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AURALISING STAGE ENVIRONMENTS IN THE PRESENCE OF THE ORCHESTRA

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ABSTRACT

One of the primary challenges for stage acoustics investigations is the ability to predict room acoustical conditions on stage which consider the presence of other performers. This was shown to be a key aspect when evaluating the acoustic qualities of a stage from a musician's perspective. As a scenario where diffraction effects are dominant and the obstacles' shape and arrangement are highly complex, geometrical acoustics methods do not yet reach sufficient accuracy for calculating room acoustical parameters or for auralisation. For the purpose of investigating a musician's acoustic impression of a stage under laboratory conditions, the attenuation caused by groups of sitting bodies was predicted using BEM for a set of predefined source to receiver paths. In order to extend results to broadband frequency range, measurements with bodies sitting in the proximity of line of sight were also carried out in an anechoic chamber with a setup that allows the attenuation to the direct sound and to the floor reflection to be recorded separately. Broadband attenuation values were eventually derived for all relevant paths and then pipelined into a ray-tracing software, allowing simulation and auralisation of arbitrary multi-person scenes, including a stage in the presence of an orchestra.

Keywords: *Stage, Orchestra, Auralisation, BEM, Diffraction.*

1. INTRODUCTION

The field of stage acoustics has been so far concerned, to a large extent, with the quality of the stage perceived by the orchestra. As opposed to the case of a solo musician or a small ensemble, when a symphonic or chamber orchestra is present on a stage, its members are faced with an issue of intelligibility: louder instruments tend to mask the sound of quieter instruments and this is further worsened by the attenuation, within the orchestra, resulting from the presence of other players sitting in the way between any potential combination of players who may wish to hear the sound of the other's instrument. Within this context, the concept of 'compensating reflections' and 'competing reflections' [1] becomes relevant when addressing the issue from an architectural acoustics perspective. Assessing the quality of a stage from an architectural perspective was the main concern when the 'Stage Support' parameters ST_{early} and ST_{late} were first introduced by Gade [2, 3]. Several subsequent studies found, however, poor correlation between these and the overall acoustic impression of a stage [1, 4–6] and proposed, along with other authors, new predictors based on new perceptual models and/or measurement methodologies. Some of these studies have also demonstrated empirically that the presence of the orchestra plays a considerable effect, and that a stage fitted with only chairs and music stands is not a viable surrogate [7].

Evaluating a musician's perception of a stage remains still today a major challenge: studies that adopt in-situ questionnaires after concerts are limited in the amount of data that can be gathered while also being faced with the issues of memory errors and the difficulty of controlling the many potentially confounding variables which are linked to the nature of such investigations. Listening experiments that can evaluate the room acoustical conditions

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in laboratory conditions would be in this respect preferable; these have been successfully carried out for solo musicians and smaller ensembles [8], but are challenging to realise for an orchestra in an ecologically valid experimental environment. This is mostly due to software and hardware limitations, since the geometrical acoustics-based softwares used to auralise virtual rooms do not provide reliable results when considering propagation through the orchestra [1, 9] and diffration effects in general [10]. The amount and order of diffraction sources required to realistically model the diffraction and scattering effects of several complex-shaped obstacles, such as sitting human bodies, in the way between source and receiver seems to be large.

Softwares where semi-analytical solutions are at all implemented, such as CATT-Acoustic and Odeon, are however in the best cases limited to 2nd order diffraction [11] due to the high degree of computational complexity required for higher orders. Numerical methods allow to take into account diffraction effects, but are limited in its applicability to this scenario since computational costs become unrealistic for the frequency range required for auralisation. Hybrid numerical-geometrical acoustics simulation softwares – where diffraction effects can be simulated up to the cut-off frequency between the two solvers – are for the same reasons not a viable solution where the whole audible spectrum is to be auralised.

