

Acoustic modelling of sports halls, two case studies

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Acoustic modelling of sports halls, two case studies

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To achieve a preferable sound field in traditionally shoebox-shaped sports halls, the sound absorbing material is often applied in the upper part of the hall. The applicability of predicting the acoustics of sports halls by three different acoustic calculation methods is investigated: a diffuse field method, a geometrical acoustics method and a full wave-based method. The predicted reverberation time and sound pressure level are compared to measured data for two sports halls in the low frequency range up to the 630 Hz $\frac{1}{3}$ octave band. From the three methods, results from the wave-based method agree best with the measured results. Results indicate the importance of the chosen material properties in the prediction methods used. Sound pressure levels resulting from the diffuse field method are comparable with results from the other prediction methods, but the reverberation time prediction is not reliable using this method.

Keywords: reverberation time; sound pressure level; geometrical acoustics method; wave-based acoustics method; diffuse field method; pseudospectral time-domain method

1. Introduction

In an early stage of the design process of a sports hall, decisions have to be made regarding several building disciplines (e.g. building construction, building physics, acoustics and climate control) to estimate the building costs and construction time. To obtain a comfortable acoustic environment in sports halls, especially regarding noise levels and speech intelligibility, a sufficient amount of sound absorbing materials should be applied. For practical reasons, the sound absorbing materials in traditionally shoebox-shaped sports halls are often applied in the upper part of the hall, above the playing area. Engineering prediction methods as used in the consultancy practice often do not lead to the actual reverberation time and sound level distribution. The engineering methods do rely on a geometrical acoustics or diffuse field approach, which are known to be less accurate for the lower frequencies and situations where wave effects prevail. Together with the partly unknown sound absorbing and scattering properties of the boundaries and the typical shoebox shape of the (empty) sports hall, these approaches could indeed be expected to be too approximative in the early design stage of a sports hall.

The application of geometrical acoustics methods to predict the acoustics of auditoria (Vorländer, 1995; Lam, 1996) and concert halls (Bork, 2000) has been studied in detail. Studies (Vorländer, 1995; Lam, 1996; Bork, 2000; 2005) showed that the most sophisticated modelling

programmes among them are applicable to predict the acoustics of spaces as auditoria and concert halls. Because of their shapes, industrial spaces are more alike sports halls than auditoria and concert halls. The applicability of various prediction methods to compute the sound pressure level and reverberation time in such spaces has previously been studied. These methods contain geometrical acoustics methods, diffuse field models and simplified expressions (Hodgson, 1990; 1998; 2003; Heerema and Hodgson, 1999; Keränen and Hongisto, 2010). It was shown that the geometrical acoustics method gave the best prediction amongst the methods, and that results from some simple sound pressure level methods were comparable with the geometrical acoustics method (Keränen and Hongisto, 2010). Most studies have been carried out for fitted rooms. This is in contrast with sports halls, which are mostly empty. In contrast to geometrical acoustics methods and the even more simplified methods, full wave-based methods are able to accurately reproduce the acoustics of spaces in detail when the geometry and material properties are at hand. The drawback of wave-based methods is their high computational costs. However, with the advances in computer power, wave-based methods for acoustic propagation problems have received increased attention in recent years. Wave-based methods are especially of interest for treating problems where wave effects such as diffraction are important and for the low frequency range. For the high frequency range however, the pressure amplitude becomes

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more smooth over space and deterministic modelling of fine geometrical structures with wave-based methods is irrelevant. A current challenge in room acoustics is therefore to find the frequency range for which wave-based methods are preferable over geometrical acoustics methods (Vorländer, 2013).

Given the difficulty of accurately predicting the acoustics of sports halls, the purpose of this work is to extend the current literature by demonstrating the applicability of three prediction methods for computing the acoustics of sports halls. Two sports halls have been selected as test cases for this analysis. They have similar dimensions and volumes. One of the halls has a balcony. The first two prediction methods belong to the two main classes of prediction methods in room acoustics (Välimäki et al. 2012), a geometrical acoustics method and a wave-based method. Various types of both methods exist and one type for each of them has been selected for the computations in this paper. The third method is a diffuse field approach, which is the extreme assumption for a sound field in a room when the energy density in the room is constant. The diffuse field approach has the advantage to be computationally very fast. For two existing sports halls, the spatial and frequency-dependent reverberation time and sound pressure level in the playing area have been calculated according to the mentioned methods. These calculated values are compared with the values measured in the real halls at the same source and receiver positions. Since the acoustic prediction in the design stage of a sports hall is mimicked, the properties of the materials as input for the prediction methods are not obtained from *in situ* measurements but from predicted or tabulated values. In addition to the applicability of the prediction methods used, this paper also demonstrates the importance of knowledge concerning material properties. As the lower frequency region is expected to be most problematic for the predicting of the halls, at least when using the geometrical acoustics method and the diffuse field method, calculations and measurements will be presented for the lower frequency range up to the 630 Hz $\frac{1}{3}$ octave band.

Many more prediction methods exist than the three methods used in this work. The purpose of this work is not to find the most suitable method for computing the acoustics of sports halls, but rather to gain insight

into the accuracy obtainable when applying the chosen methods, in a manner similar to design stage analysis, to the two selected halls. The paper is organized as follows. In Section 2, the sports halls are described as well as the locations of the acoustic sources and receivers. The acoustic prediction methods used are presented in Section 3. The computed and the measured results are then reported in Section 4 and discussed in Section 5. Finally, Section 6 contains the conclusions of this work. The paper contains two appendices.

2. Sports halls

All calculations and measurements have been performed using geometrical models of the two existing unoccupied shoebox-shaped sports halls, hall 1 and hall 2, of which hall 2 has an audience balcony at one of the side walls.

2.1. Sports hall 1

Sports hall 1 is hall 2 of the student sports centre Eindhoven (the Netherlands) and has a volume of approximately 8400 m³, with a floor area of approximately 1200 m² and a height of 7 m. From a height of 2.9 m above the ground floor, the walls have been lined with acoustic absorption material consisting of a lath construction. Figure 1 shows an impression of hall 1 and Figure 2 presents the global material distribution. Table 1 shows the estimated absorption coefficient values of this hall. The software Winflag has been used to obtain the sound absorption coefficients from the open lath constructions and pads (Vigran 2006). Values for other materials are based on common literature. The floor plan as presented in Figure 2 shows the source and receiver positions used. The simulations and measurements have been carried out along two receiver lines at a height of 1.5 m above the floor at a distance of 2 m from the central axes. The temperature during the measurements was 19.4°C.

2.2. Sports hall 2

Sports hall 2 is hall 'ABC' of sports centre De Kemmer in Oirschot (the Netherlands) and has a volume of approximately 10,000 m³, with a floor area of approximately



Figure 1. Impression of sports hall 1. Left two pictures: cross wall views. Right picture: side wall with light weight panel construction combined with a strip of glass enclosing a former balcony.

