Acoustical analysis of coupled rooms applied to the Deutsche Oper Berlin

1st Jan Michael Kimmich
Fachbereich 2 - Ingenieurwissenschaften
Hochschule für Technik und Wirtschaft
Berlin, Germany
JanMichael.Kimmich@htw-berlin.de

2nd Anton Schlesinger
Projektgruppe Computational Acoustics
Beuth Hochschule für Technik
Berlin, Germany
Anton.Schlesinger@beuth-hochschule.de

3rd Martin Tschaikner
Projektgruppe Computational Acoustics
Beuth Hochschule für Technik
Berlin, Germany
s74086@beuth-hochschule.de

4th Martin Ochmann
Projektgruppe Computational Acoustics
Beuth Hochschule für Technik
Berlin, Germany
ochmann@beuth-hochschule.de

5th Stefan Frank
Fachbereich 2 - Ingenieurwissenschaften
Hochschule für Technik und Wirtschaft
Berlin, Germany
Stefan.Frank@htw-berlin.de

***Abstract*—The aim of the project SIMOPERA is to simulate and optimize the acoustics in large and complex rooms with special focus on the Deutsche Oper Berlin as an example of application. Firstly, characteristic subspaces of the opera are considered as the orchestra pit, the stage and the auditorium. Special attention is paid to the orchestra pit, where high sound pressure levels can occur leading to noise related risks for the musicians. However, lowering the sound pressure level in the orchestra pit should not violate other objectives as the propagation of sound into the auditorium, the balance between the stage performers and the orchestra across the hall, and the mutual audibility between performers and orchestra members. For that reason, a hybrid simulation method consisting of the wave-based Finite Element Method (FEM) and the Boundary Element Method (BEM) for low frequencies and geometrical methods like the mirror source method and raytracing for higher frequencies is developed in order to determine the relevant room acoustic quantities such as impulse response functions, reverberation time, clarity, center time etc. Measurements in the opera will continuously accompany the numerical calculations. Finally, selected constructive means for reducing the sound level in the orchestra pit will be analyzed.**

***Index Terms*—Acoustics, acoustic applications, acoustic propagation, numerical simulation**

I. Introduction

In opera houses room acoustics is determined by the coupling of three rooms: the fly tower, the orchestra pit and the auditorium. Within the project SIMOPERA (simulation and optimization of room acoustical fields by considering the Deutsche Oper Berlin) room acoustics shall be simulated and optimized using the example of Deutsche Oper Berlin (DOB). It is necessary to optimize room acoustics because high sound pressure levels in the orchestra pit are potentially dangerous for the health of orchestra musicians.

The simulation of sound fields in three coupled rooms differing in volume requires the application of different simulation methods. Simulation methods based on Geometrical Acoustics can be used when the wavelength of propagating sound is small in relation to the characteristic room dimension i.e. for the auditorium large in volume. In rooms which are small with respect to the wavelength the sound field below the Schroeder frequency is dominated by modal behaviour. These effects can only be simulated by wave-based methods like the Finite Element Method (FEM) and the Boundary Element Method (BEM). Within this project the different simulation methods shall be applied to the DOB and compared to room acoustic measurements.

The DOB was rebuilt in the years from 1957 to 1961 after the formerly Städtische Oper was destroyed during World War II. The auditorium is of a modified fan-shaped type and inspired by the Bayreuth Festspielhaus [1]. Acoustic consulting was done by Lothar Cremer who documented the acoustic treatment, especially the design of the Rabitz ceiling which is designed as a staggered reflector, in [2]. The opera house holds almost 1900 seats inside the auditorium with a volume of about 11,000 m^3. Acoustically coupled to the auditorium are the fly tower with about 17,000 m^3 and the orchestra pit with 400 m^3. The upholstered chairs, the partly perforated panel absorbers that cover the side walls and the suspended Rabitz ceiling affects the acoustics of the auditorium. Further information on acoustics of the DOB can also be found in [1]–[3].

In this publication, we present the current state of the project. Results of room acoustic measurements at DOB with iron curtain opened and closed for coupling and decoupling the fly tower are presented. Furthermore, the setup and results of simulations with Geometrical Acoustics methods and with the FEM will be introduced. The influence of low frequency absorption implemented on the boundaries of the orchestra pit is simulated. For the decoupled orchestra pit a numerical eigenfrequency analysis with the FEM is presented for two different impedance boundary conditions on the cover plate of the orchestra pit.

