aretz [13](p.184) “the Achilles' heel of room acoustic finite element simulations appears to be the determination of realistic impedance conditions on the room boundaries". For this reason different methods of measuring surface impedances in-situ, e. g. the ones given in the overview of Wijnat [14], as well as the modeling of surface impedances via impedance boundary conditions or fluid-structural coupling [15] are considered for improving our FEM model.

In order to increase the range of frequency overlap between FEM and raytracing models, a coupling between FEM and the Boundary Element Method (BEM) is part of our future approach. Importantly, the computational load is reduced for large spaces by this means.

Impedance measurements of the boundaries will also improve the accuracy of the raytracing model. Proposals that improve the audibility between sections of the instruments will largely rely of geometric acoustics. Literature has shown that higher level of reflected sound energy can lead to a softer playing style [19].

6. Summary

This work aims at reducing the sound pressure level in the orchestra pit in order to comply with the requirements of the European directive 2003/10/EC.

In order to reach that goal the following steps will be executed (1) a requirements analysis regarding the room acoustics of an opera house for its repertoire, (2) the input of musicians via a questionnaire for describing the current situation and individual aims, (3) the measurement of sound exposure levels in the orchestra pit and in the audience, (4) the room acoustical measurement of the opera, (5) the generation of numerical simulation models of the low and high frequency range and (6) the numerical prediction of constructional changes.

In this article we summarized our preparatory work to capture and to simulate the room acoustics of the Deutsche Oper Berlin in order to find solutions of SPL reduction in the orchestra pit. The measurement results approved the suitability of the venue for opera, first with respect to the parameter ranges of the standard ISO 3382-1 and second in comparison with other opera houses. However, for the task given, we outlined the need for a denser spatial sampling of energy based parameters in room sections as well as the need for performing in-situ measurements of the boundary conditions. Through the application of raytracing and FEM/BEM simulation models it is possible to render the acoustics for a large scale building throughout the entire frequency range.

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