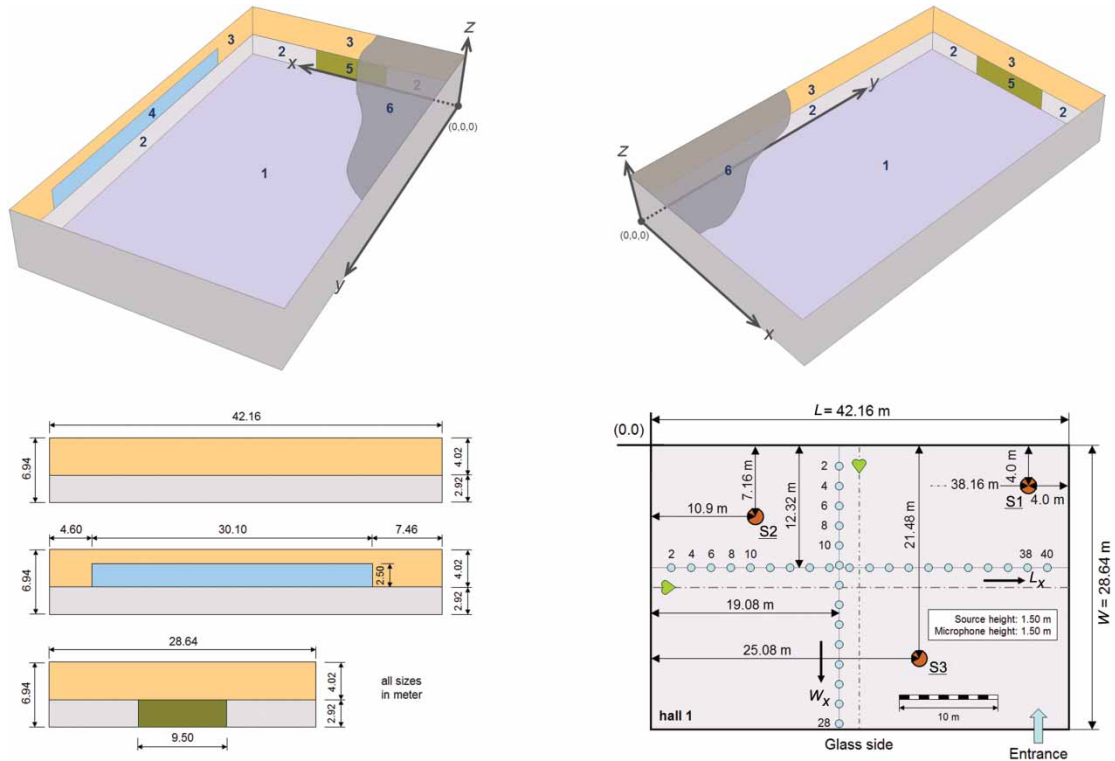


Figure 2. Sports hall 1. Top figures: Global material distribution: (1) sports floor, (2) smooth concrete blocks, (3) open lath construction on a 0.14 m deep cavity, filled with 0.03 m mineral wool at the position of the laths, (4) lightweight partition wall with windows, (5) soft pad, (6) open lath ceiling construction on 2.0 m deep cavity, filled with 0.03 m mineral wool. Bottom left figure: surface dimensions. (upper) side wall at $x = 0$ m, (middle), side wall at $x = 28.64$ m, (lower) cross wall at $y = 0$ m and $y = 42.16$ m. Bottom right figure: calculation and measurement grid used at a height of 1.5 m above the floor. Source positions are marked by S1, S2 and S3, receiver positions by L_x and W_x .

Table 1. Used diffuse field sound absorption coefficient values for hall 1.

Surface no.	Surface description	Sound absorption coefficient α		
		Octave band centre frequency (Hz)		
		125	250	500
1	Sports hall floor	0.01	0.01	0.02
2	Smooth concrete blocks	0.01	0.01	0.02
3	Open lath construction ^a	0.49	0.53	0.65
4	Light weight wall + glass	0.10	0.06	0.06
5	Pads	0.04	0.38	0.02
6	Open lath construction ^a	0.29	0.68	0.57

Note: These values are obtained from manufacturer data (standardized laboratory measurements) and calculations.

^aCalculated by 'Winflag' software.

1400 m² and a height of 7 m. The 215 m² balcony is situated at one of the side walls, at a height of 3.5 m. Figure 3 shows an impression of hall 2 and Figure 4 presents the

global material distribution. The upper part of the hall walls consist of a material with a higher absorption coefficient in the lower frequencies than the lower part of the hall. In contrast to hall 1, this hall also has some absorption patches in the lower part of the hall. The floor plan as presented in Figure 4 shows the source and receiver positions used for the predictions and measurements that have been carried out. The temperature during the measurements was 16.3°C.

3. Prediction methods and measurements

3.1. Prediction methods

Three prediction methods were used to calculate the reverberation time and sound level distribution. The first two are engineering methods: one based on the diffuse field assumption and one on a geometrical acoustics approach. The third method is a full wave-based method. The two parameters computed in this study are the reverberation time (T_{20}) and the sound pressure level. T_{20} is determined from the decay of the sound field after a sound source, turned on a long time ago, has been turned off. T_{20} can be calculated from a single impulse response (IR) using Schroeder's backwards integration method (Schroeder, 1965). T_{20} is the best fitted straight line between the decay



Figure 3. Impression of sports hall 2. Left two pictures: cross wall views. Right picture: sidewall (with balcony) and cross wall view.

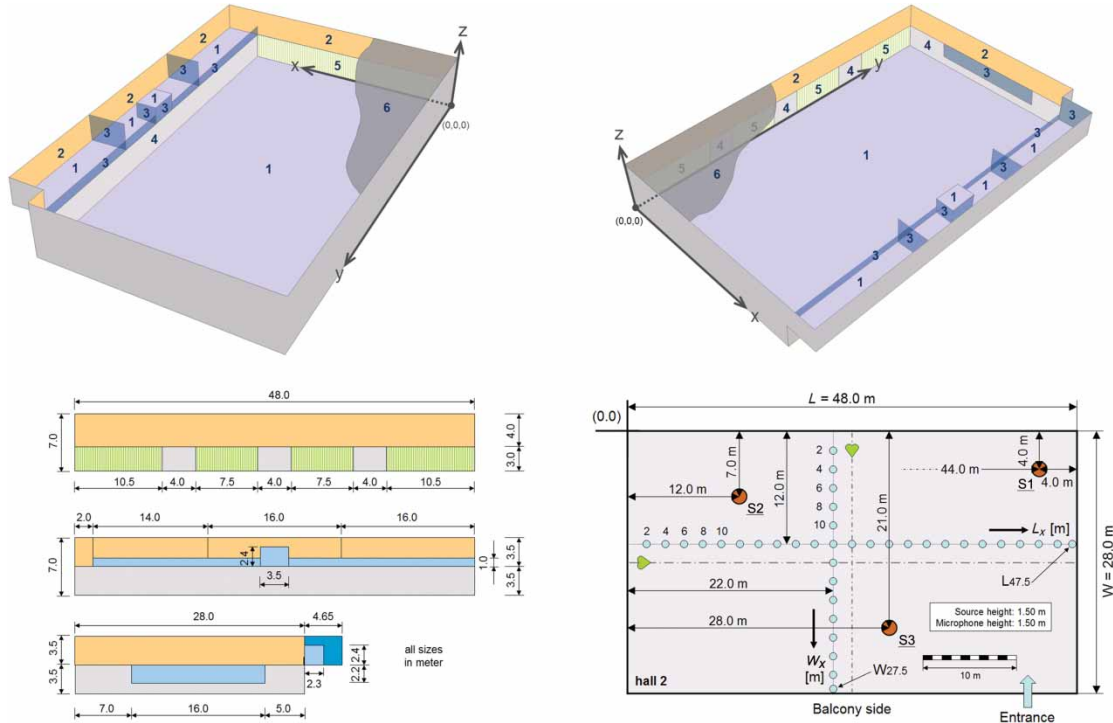


Figure 4. Sports hall 2. Top figures: Global material distribution hall 2: (1) sports floor, (2) open lath construction on 0.5 m air cavity, (3) glass panes, (4) smooth concrete blocks, (5) small cavity open lath construction, (6) porous ceiling construction. Bottom left figure: surface dimensions. (upper) side wall at $x = 0$ m, (middle) side wall at $x = 28.64$ m, (lower) cross wall at $y = 0$ m and $y = 42.16$ m. Bottom right figure: calculation and measurement grid used at a height of 1.5 m above the floor in hall 2. Source positions are marked by S1, S2 and S3, receiver positions by L_x and W_x .

of the sound level from -5 dB to -25 dB, and extrapolated to -65 dB. The sound pressure level is related to the level at 1 m from the sound source in free field $L_{re,free,1m}$.

