Calculation of Sound Level Distribution and relevant Values for Sound Immission with the Help of Computer Simulation taking a large Sports Stadium as an Example

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Introduction

Nowadays standards for sound reinforcement systems in locations for public events are very sophisticated. These do not only concern the fulfillment of certain values of speech intelligibility, but also give clear guidelines for sound immission. The planing and the necessary calculations in connection with sound distribution at public areas and surfaces relevant for immission shall be described exemplary by means of a large sports stadium (Olympic stadium in Berlin).

Substantial for planing a sound reinforcement system are the key features of the location such as the size, the audience area etc. as well as the utilization profile. Using the example of a sports stadium it is necessary to consider that sports events these days obtain more and more the character of show events. Next to pure announcements the transmission of high-quality music and special effects is required. Taking these aspects, a requirement profile for the sound installation develops, that can be divided into the following sections:

Emergency announcement

The emergency announcement is the most essential application for sound reinforcement system, since it has to contribute to an orderly evacuation of the stadium in an emergency case and has to fulfill the necessary principles. The bases for this is a sufficient speech intelligibility in all areas where the audience will stay. Examining the example of the Olympic stadium in Berlin the following key values were determined:

A well-defined sound coverage of separate zones (emergency areas) has to be possible. For every individual area, at least 90 % of all places have to reach a STI-value of 0.5 or better under consideration of all influences. The most important actuation variables are reverberation, noise level and potential echoes. The sound system therefore has to be configured in such a way that reverberation will be stimulated as little as possible and a sufficient signal to noise ratio is achieved. Considering the size of the stadium special attention has to be given to echoes, which have to be avoided under all circumstances. In connection with the selection of loudspeakers the demanded features are a good directivity with an exact beam on the audience areas and a sufficient maximum sound pressure. An average noise level within the stadium of L_{Aeq} = 92 dB(A) can be presupposed. The requested direct sound level should be at least 10 dB higher in order to reduce the influence of the factor signal to noise ratio on worsening the speech intelligibility ($STI_{S/N}$ = 0.83) to a minimum. At the same time the direct sound level on public areas shall not vary more than 6 dB. Accordingly the minimum level for the reproduction of speech at 90% of the public areas has to be 102 dB(A) and may not exceed 108 dB(A).

Aspects of technical sound insulation

Depending on the location of the stadium certain aspects of technical sound insulation have to be considered. In this case the situation can be presumed as very critical because the next residential buildings are quite close to the stadium. In order to minimize the immission values the specification in the call for tender defined certain limits for the outer surfaces and the openings of the stadium. For these calculations an assumed average frequency spectrum of the via sound system broadcasted speech and music signals was required. This was determined previously with various measurements at similar events.

For the three dominant outer surfaces – the roof opening above the pitch, the roof surface above the audience, and the roof gaps at the edge of the upper stands – the at least to reach sound reduction in comparison to the public areas was specified as follows:

	surface in m²	level difference to public areas linear weighted	level difference to public areas A-weighted
roof opening	12.700	11 dB	12 dB
roof surface	45.600	2 dB	5 dB
roof gaps	3.400	4 dB	6 dB

Table 1: The minimum sound reduction at the outer surfaces of the stadium in relation to the public areas, as required in the call for tender All in all three important criterion for the sound reinforcement system of the stadium can be itemized.

1) In case of emergency announcements, 90 % of each sector of the public areas have to be reached by a direct sound level of at least 102 dB(A) which may not be exceed by more than 6 dB.
2) On the basis of the given signal spectrum the outer surfaces in average have to fulfill the required sound reduction in comparison with the average sound level on the public areas.
3) For a high quality music reproduction a constant frequency response from 70 Hz up to 15 kHz has to be achieved on the public areas

Practical implementation

For the loudspeaker positioning hanging points were assigned under the roof surface and various sound concepts were worked out. On account of the difficult basic requirements a concept with line arrays was finally determined as a cost-effective solution and was implemented. In a circular configuration 19 line arrays are installed, regularly located under the roof surface. Every array consists of nine elements of which the bottom five address the lower stands and the top four the upper stands. Additional bass arrays are not necessary because the loudspeakers (Electro-Voice: X-Line Compact) [1] used are fullrange systems. The signal control of the 3-way system is made by a passive mid-to-high frequency crossover within the loudspeaker itself and an active split for the LF driver. With this setup the expenditure for signal processing, necessary amping and corresponding wiring can be reduced considerably. In addition the very precisely adjustable directivity of line arrays [2] [3] should secure a clean acoustical separation of every sector and minimize the stimulation of the critical outer surfaces.

Simulation results

The simulations for this stadium project were done with EASE version 4.0 and 4.1. EASE allows a presentation of level distribution at an audience area in third octave and octave bands. In addition it is possible to calculate the average of three neighboring octave bands or broadband from 100 Hz up to 10 kHz.