With the purpose of investigating the perception of a stage from the perspective of the orchestra under laboratory conditions, a new modelling pipeline has been developed via means of numerical simulations, measurements and geometrical simulations. The insertion loss given by a group of up to nine subjects in proximity of the line of sight between source and receiver was measured, in different configurations, in an anechoic chamber. The measured insertion loss curves were then used to complement numerical simulations of an orchestra arrangement in order to extend the result beyond their upper frequency limit. The insertion loss values derived from the hybrid simulated and measured responses are then converted to filters that are applied to the individual energy contributions of a ray-tracing software in order to auralise a stage which includes the presence of an orchestra. This pipeline will also allow to auralise other acoustic environments with multiple sitting bodies between a source and a receiver, such as open plan offices or restaurants, which remain a major challenge for room acoustic simulation and auralization.

2. METHODS

2.1 Orchestra arrangement

The orchestra arrangement and measurement positions were defined on the basis of several requirements. Firstly, it was desirable to obtain transfer functions for at least two receiver positions, one for strings and one for woodwinds. Since these are the most challenged instrument groups within an orchestra [1], being able to carry out auralisations from all source players within the orchestra to two such receiver players was considered as particularly relevant.

The arrangement chosen is a typical American-style chamber orchestra arrangement consisting of 53 players – see Fig. 1. This amount allows to fit the entire orchestra within the occupiable area of the anechoic chamber in a realistic arrangement. For the sake of validation of the experimental measurement procedure – which involves measuring the effect of a sub-group of the whole orchestra for each measured path, as well as measurement of direct and floor reflection independently – subsequent comparison with an existing database of measurements taken with a full orchestra [7] on a real stage without risers was made possible while outlining the methodology. The reference database consists of impulse responses for combinations between 6 source players and 11 receiver players with an omnidirectional source, where the combination of direct sound and floor reflection can be extracted through windowing. The 80-elements orchestra with German arrangement of the referenced study was altered so as to maintain the same position for 40 players, which allows comparison of at least one path between two players with the one measured in the present study.

2.2 Numerical simulations

The geometry of an average-sized [12] sitting human body has been adopted for all numerical simulations. Due to the model's required size and upper frequency limit, a series of preliminary studies was carried out with the software COMSOL Multiphysics®. These were aimed at identifying the most appropriate solver for the project's purpose as well as the maximum achievable extent of geometry, frequency limit and resolution, running on a high-range desktop computer. The Boundary Element Method (BEM) solver using adaptive cross approximation (ACA) has been chosen, allowing up to approximately 25 player bodies with respective music stands to be simulated up to 1 kHz, at third-octave band center frequency steps, and

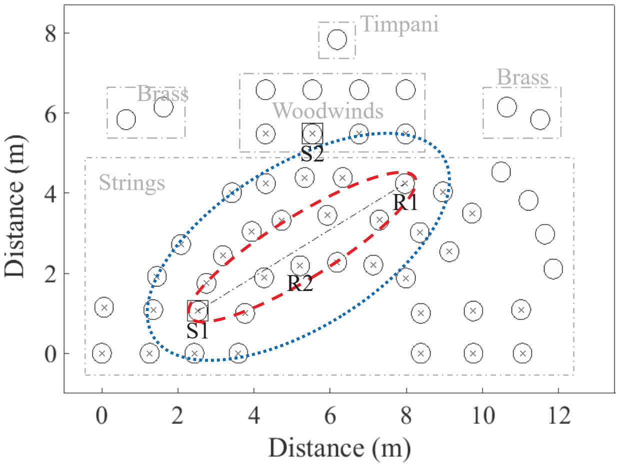

Figure 1. Top view of the orchestra arrangement. Dash-dotted line is validated path. Position in squares are loudspeaker positions (S1,S2). R1 and R2 are receiver positions whose insertion loss is shown in Fig. 4. x-marked positions are consistent with [7]. Concentric ellipses show half-sized Fresnel zones occupied by bodies in BEM models (larger, blue) and measurements (smaller, red) for validated path.