3.1.1. Diffuse field method

Assuming a diffuse sound field, several approaches can be used. The formulas of Sabine, Eyring and Millington are clearly described by Kuttruff (2009) and Cremer and Müller (1978). Other researchers like Sette (1933) and Fitzroy (1957) presented improvements to the existing calculation methods. A more recent approach to predict the late part of the sound field in rooms relies on the assumption that the sound energy density can be described by a diffusion equation (Navarro, Escolano, and López, 2012). The current investigation relies on a perfectly diffuse sound field in rooms, i.e. for which the energy density is constant.

To obtain such a sound field, boundaries should have irregular shapes and should lead to diffuse reflections. The T_{20} and sound pressure level for a diffuse sound field are computed as (Kuttruff, 2009)

$$T_{20} = T_{60} = \frac{24 \ln(10)V}{cS\bar{\alpha}}, \quad (1)$$

$$L_{re,free,1m} = 10 \log_{10} \left(\frac{1}{r^2} + \frac{16\pi}{S\bar{\alpha}} \right),$$

with V being the volume of the hall, S is the total surface area of the boundaries of the hall, $\bar{\alpha}$ is the average diffuse field acoustic absorption coefficient of the boundaries of the hall, c is the adiabatic speed of sound and r is the source to receiver distance. For computing the sound pressure level $L_{re,free,1m}$, the acoustic energy from the direct and diffuse field have been added, i.e. the two parts within the parenthesis of Equation (1). The equations are also

Table 2. Used diffuse field sound absorption coefficient values for hall 2.

Surface no.	Surface description	Sound absorption coefficient α		
		Octave band centre frequency (Hz)		
		125	250	500
1	Sports hall floor	0.01	0.01	0.02
2	Open lath construction ^a	0.61	0.81	0.64
3	Glas/window construction	0.10	0.06	0.06
4	Smooth concrete blocks	0.01	0.01	0.02
5	Open lath construction ^b	0.30	0.50	0.65
6	Porous ceiling tiles ^b	0.71	0.99	0.99

Note: These values are obtained from manufacturer data (standardized laboratory measurements) and calculations.

^aCalculated by 'Winflag' software.

^bManufacturer data.

known as Sabine's formulas. The current study will show the consequences of using this diffuse field assumption for the shoebox-shaped halls. Although improved versions of the diffuse field assumption exist, we have chosen this assumption as it is still widely used.

3.1.2. Geometrical acoustics method

In room acoustics, the Schroeder frequency is a parameter to describe the frequency above which individual modes do not govern the decay of the sound field any longer, i.e. the frequency above which wave effects are less pronounced. It is one of the criteria needed for the geometrical acoustics (and diffuse field methods) to be valid. Using the averaged reverberation time as measured in the halls up to 500 Hz, the Schroeder frequencies are 37 and 29 Hz for halls 1 and 2, respectively. Previously, geometrical acoustics methods have been shown to be applicable for the frequencies above the Schroeder frequency, and when most of the partial surfaces are larger than the wavelength of the sound that hits these surfaces. A principal limitation of the geometrical acoustics methods is the absence, by nature, of diffraction and scattering effects. Sound waves reflected from surfaces are scattered when the surface is not perfectly flat. In geometrical acoustics methods, this is often captured by assigning a frequency-dependent scattering-coefficient to a surface. Diffraction occurs near edges of surfaces or obstacles, and near the discontinuities of different materials. Attempts have been made to include diffraction into geometrical acoustics methods, which will increase the computational costs of the methods, e.g. Schröder and Pohl (2009) and Antani et al. (2010). In this work, geometrical

acoustics calculations have been carried out using the software CATT-Acoustic v9.0c (Dalenback, 2012). The 'h' method has been used in the software, which sums the pressures rather than the squared pressure values, enabling the inclusion of wave interference effects. Appendix 1 lists the used settings of the software. In contrast to the diffuse field absorption coefficient of a material, little is known about the scattering coefficients of general building materials or building constructions (Vorländer, 2013). Despite the fact that small differences in scattering may cause a big difference in the calculated reverberation time, it was decided to use a frequency-independent fixed scattering coefficient value of 0.1 for all frequency bands. This value is recommended for flat hard surfaces, and takes into account surface structure and surface discontinuities. Of course, the scattering coefficients of all the surfaces in both halls will not be 0.1. This choice was made to not adjust the scattering coefficient to obtain a better agreement with the measured results, but rather to use the recommended values as in a design application.

3.1.3. Wave-based method

For this investigation the Fourier pseudospectral time-domain (PSTD) model as developed by Hornikx, Waxler, and Forssén (2010) has been used. The PSTD method enables the computation of sound propagation by solving the linearized Euler equations:

$$\begin{aligned} \frac{\partial \mathbf{u}}{\partial t} &= -(\mathbf{u}_0 \cdot \nabla) \mathbf{u} - (\mathbf{u} \cdot \nabla) \mathbf{u}_0 - \frac{1}{\rho_0} \nabla p, \\ \frac{\partial p}{\partial t} &= -\mathbf{u}_0 \cdot \nabla p - \rho_0 c^2 \nabla \cdot \mathbf{u}, \end{aligned} \quad (2)$$

with \mathbf{u} being the velocity components, p is the pressure, ρ is the density and c is the adiabatic sound speed that depends on the temperature of the hall. The 0-subscripted variables denote the ambient quantities. The PSTD method is a domain discretization method based on an orthogonal equidistant grid, with velocity components positions staggered from the pressure positions. The method computes the temporal derivative of Equation (2) by a Runge-Kutta method and the spatial derivatives are evaluated using a Fourier pseudospectral method, see e.g. Hornikx, Waxler, and Forssén (2010). The latter requires only two spatial points to evaluate the smallest acoustic wavelength of interest. As a result, some 3D configurations have been studied (Hornikx and Forssén, 2011), while models with a similar accuracy previously focussed on 2D configurations. For outdoor acoustics, it is also possible to include meteorological effects as for example a mean wind speed field \mathbf{u}_0 (Hornikx, Waxler, and Forssén, 2010). In PSTD, boundaries are modelled by a second medium with a different density, leading to a frequency-independent reflection coefficient with a quasi-locally reacting approach. This method was shown to be reliable (Hornikx et al. 2012;

Van Renterghem et al. 2013). In the current work, the frequency dependency of the boundary conditions is taken into account by separate PSTD computations per octave band. The octave band absorption coefficients of Tables 1 and 2, which also have been used in the geometrical acoustics method (CATT-Acoustic) and the diffuse field method, have been converted to real-valued impedances for the boundary media in PSTD. All boundaries are treated as locally reacting boundaries, by not computing spatial derivatives of the acoustic variables in the boundary media parallel to the surface. In the applied PSTD method, the sports halls are discretized by a grid with a discretization of $\Delta x = 0.2$ m. According to the two points per shortest wavelength requirement inherent to the method, the maximum-modelled frequency with a sound speed of 340 m/s is 850 Hz. The discrete time step in the method is $\Delta t = \Delta x / (2c)$. Initial pressure values represent the source with its predefined position from Figures 2 and 4. Calculations with the 3D PSTD method are carried out using an in-house MATLAB implementation of the method and making use of the high performing computing grid of the department of the Built Environment (Eindhoven University of Technology). On this grid, computational nodes with 16 parallel processors are available. The in-house PSTD implementation will soon be available in an open-source implementation (Krijnen and Hornikx 2014). The computed results at the defined receiver positions are obtained by spectrally interpolating the spatial results at every discrete time step. Using a wave-based method such as PSTD, diffraction is taken into account by modelling all

room and surface details such as material structure, material transitions and discontinuities (balcony edge etc.). The more accurate the room and surface details the more accurate the effect of diffraction. Since this study is limited to a spatial discretization of 0.2 m, the modelling has been limited to the exact room dimensions and flat surfaces.