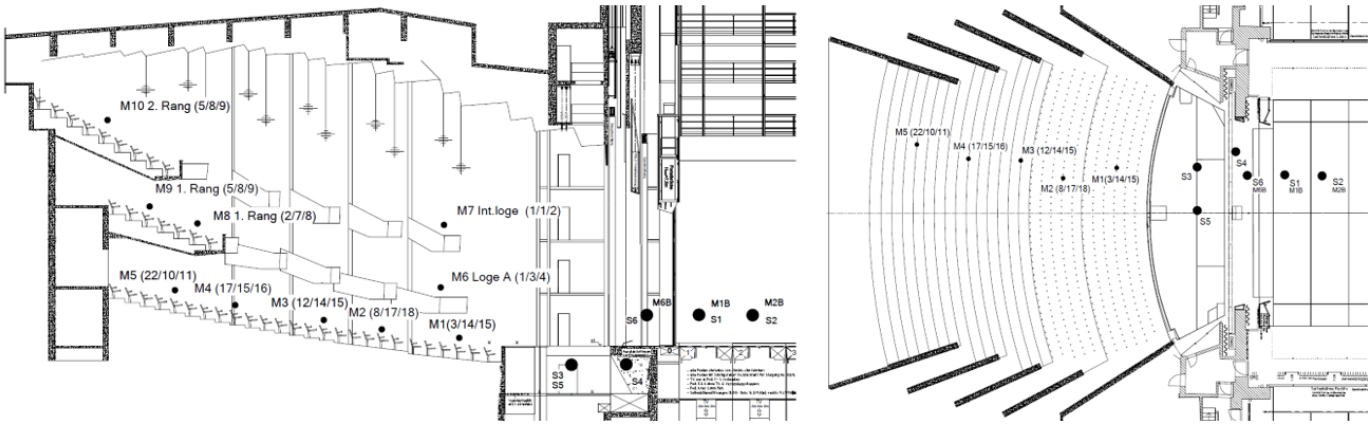

Fig. 1. Source- (S) and measurement positions (M) used for room acoustic measurements at the Deutsche Oper Berlin. Ten measurement positions inside the auditorium were choosen according to [5] in the stalls, galleries and lodges. Impulse responses for three source positions on the stage and another three in the orchestra pit were measured. Source position S4 is located in the overhang area under the stage.

II. Room Acoustic Measurements

Results of room acoustic measurements within the project SIMOPERA were originally published in [4] and pictured for the reverberation time and sound strength G in comparison with other opera houses. Here we focus on room acoustic parameters for transparency and stage acoustics.

A. Setup, equipment and method

For capturing the current state of room acoustics, measurements were carried out according to ISO 3382-1:2009 [5] in the absence of audience and scenery. The orchestra pit which is adjustable in height was positioned in the most frequently used setting for opera performance which is 2.9 m below stage level. The side walls of the empty fly tower were covered with theater curtains to avoid the occurence of flutter echos. A small part of the staggered reflector under the ceiling of the auditorium was opened because the lighting bridge located there was used in the previous performances. The location of the lighting bridge can also be seen in Fig. 1. The influence of opening this part of the ceiling on room acoustic quantities was already shown by Cremer [2] in scale model experiments. Ten measurement positions in the stalls, balconies and lodges were choosen, which are shown in Fig. 1. The omnidirectional sound source was placed at three different positions in the front and middle part of the stage. Inside the orchestra pit also three source positions were used with source position S4 lying in the so-called overhang area below the stage.

The measurement equipment consists of the sound sources Brüel & Kjær Type 4292-L and QSAM Type QS-12 as dodecaedron loudspeakers and the Brüel & Kjær Omnisource Type 4295 with the power amplifiers PA 1000 and Brüel & Kjær Type 2734. As a receiver the omnidirectional microphone Earthworks Type M30 was used with the interface RME Type Fireface UCX.

A logarithmic sweep was used as excitation signal which was applied three times per source-receiver combination for increasing the SNR of the measurements. For some measurements the SNR was still below 35 dB in the one-third octave bands lower than 160 Hz. The corresponding room impulse responses were not included when evaluating the measurements.