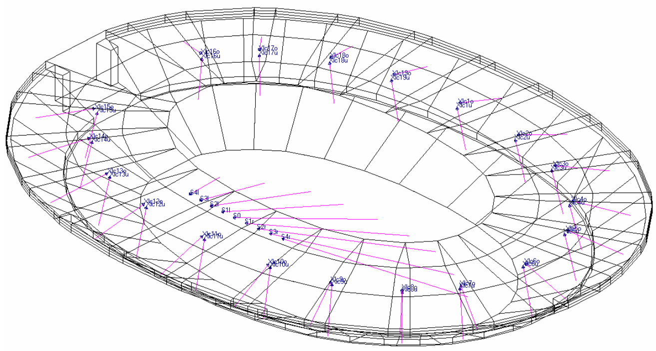

Figure 3: The Olympic Stadium as a grid model with loudspeakers at 19 positions, divided into different sections for the upper stands, lower stands and pitch

The presentation of the level distribution as a sum of several third octaves or a complete spectrum is not possible. It could have been the easiest procedure to do the simulation with the loudspeakers used to full capacity with a signal corresponding to the speech spectrum and to present the a-weighted sum at the audience areas. This sum was defined in the specification as 102 dB(A) at 90% of the areas.Alternatively the loudspeakers were simulated with a pink noise signal that used the peak power in each frequency band. So the presentation of third octaves displays the maximal possible level, as if every loudspeaker would get the maximal permissive power completely in this third octave. The brown graph in figure 4 shows the frequency response in dB SPL, calculated with this premise and averaged over all audience areas

With the same calculation method the mapping of the audience areas in figure 5 was evaluated. It displays the broadband average for the frequency range from 100 Hz to 10 kHz. All green surfaces have a sound level between 104.5 and 110.5 dB, so all values are within a tolerance margin of 6 dB. This presentation clearly shows the homogeneity of sound distribution at all audience areas, but does not permit an exact statement about the achievable A-weighted level with the sound system used to full capacity with a speech spectrum according to the specification.

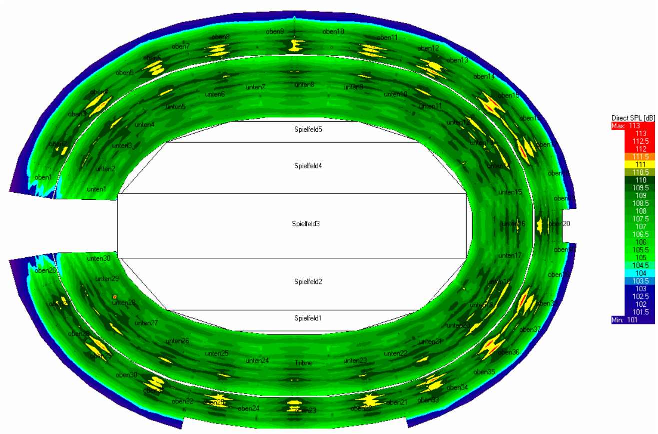

Figure 5: Distribution of direct SPL at the audience areas averaged over the frequency range from 100 Hz to 10 kHz (green surfaces from 104.5 to 110.5 dB). The outer blue boundary originates exclusively from a slide reduction of the sound level in this area, made on purpose in regard to the immission value at the roof gaps.

Therefore another mathematically conversion is necessary. Taking the averaged response of all areas in each third octave bands, it is possible for any kind of excitation signal to calculate the maximum accessible level for the sum of all frequency bands on the presumption that the system is run at full capacity. In this contexts full capacity means, that the loudspeakers are fed with a signal spectrum, that in its sum over all third octaves bands attains the maximal permissive power. In contrast to this EASE simulates the loudspeakers, as if the peak power would be available in every third octave. Now three conditions have to be distinguished, all under the assumption that the signal spectrum as a sum (!!) of all frequency bands reaches the maximum power capacity of the loudspeakers. Correspondingly for the calculation of the averaged sound pressure at the audience areas the values of all third octave bands are added up. To evaluate this data from the EASE simulation, a correction factor has to be computed for each third octave band. This factor depends on the signal spectrum. With a pink noise signal the correction factor for 21 third octaves is 13.22 dB, if the maximum power is not assumed for each frequency band but is constantly distributed to all frequency bands. Figure 7 demonstrates the output of the loudspeaker used in this application, if the total power is equivalent to the nominal power of 700 W. Beside the power distribution with pink noise it shows the power distribution with an unfiltered and filtered speech signal matching a male speaker's spectrum. Table 2 displays the level at the public areas for these excitation signals.