3.2. Measurement method

Measurements have been carried out in the two sports halls using a dodecahedron sound source and an omnidirectional microphone. The used dodecahedron source behaves like a real omnidirectional sound source within the considered frequency range (Hak et al. 2011). Impulse responses have been measured, i.e. the acoustic time response of the room found by exciting it with an impulsive signal. The measured IRs were obtained by using a deconvolution technique with an exponential swept sine as the measurement signal. The quality of the obtained IRs was high enough to be able to extract the targeted acoustical parameters (Hak, Wenmaekers, and van Luxemburg, 2012). The used equipment has been tested in a reverberation room of the Eindhoven University of Technology (volume 100 m³). From 120 identical measurements with an interval of 30 s, the standard deviation of T20 was within 0.1% for all $\frac{1}{3}$ octave bands and the standard deviation of the sound pressure level was within 0.1 dB for all $\frac{1}{3}$ octave bands. This evidences of a low uncertainty of the measurements in the sports halls.

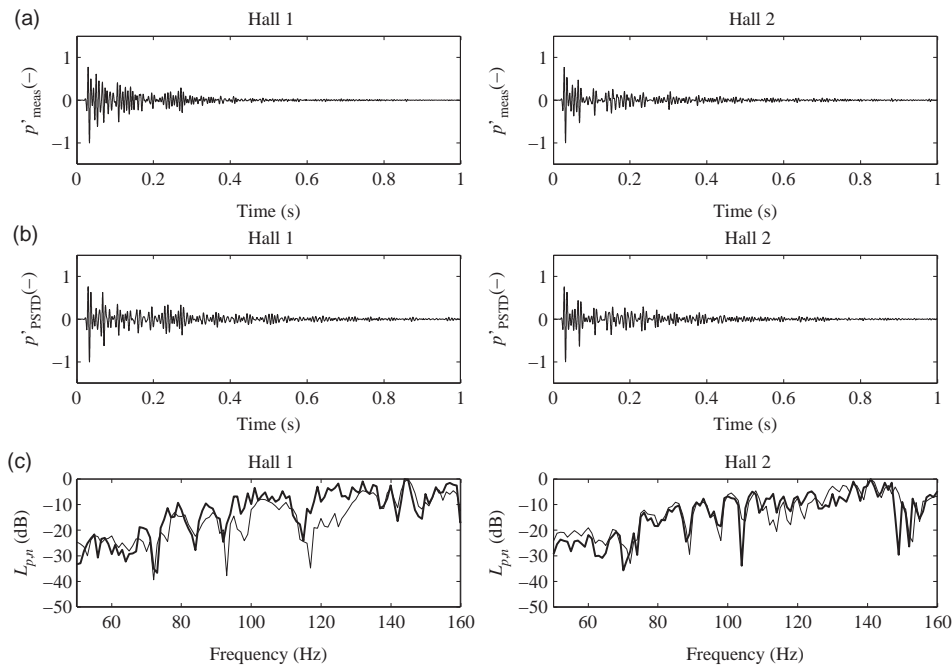


Figure 5. Modified IRs and frequency responses (FRs) at source position S3 and receiver position W14. IRs are shown for pressure level values and FRs for sound pressure level values $L_{p,n}$, both normalized to their maximum value. (a) Modified measured IRs, (b) Modified PSTD IRs, (c) Modified FR: Measured (shown in bold); PSTD (thin line).

4. Results

Some of the measured IRs will first be compared with predicted IRs. Thereafter, the experimental results are compared with the predicted results for the reverberation time T_{20} and the sound pressure level $L_{re,free,1m}$.

4.1. Impulse responses

In Figure 5, IRs at a single receiver position, i.e. source position S3 and receiver position W14 (in short S3 W14) in Figures 2 and 4, are shown for both halls and from measurements and PSTD results. Plotted are modified IRs, where the signals from measurements and PSTD have been equalized regarding their source spectrum. The modified IRs are denoted by $p'_{meas}(t)$ and $p'_{PSTD}(t)$, and are obtained as follows;

$$\begin{aligned} p'_{meas}(t - t_1) &= \int_0^{t_2} p_{meas}(t - \tau) p_{PSTD}(\tau) d\tau, \\ p'_{PSTD}(t - t_1) &= \int_0^{t_2} p_{PSTD}(t - \tau) p_{meas}(\tau) d\tau, \end{aligned} \quad (3)$$

with t_2 being the time where only the direct and ground reflected signal have reached the receiver position. For S3

W14, $t_2 = 28$ ms. Furthermore, t_1 corrects for the delay as caused by the convolution of Equation (3), and corresponds to the source to receiver distance. The signal $p_{PSTD}(t)$ has been resampled such that the same sample frequency has been obtained for measured and predicted signals. The modified IRs p'_{meas} and p'_{PSTD} now have the same source spectrum, which is further detailed in Appendix 2. Since computed IRs with PSTD are valid per octave band only, the modified IRs have been low-pass filtered for the lower frequency range including the 125 Hz octave band. In Figure 5(a) and 5(b), these low-pass filtered variables $p'_{meas}(t)$ and $p'_{PSTD}(t)$ are shown. These modified IRs from measurements and predictions are similar for both halls. The normalized sound pressure level values are obtained after a Fourier transform has been applied to the full signals of Equation (3), and are plotted in Figure 5(c) as a function of frequency. The interferences from both methods do match, but the amplitudes deviate for some frequency ranges. This indicates a suboptimal choice of boundary conditions, at least for this frequency range. Note that the time-domain and frequency-domain analysis of this section cannot be applied to the geometrical and diffuse field methods used since their computed octave band results, as presented in the subsequent sections, are directly resulting