B. Analysis of room acoustics

1) Reverberation Time: Measurements of the reverberation time were performed for three different configurations. Firstly, with closed iron curtain and source and receiver in the ochestra pit (CC). Secondly, with iron curtain closed, sound sources in the orchestra pit and receivers on measurement positions M1 - M10 as depicted in Fig. 1. Thirdly, with iron curtain open, receivers on positions M1 - M10 and sound sources on the stage and in the orchestra pit. The mean values are given in Fig. 2 for one-third octave bands together with the median and 25 as well as 75 percentils.

From the increasing percentil bars below 250 Hz, it can be seen that there is a dependency of reverberation time on the measurement positions. This variation of the reverberation time with different positions is a characteristic property of coupled rooms. For the configuration with the iron curtain openend which couples the fly tower large in volume, the results (CO) vary even more. The linear regression applied to the logarithmic energy decline for calculating the reverberation time as described in [5] implicates uncertainty since the decline is not linear in coupled rooms [3], [6].

2) Room acoustic parameters: In accordance with [5] the perceived transparency of sound in the auditorium was evaluated with the room acoustic parameters clarity C_{80}, definition D_{50} and center time T_S. For clarity and definition in Figure 3, a common tendency with higher values towards rear listener positions can be seen. The highest values for both parameters were measured at position M9 on the first balcony which benefits from early reflections of the ceiling under the second balcony floor. Slightly lower are the parameters for position M10 which benefits from the proximity to the sidewalls in

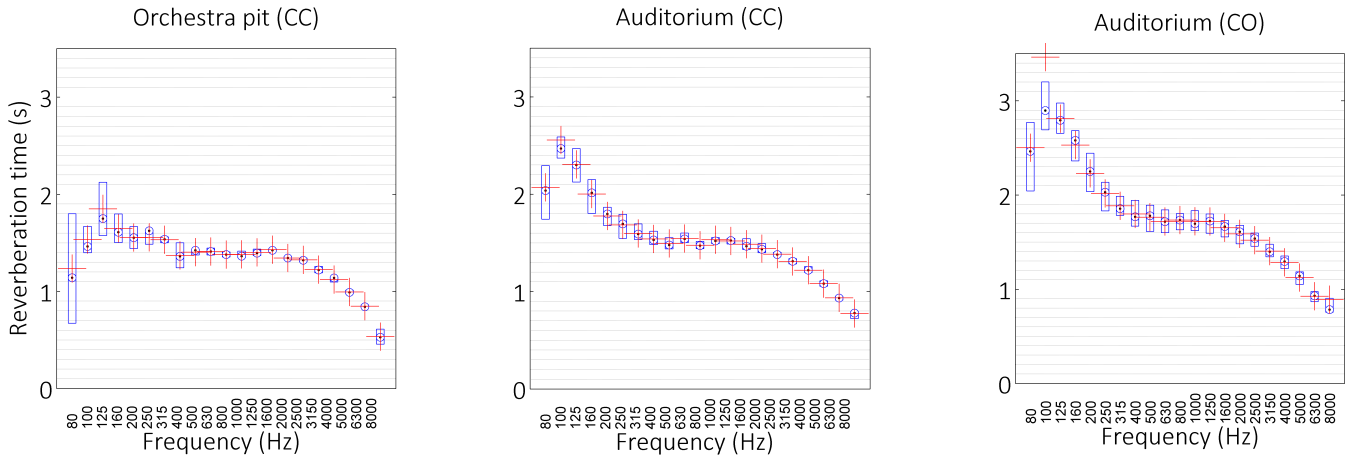

Fig. 2. Reverberation times in one-third octave bands for the three measured configurations: measurement positions in the orchestra pit with the iron curtain closed (CC), measurement positions M1-M10 in the auditorium with the iron curtain closed (CC) and measurement positions in the auditorium with the iron curtain open (CO). The median is marked with a circle, the mean value with a plus sign and the boxes show with its lower edge the 25 and with its higher edge the 75 percentiles.