subsequently interpolated. This frequency resolution and upper limit enables adequate interpolation and leaves an adequate amount of room to be combined with the measured responses with a crossover filter for all paths. An amount of 25 bodies allows to have, even for the longest measured distance of 10.2 m, all bodies and music stands contained within the inner half of the first 60 Hz Fresnel zone. The measured response of the same path is valid for nine bodies, according to the same principle, from 600 Hz upwards, which is the value of the highest crossover frequency for this database. A more detailed outline concerning the Fresnel zones-based rationale can be found in paragraph 2.3. The human geometry has been simplified in order to be able to use a structured mesh for a large portion thereof, allowing a considerable reduction of the degrees of freedom in comparison to the use of unstructured meshes. The amount of elements per wavelength has been set to six as per standard BEM modelling practice. The boundary condition is a complex impedance defined for random incidence, calculated with a Delaney-Bazley-Miki model [13] within the built-in acoustic interface of the adopted software. The input flow resistivity was taken as the average from a collection of textile measurements [14] in order to model the effect of clothes.

2.3 Anechoic measurements

The measurements were carried out in the anechoic chamber of TU Berlin, whose length and width measure 13.5 m and 8.6 m, with a lower cut-off frequency of 63 Hz. The orchestra arrangement was laid out to fit the size of the room as it can be seen from Fig. 1. The main objective of the measurement is to obtain broadband insertion loss curves of the paths between two players – one first violin and one flute – and the remaining players of the orchestra.

With impulse responses from an in-situ measurement such as the one carried out by [7] it is not possible to separate direct sound from floor reflection due to their proximity in the time domain. For implementation of the curves as filters within a ray tracing environment as well as for their availability for further investigations, it is desirable to be able to measure direct sound and floor reflection separately. In order to achieve this, a custom-built measurement set-up was designed. This enables to obtain the image source, with respect to the floor, of the loudspeaker standing above the floor level. Due to the acoustical transparency of the wire floor, an impulse response across the floor level can be measured. The set-up consists of a double loudspeaker stand mounted on a rotating plate, which allows to change the horizontal angle of both loudspeakers simultaneously. In an ideal image source scenario, the obstacles present above the floor would also be reflected on the opposite side of the floor: this is to be able to correctly reproduce the diffraction and scattering effects, for the floor reflection, of the obstacles on the path from source to floor. In order to achieve such effect for the floor reflection, an image receiver microphone was also installed to measure the pressure below the floor level.

An overview of the measurement set-up is given in Fig. 2. The time responses of the paths $S_{\text{floor}} \rightarrow R$ and $S \rightarrow R_{\text{floor}}$ are halved and then summed together, with and without bodies present. By subtracting the occupied floor pressure sum from the empty floor sum, a total loss for the floor reflection is obtained. This procedure is to be considered as an approximation of a real floor reflection, since it consists in effect of the sum of two individual insertion losses, one with respect to the path from source to floor, and one with respect to the path traveling from floor to receiver. The extent of the error of this procedure was estimated through validation against measurements

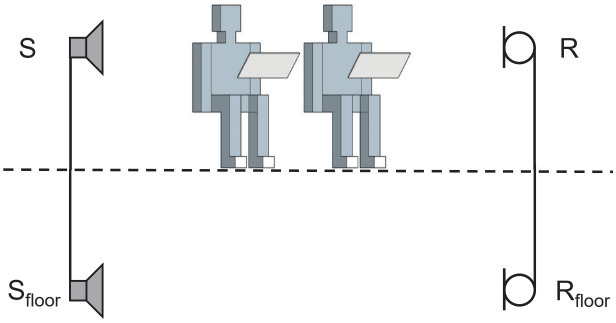

Figure 2. Measurement setup. Dashed line represents wire floor. S_{floor} and R_{floor} are image source and image receiver to measure insertion loss of floor reflection.

Figure 3. Measurement in anechoic chamber, loudspeaker and microphone pairs on the sides of the picture.

by [7] which can be found in paragraph 3.1. Transducer height above and below the floor was set to 1 m, consistent with [7].