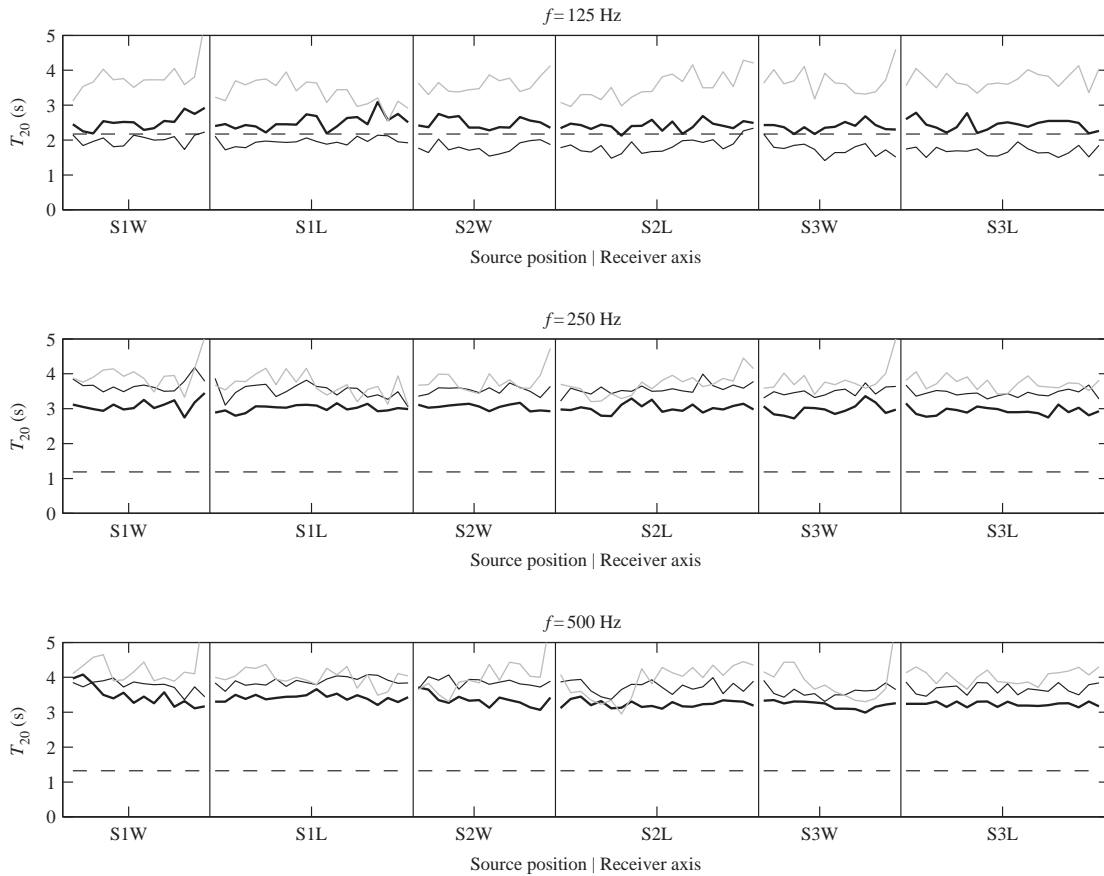


Figure 6. Reverberation time T_{20} results for sports hall 1. Solid thick: experimental; solid thin: wave-based method (PSTD); solid grey: geometrical acoustics method (CATT-Acoustic) and dashed: diffuse field method.

from a frequency-domain analysis rather than originating from a transformed time signal.

4.2. Reverberation time and sound pressure level

4.2.1. T_{20}

The results of T_{20} of halls 1 and 2 are presented in two ways. Figures 6 and 7 show the T_{20} values for three

octave bands for all source–receiver combinations and all four measurement and prediction methods. Furthermore, in Figure 8, the T_{20} values averaged over all receiver positions per octave band are shown. Generally, for both halls, Figures 6 and 7 show a low spatial spread of T_{20} results, with a standard deviation between 0.1 s and 0.2 s for both halls and the three octave bands. No clear tendency is visible regarding the spatial fluctuating T_{20} values. The measured

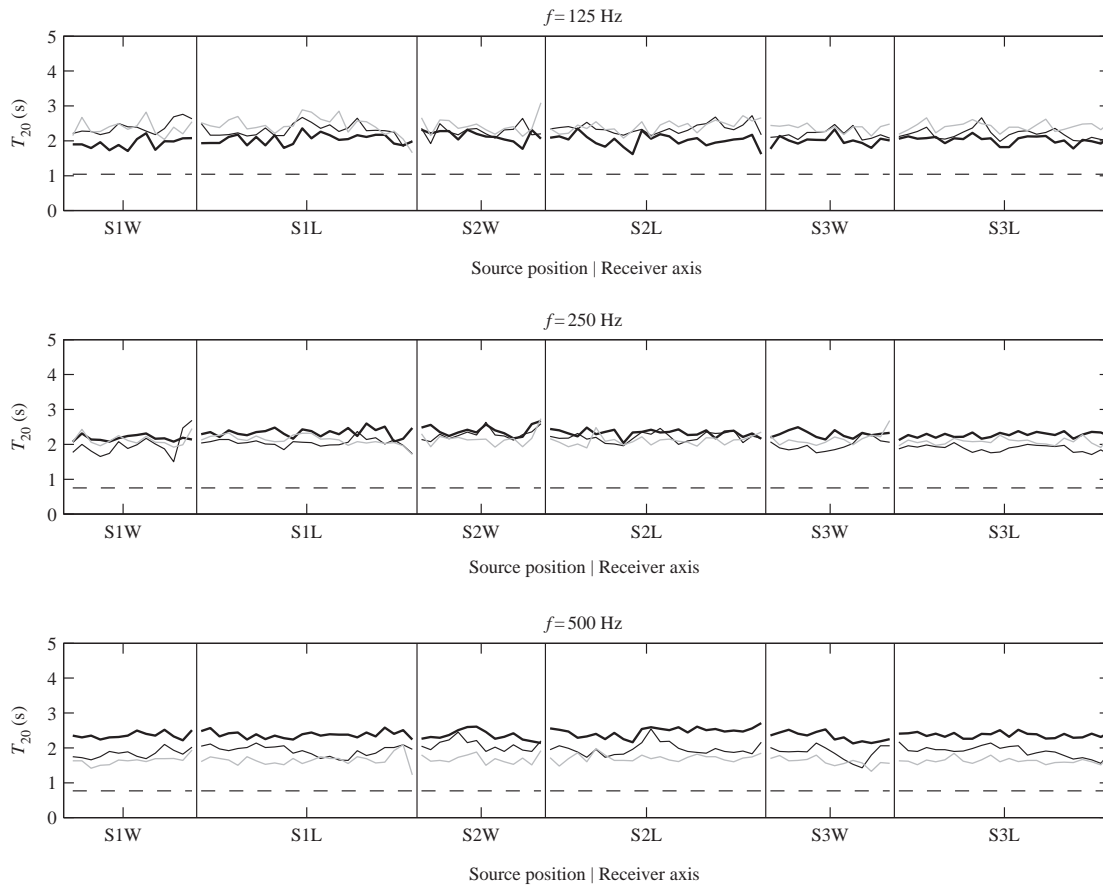


Figure 7. Reverberation time T_{20} results for sports hall 2. Line indexing same as in Figure 6.

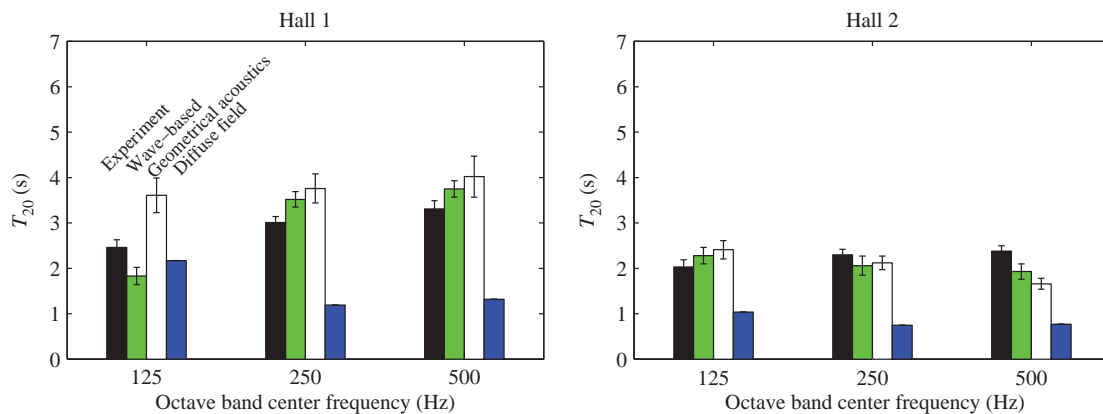


Figure 8. Reverberation time results for the two halls, arithmetically averaged over all receiver and source positions. Standard deviations are shown on top of the averaged values.