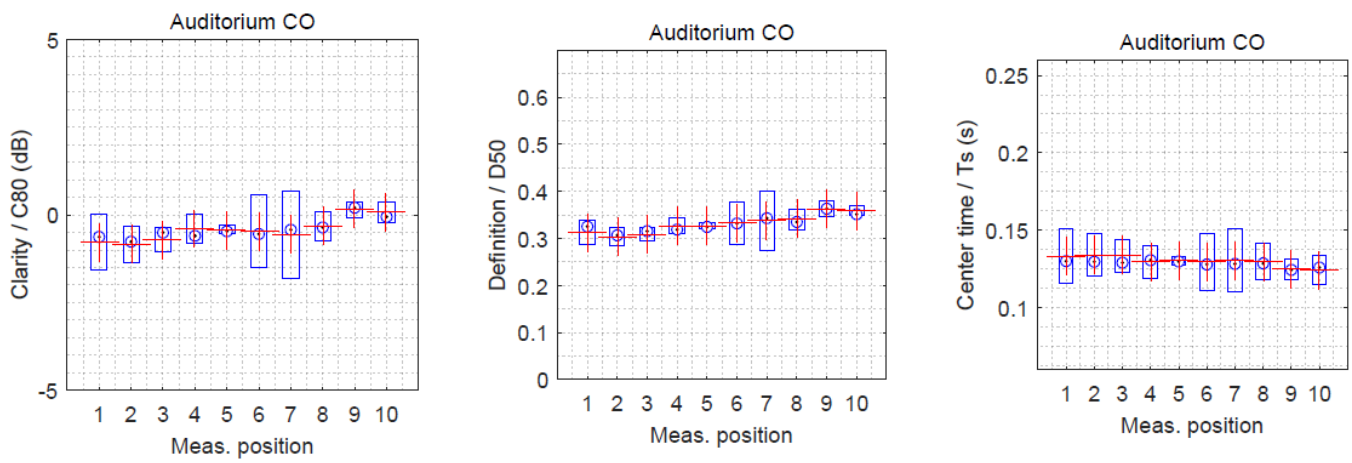

Fig. 3. Evaluated room acoustic parameters for transparency: clarity C_{80}, definition D_{50} and center time T_s in the auditorum for 10 measurement positions and source positions on the stage and in the orchestra pit. The median is marked with a circle, the mean value with a plus sign and the boxes show with its lower edge the 25 and with its higher edge the 75 percentiles.

the rear part of the auditorium as well as from the reflecting ceiling. As averaged values for all ten measurement positions inside the auditorium one obtains the mean values with given standard deviations for clarity C_{80}=-0.43±0.33 dB, definition D_{50}=0.33±0.02 and center time T_S=130±3.4 ms. The center time T_s, which is a measure for the balance between clarity and reverberance [7], decreased towards rear positions from about 0.135 s to 0.125 s. Alltogether the parameters shown are within the range described in [5].

3) Stage acoustics: As a measure of the room acoustic support on stages for musicians, Early Support ST_{early} was measured. Extensive work was done in the field of stage acoustics which comprises research on physical room acoustic measures as ST_{early} and their correlation with perceptual evaluations by musicians e.g. by Gade [8], Dammerud [9], Schärer Kalkandjiev [10] and Wenmaekers [11]. However, less attention is paid to the situation in orchestra pits where one has to minimize sound exposure for musicians and simultaneously ensure mutual audibility within the orchestra.

For assessing stage acoustics inside the orchestra pit, ST_{early} was measured at three positions S3, S4 and S5 where S4 lies in the overhang area. The measured values are $ST_{early,S3}$ = -9.3 dB, $ST_{early,S4}$ = -7.3 dB and $ST_{early,S5}$ = -10.8 dB with the highest value in the overhang area as might be expected. These values lie within the range of comparable measurements in orchestra pits [11], [12].

III. Room acoustic simulations

For the development of acoustic treatment which can lower sound pressure levels in the orchestra pit, room acoustic simulations were carried out. There are two different objectives for the simulations within the project: firstly the low frequency sound field inside the orchestra pit has to be calculated to develop selective room acoustic treatment in order to supress the room modes. Secondly, the effect of room acoustic or constructional changes inside the orchestra pit on the radiation of sound into the coupled auditorium must be assessed. For the first task the use of wave-based simulation methods is suitable. The second part makes use of Geometrical Acoustics since the volume of the auditorium is to big to be simulated with wave-based methods. In this section the efforts in setting up simulations as well as first results will be presented.