In order to measure with sound traveling undisturbed across the floor, it was necessary to measure on the wire floor without any additional supporting grid. Since this structure can support the weight of up to 10 persons plus instrumentation, it was decided to measure the insertion loss across a group of nine sitting subjects with music stands. When considering spherical propagation between a source and a receiver with scattering and diffraction, it is of relevance to take into account the size of the Fresnel zones: these are concentric ellipsoid-shaped zones of finite order whose foci are the source and receiver point, with a frequency-dependent size. According to the Huygens-Fresnel principle, it can be assumed that the disturbance generated by half of the contribution of the first Fresnel zone is approximately equal to that generated from an entire unobstructed wavefront [15].

Based on this rationale, the largest possible ellipsis – one able to contain nine orchestra players in proximity of line of sight – with foci at source and receiver was drawn on a 2D top-view map of the orchestra for each measured path. The diameter of this ellipsis determines the half-size of the first Fresnel zone of the frequency that was subsequently taken as the crossover threshold of the hybrid model. Below this frequency, the insertion loss was calculated with BEM models. This allows, even for the longest path measured (approximately 10 m), to be able to measure within half of the first Fresnel zone, down to approximately 600 Hz. An overview of the Fresnel zones for the BEM models and the measurement for the validated case is shown in Fig. 1.

Due to reciprocity, source and receiver positions could be swapped to reduce the complexity of the measurement procedure. The loudspeaker set-up was therefore installed across the wire floor of the anechoic chamber only twice, at the two locations to auralise. This solution requires to move the microphones, rather than the loudspeakers, to 52 different positions for each player, remarkably reducing the necessary time and effort needed to carry out the measurement.

Upon inspection of insertion loss curves measured with a full orchestra on a real stage [7] it was noticed that the effect of the frequency response of the loudspeaker and the measurement error was considerable at high frequencies, where the limited energy of the dodecahedron loudspeaker used leads to an underestimation of the insertion loss. To obtain reliable values for a broadband frequency range, the present study was conducted with a pair of Genelec 8331A, with the source rotated in order to measure each path aligned with the loudspeaker axis. The chosen loudspeaker has a coaxial design, which allows the whole frequency range to be emitted from a common acoustic center. The effect of loudspeaker can be observed upon validation with the in-situ measurement in the following paragraph.

It was of interest to investigate the effect of measurement errors when measuring sound propagation through an orchestra. This was done by evaluating the results of some of the paths of the reference in-situ measurement [7]. The measurement error was estimated by observing the difference in insertion loss when source and receiver were swapped: some of the measured paths in the referenced database of measurements are in effect doubled, since their only difference is the inversion of source and receiver (i.e. source in A, receiver in B, then source in B, receiver in A). It could be observed that third-octave band differences in insertion loss at high frequencies (>1 kHz) can reach values up to a range of 5 to 10 dB when measuring one static position. This illustrates the considerable uncertainty due to the precise geometry of the obstacle. Moreover, measuring a static orchestra position for the sake of auralisation seems to have limited relevance when considering the notable, voluntary and involuntary movements that musicians always make when playing. These lead not only to changes in the sound radiation [16]; in this context, small changes of the position of head and torso of the in-between players, of the source, and of the head of the receiving player, can also result in large differences, especially at high frequencies, in the sound reaching a fellow orchestra player. In order to address this effect, each path was measured five times by asking the participants acting as obstacles to randomly variate the position of their upper body for each partial measurement of each path. Averaging these curves for each measurement is expected to provide a mean curve with the minimum possible deviation from the insertion loss that could occur in any instant, during a concert, between moving orchestra players. The position-average procedure has not been replicated for the BEM models since this was found to be significant, as it will be seen in paragraph 3.1, only at higher frequencies.

3. RESULTS AND DISCUSSION

3.1 Validation

Fig. 4 shows the measured and simulated insertion loss of direct sound and floor reflection when players are present in the way for three selected paths between two sources and two receivers, refer to Fig. 1 for their positions. The orchestra arrangement allows comparison of one path (S1-R1) with the corresponding one measured in the previously described in-situ measurement [7], which allows to validate the methods of the present study. After windowing of the direct sound together with floor reflection, measurement results from [7] are reliable down to a frequency of 100 Hz. The insertion loss for all five randomised torso positions measured is shown together with a dB-averaged curve. The remaining two paths are shown to give an insight into the current database with respect to the insertion loss trends when source-receiver distances are shorter and less players are sitting in line of sight.