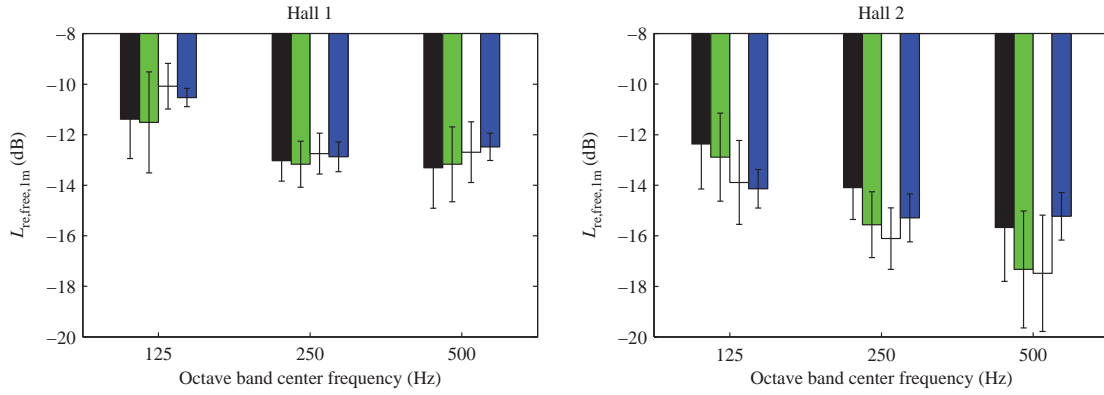


Figure 9. Sound pressure level results for the two halls, arithmetically averaged over all receiver and source positions. Standard deviations are shown on top of the averaged values.

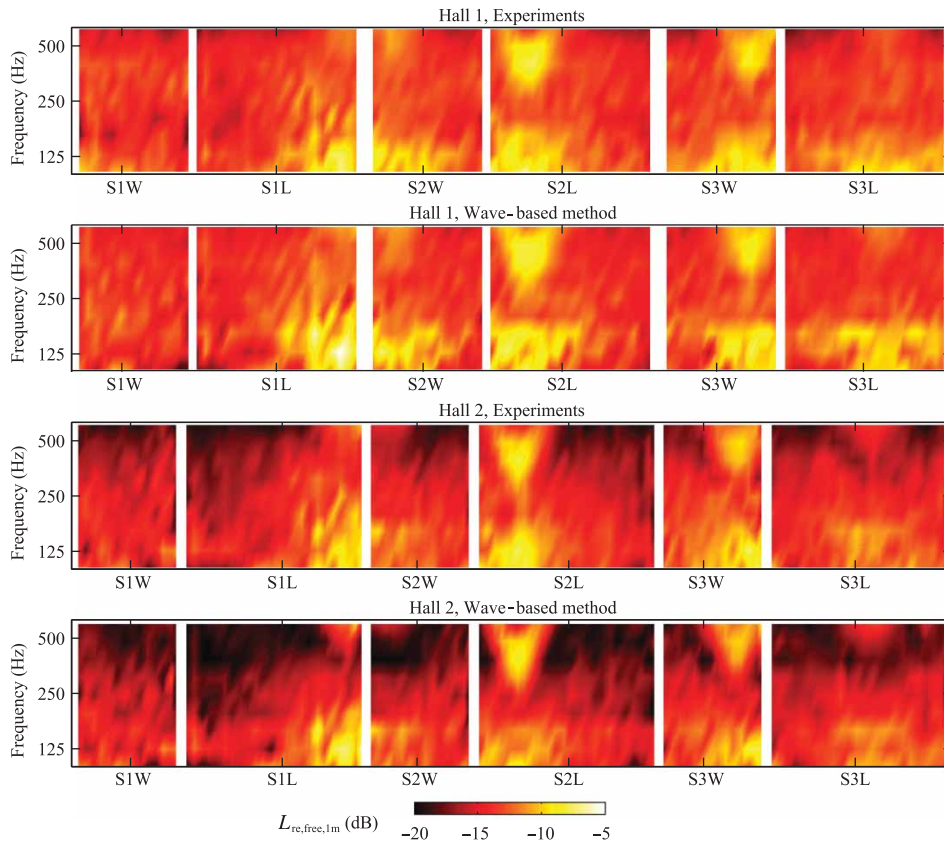


Figure 10. Sound pressure levels $L_{re,free,1m}$ for both halls in $\frac{1}{3}$ octave bands, for the experiments and the wave-based method.

T_{20} values are higher for hall 1 than for hall 2, which is in line with the higher amount of total acoustic absorption in hall 2.

For hall 1, a fairly good agreement between results from PSTD and measurements is found. For the highest two bands, PSTD results are higher than the measured results, whereas results are lower for the 125 Hz octave band. The standard deviations in the PSTD results (Figure 8) are comparable to the values from the measurements, but the spatial fluctuations in the PSTD results do not match the measured results very well. Like the PSTD results, the

CATT-Acoustic results overpredict the measured values for the higher 2 octave bands, and even to a greater degree. In contrast to the PSTD results, CATT-Acoustic overpredicts the measured values for the lowest octave band. The use of Sabine's formula for hall 1 clearly underpredicts the measured values, in particular for the highest two octave bands. The averaged results in Figure 8 demonstrate that the PSTD results are closest to the measured results. The figure also shows a higher standard deviation for the CATT-Acoustic results compared to the measured results.