A. Eigenfrequencies of the decoupled Orchestra Pit

In small rooms like the orchestra pit the low frequency sound field beneath the Schroeder frequency is dominated by the existence of well separated room resonances [6]. For a complex shaped room there is no analytical solution and therefore the application of the FEM for eigenfrequency analysis is appropriate. However, the FEM is not inherently suitable for dealing with exterior problems as it is the case for the open orchestra pit. Several methods for treating exterior problems with the FEM exist [13], [14]. Here, for first calculations the plane wave boundary condition $Z = \rho_0 c$ was applied to the cover plate and compared to the rigid case as depicted in Fig. 4. A detailed description of the orchestra pit and the setup of the FEM simulation can be found in [4].

As it can be seen from the comparison of sound pressure distributions on the top boundary, the damping is the more efficient the higher the eigenfrequency. Since $Z=\rho_0 c$ is the impedance in the far field i.e. for plane waves this approximation seems not to work well for low frequencies. In future works, it is planned to calculate the low frequency sound field with alternative methods like Perfectly-Matched-Layers or with FEM-BEM coupling. A first approach can be seen in Fig. 5. Using FEM-BEM coupling, it is possible to calculate the sound field in the auditorium for low frequencies too by utilizing the computational efficiency of the FEM for small rooms and of the BEM for large volumes.

B. Calculations with Geometrical Acoustics

For investigating room acoustics of coupled rooms considerably higher than the Schroeder frequency, Geometrical Acoustic methods can be applied. For Geometrical Acoustics simulations a simplified model of the DOB has been set up. In order to match T_{30} in the CATT-Acoustic model, first the given equivalent absorption area data in [2] was inserted. The derived absorption coefficients had than to be adjusted, in order to obtain the measured T_{30} depicted in Fig. 2 with closed iron curtain. Auto edge scattering was enabled and a default surface diffuse reflection coefficient of 0.1 was applied to all surfaces besides the audience planes. For these planes separate coefficients were used.

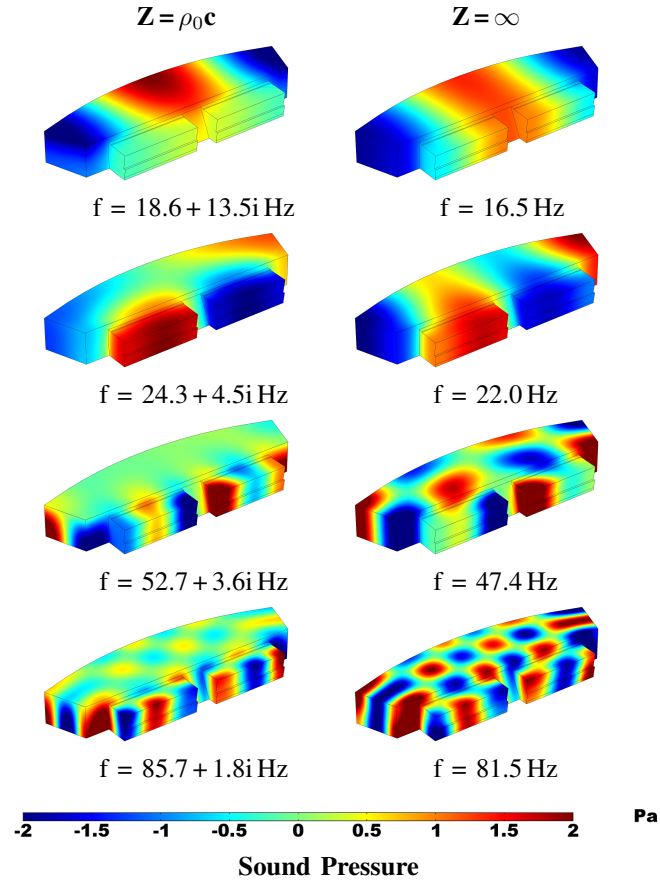

Fig. 4. Real part of the acoustic pressure for selected eigenmodes with corresponding eigenfrequencies of the orchestra pit. The impedances on the cover plate are $Z=\rho_0 c$ for the left and $Z=\infty$ for the right column. In both cases all the other boundaries are rigid. Calculated with COMSOL Multiphysics 5.3a.