For what concerns the validation path (S1-R1), all insertion loss curves show a similar shape, with main destructive interference due to diffraction sources as well as with the dips and peaks of constructive and destructive interference between direct sound and floor reflection that are interfered with when the players are present. The time difference between direct sound and floor reflection is of 0.918 ms, which results in a first dip occurring at 545 Hz and a first peak occurring at 1090 Hz, frequencies at which a local minimum and a point of inflexion or local maxima can be found in all measured curves.

Since the comb-filter-like structures of the curves tend to disappear when averaging over the different measurements after a natural realignment of the subjects' upper bodies, octave band smoothing seems most appropriate for the creation of the database if these curves are to be used as filters for simulation and auralisation.

It is worth noticing that the impact of the movement of head and torso of the orchestra players is extremely significant at large distances (S1-R1), and that it can be even more dramatic at shorter distances (S1-R2, S2-R2), with differences up to 12 dB at high frequencies between different torso positions for the three paths shown. This is mostly due to the relationship between source, receiver and the shadow zone created by the obstacles: for a short path with one obstacle in line of sight (S2-R2) a movement of the upper body of the subject-obstacle that is large enough will result in a drastic drop of insertion loss. An average between all position is, for this reason, assumed to have the smallest possible discrepancy with respect to the loss given by the orchestra at any moment during a concert.

Results from the in-situ measurement from [7] and the average measured curve (S1-R1) show good agreement, with a discrepancy up to ± 3 dB up to 8 kHz. The discrepancy increases dramatically beyond 8 kHz, which confirms the inadequacy of the dodecahedron for measurements aimed at auralisation. For this path distance (6.3 m), the half-diameter of the occupied first Fresnel zone in the measurements corresponds to a threshold frequency of approximately 400 Hz. It is worth noticing that below the 400 Hz threshold frequency the discrepancy between measured and simulated insertion loss is still small. This is likely due to the increasing size of the wavelength with