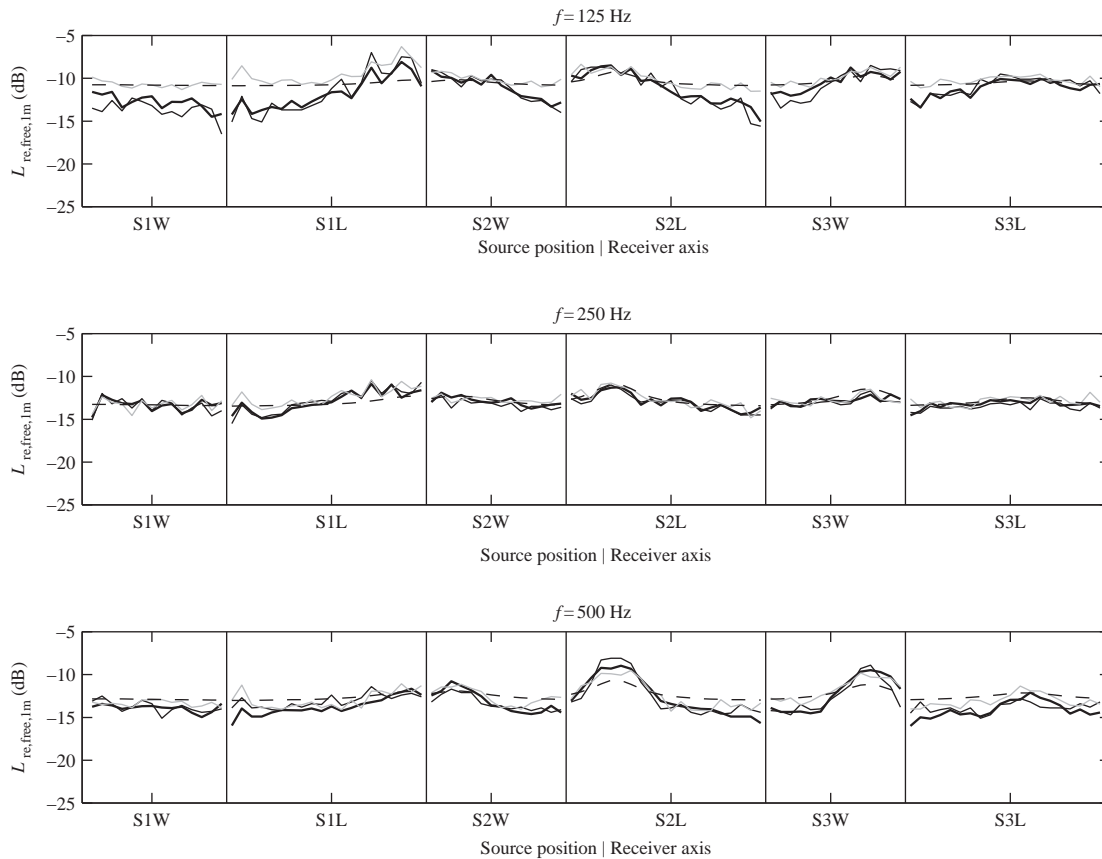


Figure 11. Sound pressure level $L_{re,free,1m}$ results of sports hall 1. Solid thick: experimental; solid thin: wave-based method (PSTD); solid grey: geometrical acoustics method (CATT-Acoustic) and dashed: diffuse field method.

For hall 2, the agreement between measured and predicted T_{20} values is better. Figure 7 shows that both the PSTD method as well as the CATT-Acoustic method produce results close to the experimental results for the lowest two octave bands. Both methods have the same tendency to under predict the experimental results for the 500 Hz octave band. As for hall 1, the prediction relying on the diffuse field approach under predicts the measured results. Overall (Figure 8), PSTD performs slightly better than CATT-Acoustic and clearly better than the diffuse field approach. Both methods have the same tendency in deviating from the experimental results per octave band and have standard deviations similar to the measurements.

4.2.2. Sound pressure level

As for the T_{20} , the sound pressure level is presented for three octave bands for all source–receiver combinations and all measurement and prediction methods, see Figures 11 and 12. The sound pressure levels averaged over all receiver positions per octave band are shown in Figure 9. Moreover, a more detailed comparison between results from the measurements and PSTD is shown in Figure 10, where $\frac{1}{3}$ octave band results for all source–receiver combinations are shown. We have chosen

to compare measurements with PSTD results only, as CATT-Acoustic does not compute $\frac{1}{3}$ octave band results and the deviations between the diffuse field results and measurements is obvious from Figures 11 and 12. Figures 11 and 12 show that the measured sound pressure level has a more pronounced spatial dependency than T_{20} . Among the two halls, the sound pressure level in hall 2 has the highest spatial dependency, which can be related to the higher amount of absorption in this hall. In agreement with the high T_{20} values of hall 1, the measured levels in this hall are higher than the levels of hall 2.

For hall 1, a good agreement is found between results from the experiments and PSTD. Figure 11 also shows that the spatial dependency of the levels agrees very well. Figure 10 confirms this agreement on a more detailed level of $\frac{1}{3}$ octave bands, although some deviations for the lowest $\frac{1}{3}$ octave bands are visible. For the spatially averaged values, PSTD results are within 0.2 dB of the measured results for the three octave bands. A good agreement between results from CATT-Acoustic and measurements is found for the 250 and 500 Hz band, but CATT-Acoustic results show somewhat higher values for the lowest band. This agrees with the higher T_{20} as predicted using this method. As for the PSTD results, the spatial dependency of the measurement results can be retrieved in the CATT-Acoustic

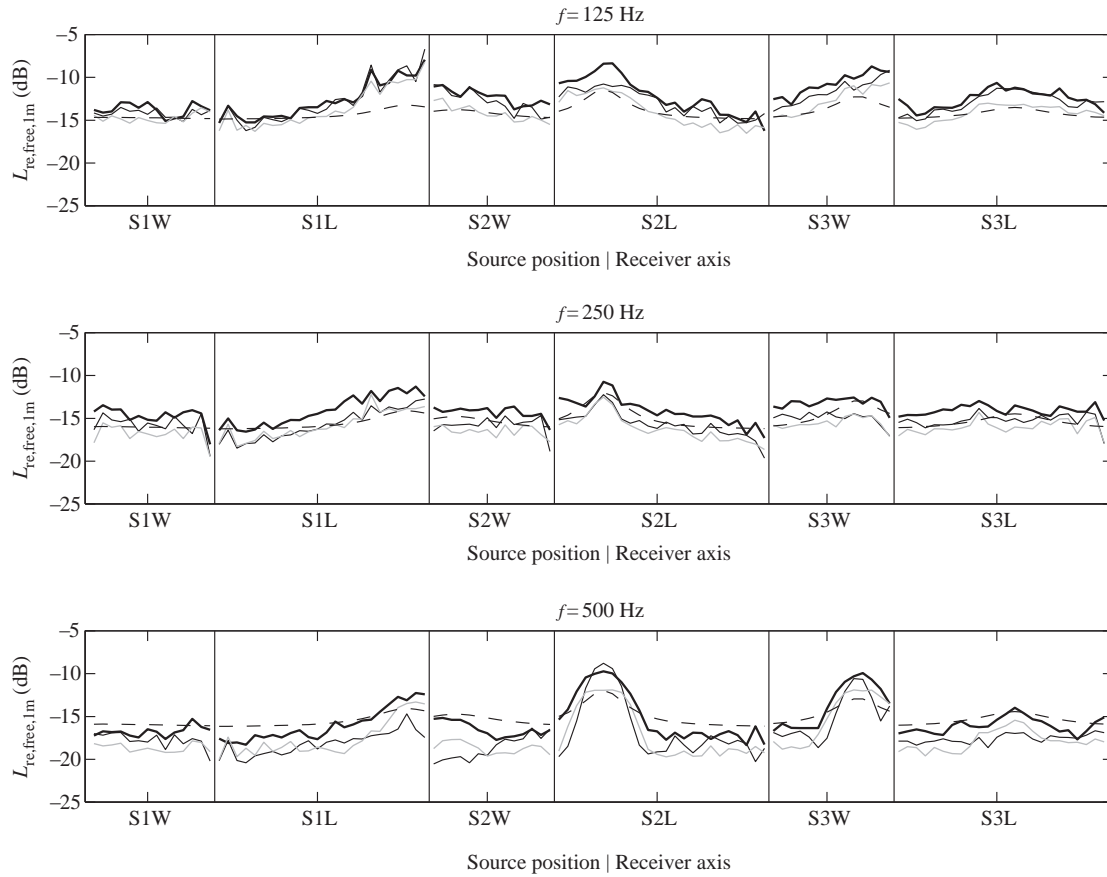


Figure 12. Sound pressure level $L_{re,free,1m}$ results for sports hall 2. Line indexing same as in Figure 11.

results. The results of the diffuse field method are on average close to the measured results (1.1 dB is the largest deviation for the 125 Hz octave band), but the results do not exhibit the spatial dependency very well.

Despite the fact that PSTD exhibits a similar spatial dependency as the measured results for hall 2, PSTD generally under predicts the measured levels of hall 2. For the highest two octave bands, this is in accordance with the lower T_{20} values as predicted by PSTD. The lower sound pressure levels for the 125 Hz octave band are somewhat counterintuitive when considering the T_{20} values in this band, where PSTD exhibits higher values. CATT-Acoustic results show the same tendency as PSTD, but show larger deviations for all octave bands. Both PSTD and CATT-Acoustic have standard deviations similar to those measured. As for hall 1, results from the diffuse field method do not follow the spatial dependency of the measured results in detail, but the deviations are on average not systematically larger than with the other two methods.