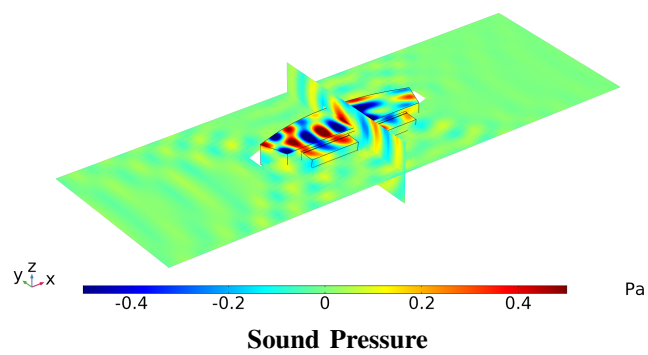

Fig. 5. Real part of the radiated sound pressure from the orchestra pit at f = 88 Hz with FEM-BEM coupling on the cover plate. As a sound source a monopole which generates a sound pressure of 90 dB in 1 m distance under free field conditions was defined inside the orchestra pit.

The model can be used for estimating the influence of acoustic treatment and constructional changes in the orchestra pit on acoustics in the auditorium. A first study was carried out by modeling the influence of low frequency absorption in the orchestra pit. As a limiting case, all of the surfaces

inside the pit were covered with low frequency absorbers in the model. The results are compared with the current state of the room acoustic parameters sound strength G, clarity C_{80} and reverberation time T_{30}. In Fig. 6, the effect of low frequency absorption treatment on sound strength G and Clarity C_{80} for the audience planes in the stalls and the galleries is depicted. The calculated reduction of sound strength G is of the order of 3 dB, while there is a smaller increase in clarity of about 1 - 2 dB depending on the seating position.

Inside the orchestra pit the reduction of the summarized sound strength G is of the order 5 dB as shown in Fig. 7. Since sound strength G is related to the perceived loudness, this room acoustic parameter is relevant for evaluating the effect of acoustic treatment besides the Sound Pressure Level, which is relevant for legal terms regarding health and safety. For improving acoustic transparency and mutual audibility between orchestra musicians, a constant reverberation time over the whole frequency range is beneficial. The reverberation time inside the orchestra pit is depicted in Fig. 2 and shows about 0.4 s higher reverberation times for the 125 Hz octave band as in the range around 500 Hz. To obtain lower reverberation times in the low frequency range, the reduction of T_{30} at 250 Hz by implementing low frequency absorption is considered too. In Fig. 7 the reverberation time decreases by about 0.4 s with low frequency absorption.

Since the Schroeder frequency of the decoupled orchestra pit is approximately around 100 Hz, results of Geometrical Acoustic simulations should be critically evaluated here. For this case, FEM calculations shall be carried out for comparing them with the results obtained by Geometrical Acoustics simulations.

The results presented here have to be considered as a limiting case and a first test of the simulation model since the implementation of absorbers all around the orchestra pit is not a realistic measure.

IV. Conclusion and Future Work

This publication presents the current state of the project SIMOPERA, which aims at simulating and optimizing room acoustic fields applied to Deutsche Oper Berlin, is presented. Results of room acoustic measurements show the characteristic dependency of the reverberation time on the receiver position in coupled rooms. The evaluated reverberation time and the room acoustic parameters clarity, definition and center time for the unoccupied auditorium are all in the range declared in [5]. Further measurements with a higher SNR are necessary to clarify increasing reverberation times around 100 Hz which differ slightly from the results given in [2]. First simulation results with Geometric Acoustic methods for the evaluation of measures inside the orchestra pit and their effect on acoustics in the auditorium were shown. For calculating the low frequency sound field inside the orchestra pit, an approach using the FEM with simplified boundary conditions was succesfully applied.

In order to compare simulation results of the FEM with measurements for the low frequency range in the orchestra pit, different methods are considered such as the one described in [15] and other microphone array techniques.