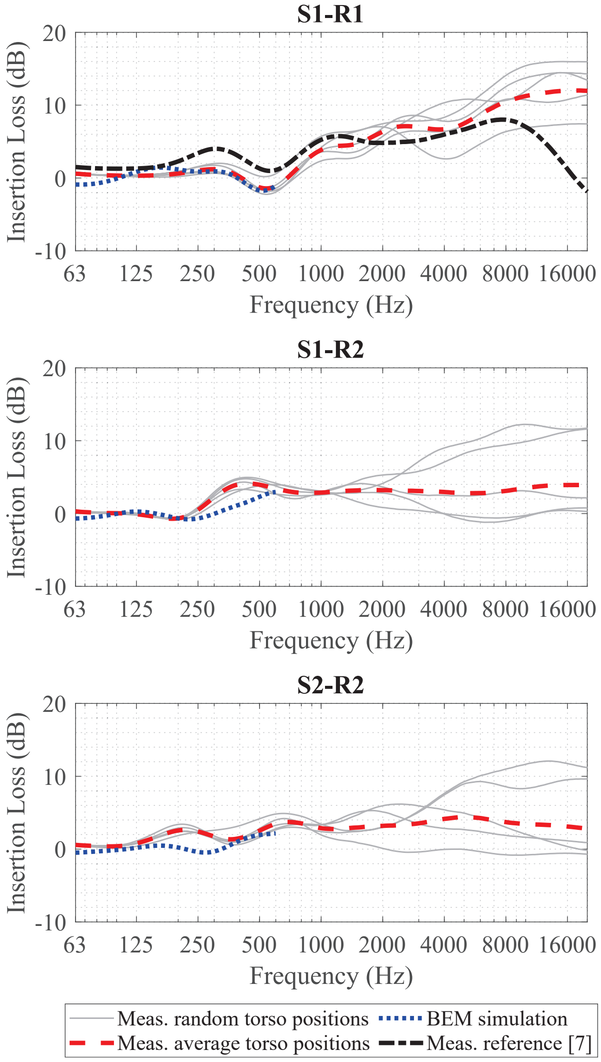

Figure 4. Measured and simulated insertion loss values for direct sound and floor reflection, octave-band smoothing, for three selected source-receiver paths. Positions refer to Fig. 1. Continuous curves show effect of random torso positions of the present bodies. Dashed line is dB-average of random position curves. Simulated curves result from a static bodies setting, here shown up to maximum crossover frequency of the database. Path shown in top figure (S1-R1) includes reference curve from [7] which approximates the same configuration for validation purposes. Middle and bottom figure are shorter propagation paths with grazing incidence over obstacle (S1-R2) and with no line of sight due to obstacle (S2-R2).

respect to the size of one sitting body, reason for which the insertion loss within the orchestra is generally small at low frequencies.

For the remaining two cases (S1-R2, S2-R2), the half-diameter of the occupied first Fresnel zone in the measurements correspond to the threshold frequencies of approximately 50 Hz and 150 Hz. Since 50 Hz is below the threshold frequency of the anechoic chamber, a crossover frequency of 63 Hz was adopted for this and such other cases within the database. Comparison of their simulated curves with the average measured curves show good agreement, with a discrepancy up to ±3 dB, even considering that the body structures differences between simulated and measured cases become more significant on the spectrum at shorter distances due to their role within diffraction phenomena.

3.2 Hybrid model

The insertion loss curve of the resulting hybrid model, for one of the previously shown source to receiver paths (S1-R2), is plotted together with the low and mid-high frequency components in Fig. 5. As previously mentioned, the crossover frequency is set at the largest occupied half-sized Fresnel zone frequency of the measurement. The crossover is built with fourth order Linkwitz–Riley filters [17], in order to prevent magnitude changes due to the filtering process at the crossover frequency. The crossover frequency was set to be the lower frequency limit of the measurements rather than the upper frequency limit of the BEM models, since the former are considered most reliable due to the position-average and fine frequency resolution.

4. CONCLUSIONS AND OUTLOOK

For an orchestra of 53 persons, the present dataset contains a total of 520 impulse responses for both direct sound and floor reflection. Along with this, a total of 104 insertion loss curves, averaged over small variations of the exact seating position for all measured paths between two player positions and the remaining players of the orchestra are available. For the simulation and auralisation of an orchestra, these position-averaged curves are considered more meaningful than a static snapshot measurement.

The results shown from the validation procedure indicate that the influence of the entire orchestra on sound propagation can be approximated by measuring the attenuation caused by small groups of subjects (9 for the measured spectrum, 25 for the simulated spectrum) with mu-

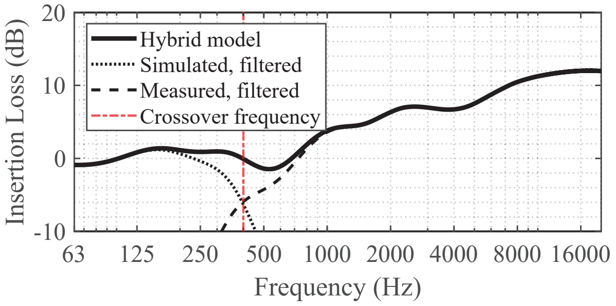

Figure 5. Hybrid insertion loss curve (S1-R2, positions refer to Fig. 1) for direct sound and floor reflection, octave-band smoothing.

sic stands. The subjects sit in proximity of the line of sight between the source and receiver players, within the inner half of the first Fresnel zone of interest.

From the hybrid insertion loss curves obtained, a series of filters were subsequently derived. These allow to filter individual energy contributions, from all orchestra players to a single player, in geometrical acoustics simulations such as within the software RAVEN. This pipeline will enable the auralisation of the direct sound and floor reflection within the orchestra arrangement presented in this study, as well as any other multi-person scene where diffraction effects caused by sitting bodies may be relevant.