5. Discussion

When selecting an acoustic calculation method to predict the sound field in rectangular shaped sports halls,

the expected suitability of the chosen method should be kept in mind. A full wave-based method would be most appropriate. Although the Schroeder frequency of both sports halls is very low and the surfaces are large compared to the wavelength, a geometrical acoustic and diffuse field method should still be used carefully since the walls are parallel to each other implying that wave interference effects might occur. The spatial-dependent deviations in $L_{re,free,1m}$ from the measurements are rather well predicted by PSTD and CATT-Acoustic, showing that wave interference effects are still significant, even if the frequency is far above the Schroeder frequency. These interference effects are captured by the used algorithm in the CATT-Acoustic software. A geometrical acoustics approach with an algorithm that adds the squared pressure values will not show these effects. The parallel walls will likely also lead to larger reverberation times (characterized by flutter echoes) than a diffuse field approach would predict. When predicting the acoustics with any method, the boundary conditions (absorption and scattering coefficients) should be chosen properly. In the design phase of a sports hall, the properties of the applied materials are not always known. In this work, the boundary properties have been adopted to the best of our knowledge, which would be the most obvious approach in practice.

When inspecting the results of Section 4, it can be seen that results from the wave-based method (PSTD) and geometrical acoustics method (CATT-Acoustic) exhibit a similar tendency in deviating from the measured results. In particular, their spatially dependent sound pressure levels agree well with the measured results, but levels do systematically deviate for some octave bands. These observations point out that the chosen boundary properties are suboptimal to predict the acoustics of the hall. Although the used absorption coefficients of the boundaries are equal in both methods, the locally reacting approach in PSTD implies that the absorption is angular dependent, whereas an angular independent coefficient is used in CATT-Acoustic. Furthermore, note that in PSTD, a low level of scattering is included as all materials are assumed to be specular reflecting surfaces. In CATT-Acoustic, the choice of the scattering coefficient of boundary surfaces is kept equal to 0.1 for all surfaces and all frequencies. It is obvious that some boundaries in the hall, e.g. the open lath construction, do in reality have different scattering properties. A better estimation of the boundary conditions would likely lead to better predicted values for both PSTD and CATT-Acoustic. For the frequencies considered, the wave-based model performs only slightly better than the geometrical acoustics method. Only for the 125 Hz octave band in hall 1, CATT-Acoustic does deviate from the measured results to a larger degree. The correct choice of the boundary conditions shows to be most critical for the reverberation time in hall 1, which has the lowest amount of sound absorbing material of the two halls and a lower degree of diffusion (no balcony present).

From the results for the two halls investigated in the chosen octave bands, the diffuse field method does not seem to be a reliable approach for estimating the reverberation time properly. On the other hand, the estimation of the spatially averaged sound pressure level using the diffuse field method in the hall is good.

6. Conclusions

With their inhomogeneously distributed sound absorption materials and their typical shoebox-shaped layouts, the prediction of sports halls is not an obvious task. To assess the suitability of acoustic prediction methods for such halls, a case study is performed for two sports halls using three different acoustic prediction methods. The prediction methods vary in accuracy according to the nature of the underlying governing equations: a diffuse field method, a geometrical acoustics method and a full wave-based method. The acoustic properties of the materials (absorption and scattering coefficients) in the hall have been adopted according to best practice, using manufacturer data and prediction methods. The study focuses on the lower frequency range, i.e. up to the 630 Hz $\frac{1}{3}$ octave band, as this is the most problematic range for prediction. Both the reverberation time (T_{20}) and the sound pressure level have

been investigated. Results show that both the full wave-based method and the geometrical acoustics method give reasonably good results when compared to the measured data, with a slightly better agreement using the wave-based method. The diffuse field method heavily under predicts the T_{20} values, but gives a reasonably good prediction for the sound pressure level. The deviations between the full wave-based method and the geometrical acoustics method on the one hand, and the measured results on the other, typically demonstrate a consistently lower or higher trend. A better assumption of the boundary properties (absorption and scattering coefficients) will therefore likely lead to an even better agreement for both methods.

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Appendix 1. CATT-Acoustic settings

The settings used in the calculations with the geometrical acoustics method are summarized in Table A1. The choices are motivated as follows. Algorithm 2 is used, as this method is recommended to be used for rooms with non-mixing shapes, unevenly

Table A1. Settings used in the calculations with the geometrical acoustics method.

	Hall 1	Hall 2
Version	CATT-Acoustic v9.0c (build 1.01)/TUCT v1.1a:1	CATT-Acoustic v9.0c (build 1.01)/TUCT v1.1a:1
Algorithm	2 (AUTO)	2 (AUTO)
Method	h	h
Primary number of rays (–)	80,472	103,985
Impulse response length (ms)	3000	3000

distributed and high material absorption, an uneven dimension regarding widths and height as well as when effects of flutters or modes may be expected. Algorithm 2 makes use of ray splitting, i.e. for the first and second order of reflections, new rays are generated for the scattering reflection part. This means that even more rays are generated compared to the number of primary rays, leading to time consuming calculations. The ‘AUTO’ setting returns a number of primary rays such that amongst others at least one first-order ray hits 0.25 m² on every surface of the room. The IR length is chosen to be at least 2/3 of the measured reverberation time. Finally, the ‘h’ method is the pressure summation method, which is needed for taking into account interferences in sound pressure level calculations.

Appendix 2. Normalization of IRs from measurements and calculations

To compare the IRs from the measurements and the calculations using the PSTD method in Section 4.1, it is important that the spectrum of the source is equal in both methods. The modified IRs p'_{meas} and p'_{PSTD} as presented in Section 4.1 have the same source spectrum, which can be seen by transforming the signals to the frequency-domain:

$$\begin{aligned}
 P'_{\text{meas}}(\omega) &= \int_0^T p'_{\text{meas}} e^{-j\omega t} dt, \\
 &= P_{\text{meas}} \hat{P}_{\text{PSTD}}, \\
 &= (A_{\text{meas}} H_{\text{meas}})(A_{\text{PSTD}} H_{\text{ana}}), \\
 &= (A_{\text{meas}} A_{\text{PSTD}} H_{\text{ana}}) H_{\text{meas}}, \quad (\text{A1})
 \end{aligned}$$

and similarly

$$\begin{aligned}
 P'_{\text{PSTD}}(\omega) &= \int_0^T p'_{\text{PSTD}} e^{-j\omega t} dt, \\
 &= P_{\text{PSTD}} \hat{P}_{\text{meas}}, \\
 &= (A_{\text{PSTD}} H_{\text{PSTD}})(A_{\text{meas}} H_{\text{ana}}), \\
 &= (A_{\text{meas}} A_{\text{PSTD}} H_{\text{ana}}) H_{\text{PSTD}}, \quad (\text{A2})
 \end{aligned}$$

with P'_{meas} being the Fourier transformed signal p'_{meas} , A_{meas} is the complex amplitude of the measurement signal, H_{meas} is the FR of the hall as obtained from the measurement, and H_{ana} is the FR of the direct and ground reflected sound wave hidden in the part of the time signals up to t_2 . The hatted components \hat{P}_{meas} and \hat{P}_{PSTD} denote that only the first part of the signal up to t_2 has been used in the transform. Comparing P'_{meas} and P'_{PSTD} , it is obvious that they indeed have equal source amplitudes ($A_{\text{meas}} A_{\text{PSTD}} H_{\text{ana}}$) and only differ by their FRs H_{meas} and H_{PSTD} .