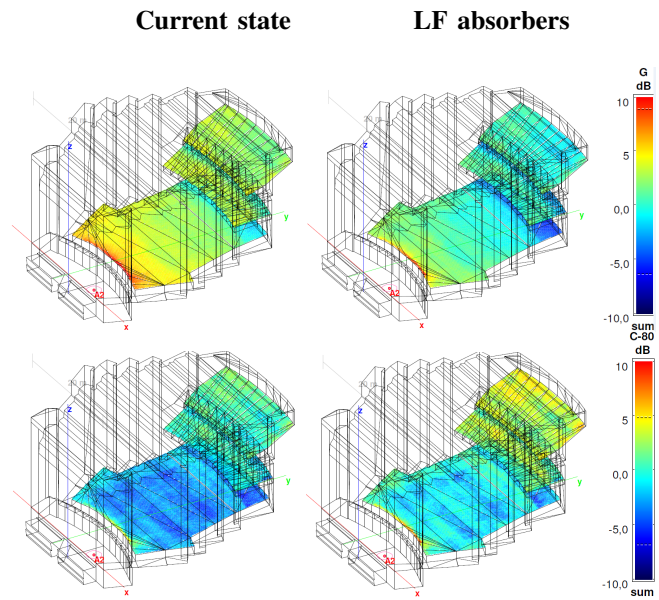

Fig. 6. Change in sound strength G and clarity C_{80} for a source A2 inside the orchestra pit for the current state on the left and with low frequency (LF) absorbers inside the orchestra pit. The calculated reduction of sound strength G is of the order of 3 dB while there is a lesser increase in clarity of about 1 - 2 dB depending on the seating position. Calculated with CATT-Acoutic v9.1c TUCT2 v2, 962950 rays, t = 1638 ms (left), t = 1185 ms (right).

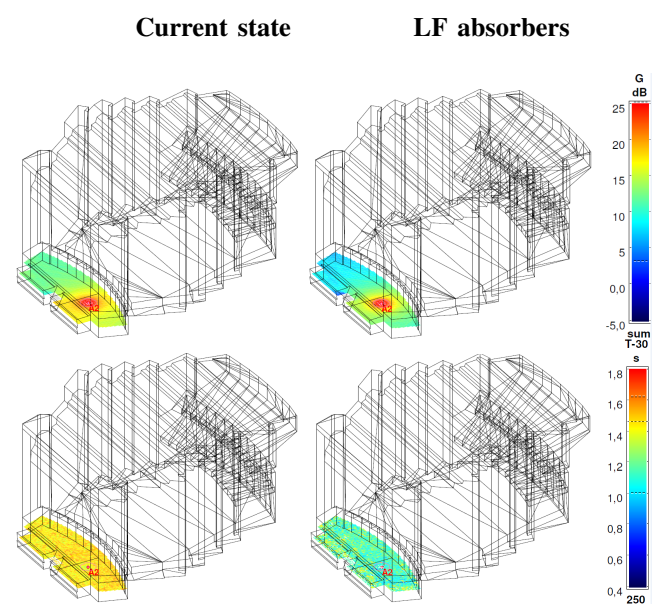

Fig. 7. Change in sound strength G and reverberation time T_{30} inside the orchestra pit for the current state on the left and with low frequency (LF) absorbers inside the orchestra pit. The reduction of sound strength inside the orchestra pit is in the order of 5 dB. Reverberation time at 250 Hz is lowered up to 0.4 s. Calculated with CATT-Acoutic v9.1c TUCT2 v2, 962950 rays, t = 1643 ms (left), t = 1112 ms (right).

The FEM simulation results presented here are based on simplified assumptions for the impedance boundary conditions. All walls besides the cover plate are considered rigid. Since the implementation of realistic impedance conditions is not a simple task, different approaches will be considered in the future. Techniques for measuring impedances in-situ are described e.g. by [16]. However, in-situ measurements of impedances have limitations, especially in the low frequency range which is of importance here. By the assumption of locally reacting boundaries, the implementation of impedance boundary conditions is possible. Another possibility is to model the boundaries with FEM as well and couple them to the acoustic domain via fluid-structural coupling [17], [18]. Different approaches will be considered for improving the results of the FEM simulations. Acoustic measures for damping eigenmodes of the orchestra pit with different absorbers and resonators can subsequently be simulated.