The dataset will also serve as a basis for a statistically-backed analytical model that aims to predict the average insertion loss, for direct sound and floor reflection, of any arbitrary path and arrangement of sitting bodies between source and receiver. Due to the limitations at increasing distances, where Fresnel zones become larger together with the amount of obstacles required to consider, an analytical model of such kind would also allow to predict the insertion loss associated with the early reflections from the surrounding stage enclosure on the horizontal plane. This would be sufficient for a simple stage enclosure, since reflections from stage canopies are mostly unaffected by the presence of the orchestra [9].

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6. REFERENCES

[1] J. Dammerud, *Stage Acoustics for Symphony Orchestras in Concert Halls*. PhD thesis, University of Bath, 2009.

[2] A. Gade, "Investigations of musicians' room acoustic conditions in concert halls, Part I: Methods and laboratory experiments," *Acta Acustica united with Acustica*, vol. 69, pp. 193–203, 11 1989a.

[3] A. Gade, "Investigations of musicians' room acoustic conditions in concert halls, Part II: Field experiments and synthesis of results," *Acustica*, vol. 69, pp. 249–262, 12 1989b.

[4] M. Cederlöf, "Podium acoustics for the symphony orchestra." M.Phil. thesis, Royal Institute of Technology, Stockholm, 2006.

[5] J. Y. Jeon and M. Barron, "Evaluation of stage acoustics in seoul arts center concert hall by measuring stage support," *J. Acoust. Soc. Am.*, vol. 117, pp. 232–9, 02 2005.

[6] J. Dammerud and M. Barron, "Early subjective and objective studies of concert hall stage conditions for orchestral performance," in *Proceedings of the 19th international congress on acoustics*, (Madrid, Spain), pp. 1–6, 09 2007.

[7] R. H. C. Wenmaekers, C. C. J. M. Hak, and M. C. J. Hornikx, "How orchestra members influence stage acoustic parameters on five different concert hall stages and orchestra pits," *J. Acoust. Soc. Am.*, vol. 140, pp. 4437–4448, 12 2016.

[8] Z. Schärer Kalkandjiev and S. Weinzierl, "The influence of room acoustics on solo music performance. an experimental study," *Psychomusicology: Music, Mind and Brain*, vol. 25, no. 3, pp. 195–207, 2015.

[9] L. Panton, D. Holloway, and D. Cabrera, "Effect of a chamber orchestra on direct sound and early reflections for performers on stage: A boundary element method study," *J. Acoust. Soc. Am.*, vol. 141, pp. 2461–2472, 04 2017.

[10] F. Brinkmann, L. Aspöck, D. Ackermann, H. Steffen, M. Vorländer, and S. Weinzierl, "A round robin on room acoustical simulation and auralization," *J. Acoust. Soc. Am.*, vol. 145, no. 4, pp. 2746–2760, 2019.

[11] B.-I. Dalenbäck, "Whitepaper regarding diffraction (v8 january 9, 2023) for prediction using catt-acoustic v9.0c and higher," tech. rep., CATT-Acoustics, 2023.

[12] M. Potkány, M. Debnár, M. Hitka, and M. Gejdoš, "Requirements for the internal layout of wooden house from the point of view of ergonomic changes," *Quality Production Improvement*, vol. 09, pp. 43–70, 09 2018.

[13] Y. Miki, "Acoustical properties of porous materials-modifications of Delany-Bazley models," *The Journal of the Acoustical Society of Japan*, vol. 11, no. 1, pp. 19–24, 1990.

[14] I. Prasetiyo, G. Desendra, M. N. Hermanto, and D. R. Adhika, "On woven fabric sound absorption prediction," *Archives of Acoustics*, vol. 43, no. 4, p. 707–715, 2018.

[15] E. Hecht, *Optics, 5e*. Addison-Wesley, 2002.

[16] D. Ackermann, C. Böhm, F. Brinkmann, and S. Weinzierl, "The acoustical effect of musicians' movements during musical performances," *Acta Acustica united with Acustica*, vol. 105, no. 2, pp. 356–367, 2019.

[17] S. H. Linkwitz, "Active crossover networks for noncoincident drivers," *J. Audio Eng. Soc.*, vol. 24, pp. 2–8, 2 1976.