Further analysis has to be done concerning the influence of different absorbing boundary conditions which are implemented on the cover plate of the orchestra pit. Simulation results for the simple impedance boundary condition $Z = \rho c$, a Perfectly-Matched-Layer and FEM-BEM coupling will be compared in order to evaluate the effect on the sound field inside the orchestra pit. Especially the occurence of complex eigenfrequencies in the case of absorbing boundaries is not easy to interpret.

With the objective of developing a simulation tool for calculating the sound field in a complex shaped room over the whole frequency range, future work will include the creation of room impulse responses composite of calculations with FEM and BEM for the low frequency range and Geometrical Acoustics for the middle and high frequency range. Then it would be possible to use the impulse response for auralization as well as for the prediction of room acoustics for the complete audible frequency range.

V. Acknowledgement

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References

[1] Barron, M. (2010), Auditorium Acoustics and Architectural Design, Second Edition, Spon Press, London and New York

[2] Cremer, L., Nutsch, J. and Zemke, H.J. (1962) Die akustischen Maßnahmen beim Wiederaufbau der Deutschen Oper Berlin. Acustica 12, 428-433

[3] Cremer, L., Müller, Helmut A. (1978) Die wissenschaftlichen Grundlagen der Raumakustik - Band 1: Geometrische Raumakustik, Statistische Raumakustik, Psychologische Raumakustik. Hirzel Verlag, Stuttgart

[4] Schlesinger, A., Ochmannn, M., Kimmich, J. M., Frank, S. (2018), Controlling multiple acoustic objectives during the implementation of the European directive 2003/10/EC at an opera house. In: Euronoise 2018 Conference Proceedings, Heraklion, Greece

[5] ISO 3382-1:2009. Acoustics – Measurement of room acoustic parameters – Part 1: Performance spaces (ISO 3382-1:2009)

[6] Kuttruff, H. (2009), Room Acoustics, Fifth Edition, Spon Press, London and New York

[7] Gade, A. C. (2007), Acoustics in Halls for Speech and Music, In: Rossing, T. D. (Ed.): Handbook of Acoustics, Springer, New York

[8] Gade, A. C. (2010), Acoustics for Symphony Orchestras; status after three decades of experimental research. Proceedings of the International Symposium on Room Acoustics, ISRA 2010, Melbourne, Australia

[9] Dammerud, J. J. (2009), Stage Acoustics for Orchestras in Concert Halls. PhD Thesis, University of Bath

[10] Schärer Kalkandjiev, Z., Weinzierl, S. (2013), The influence of room acoustics on solo music performance: An empirical case study. Acta Acust. united with Acust., 99(3), pp. 433 - 441

[11] Wenmaekers, J. H. C., Stage acoustics and sound exposure in performance and rehearsal spaces for orchestras. PhD Thesis, TU Eindhoven

[12] Vercammen, M. and Lautenbach, M. (2016), Stage and pit acoustics in opera houses. Proceedings of the ISMRA 2016, Buenos Aires, Argentina

[13] Ochmann, M., Lippert, S., von Estorff, O. (2017), Numerische Methoden der Technischen Akustik. In: Müller, G., Möser, M. (Hrsg.): Fachwissen Technische Akustik, Springer Vieweg, Berlin

[14] Tomiku, R. et al. (2014), Room Acoustics Simulation. In: Sakuma, T., Sakamoto, S., Otsuru, T. (Eds.): Computational Simulation in Architectural and Environmental Acoustics, Springer Japan

[15] Vu, T. P., Rivet, E., Lissek, H. (2018), Low Frequency Sound Field Reconstruction in Non-rectangular Room: A Numerical Validation. In: Euronoise 2018 - Conference Proceedings, Heraklion, Greece, 2018

[16] Wijnant, Y. H., Kuipers, E. R., de Boer, A. (2010), Development and application of a new method for the in-situ measurement of sound absorption. In: Proceedings of ISMA 2010 with USD 2010, 109-122

[17] Aretz, M. (2013), Combined Wave and Ray Based Room Acoustic Simulations Of Small Rooms. Ph.D. Thesis, RWTH Aachen, Aachener Beiträge zur Technischen Akustik, Band 12, Logos Verlag Berlin

[18] Franck, A., Aretz, M. (2007), Wall structure modeling for room acoustic and building acoustic FEM simulations. In: 19th International Congress on Acoustics Madrid, 2-7th September 2007

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