Signal	SPL / dB	SPL / dB(A)
Pink noise	107	105
Speech unfiltered	110	103
Speech filtered	109	**105**

Table 2: Averaged sound pressure level at all audience areas and peak level of the sound system with pink noise, an unfiltered and a filtered speech signal (HP-Filter and EQ)

This data indicate that at peak level of the system speech signal and pink noise achieve comparable values. Therefore the distribution function in figure 6 is valid approximately for speech signals as well. For a totally unfiltered spectrum of a male speaker about 2 dB have to be subtracted for an A-weighted result. Consequently the green range in figure 6 relocates between 102.5 and 108.5 dB. The demanded value of 102 dB(A) on at least 90% of the areas is reached even under adverse conditions.

Outer surfaces

In order to minimize the immission values the specification demanded a certain level difference in average sound level on critical outer surfaces in relation to audience areas. For calculation the given signal spectrum in figure 2 had to be used. Table 3 shows the calculated values under this premises for the critical surfaces. The sound system at full capacity fed with the signal spectrum, as shown in diagram 2, will create an average sound level of 111 dB or 100,7 dB(A) in the public areas. The columns 3 and 4 of the table include the difference value of the outer surfaces compared to the public areas for the unweighted and the A-weighted level and in addition in brackets the required minimum value.

For this constellation the simulation results barley miss the demanded values. However, by moving the power distribution of the given signal spectrum at constant total power only slightly towards the region of 200 Hz, all limits are fulfilled. This does not surprise since the given signal spectrum includes a good share of low frequency signals while the directivity of the loudspeakers in this frequency range is not jet fully distinguished.

	audience	**roof opening**	**roof membrane**	**roof gaps**
SPL dB	111.0	100,.	110.8	107.7
SPL dBA	100.7	89.6	97.6	95.7
difference unweighted	-	10.2 [11.0]	0.2 [2.0]	3.3 [4.0]
difference A-weighted	-	11.1 [12.0]	3.1 [5.0]	5.0 [6.0]

Table 3: Absolute level values and level differences to the public areas averaged over each surface at full capacity of the sound system with a signal spectrum as in figure 2. The square brackets show the demanded values which were not quite reached in the simulation, since in the bass range the DLL expected a far worse directivity than the array will show in reality.

This procedure might seem odd at first, but justifies itself when taking into account the directivity of the loudspeaker within the low frequency range. Figure 9 shows the vertical polar diagrams for the 125 Hz band as it was given by the DLL of the EASE simulation and how it was measured with an array under free field conditions.

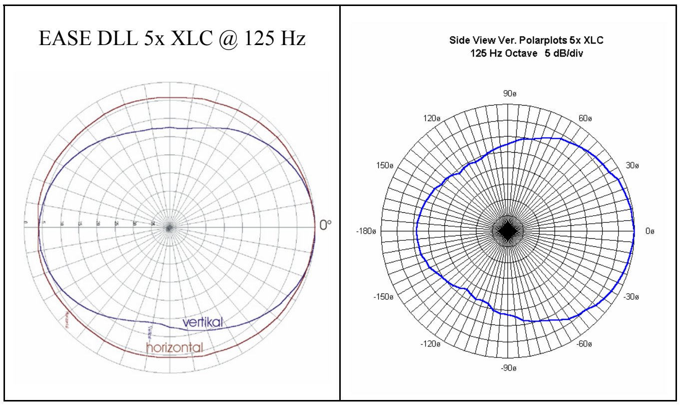

Figure 8: Polar diagram for the 125 Hz third octave ; left: data setup for the simulation (blue = vertical) ; right: measured directivity for a 5er array XLC-systems (scaling each 5 dB/div.)

Here it is clearly shown, that the simulation is accounting a backward attenuation of only 4.5 dB, whereas with the real array a level of 10.5 dB was measured. Especially this value is crucial because the loudspeakers back side points straight towards the roof membrane Therefore it is to be expected, that better values will be reached in reality than the simulation predicted. The deviation can be explained by the point source approach for the line array simulation used by the DLL in order to calculate the vertical coverage.

Conclusions

In the call for tender for planing the Olympic stadium in Berlin clear definitions were made for the reachable minimum sound level concerning emergency announcements as well as for the homogeneity of sound distribution concerning the public areas. In order to minimize the immission values at least to reach level differences for the relevant outer surfaces compared to the public areas were demanded. To calculate these values by simulation turned out to be partially quite problematic because it was not possible to compute the expected values within the EASE simulation and detours were necessary for an approximate evaluation. But it was still possible to establish with an adequate planning security, that the demanded minimum sound level and the appropriate steadiness of level distribution for emergency calls were achieved. In order to estimate the relevant values for immission a problem developed from not taking the directivity behaviour of low frequencies adequately into account in the simulation. But the limit value was just barley missed with the adverse assumption of a 6 dB lower backward attenuation at 125 Hz in the simulation compared to the measurements of the actual array. So even in this context the complete fulfillment of the specified demands is sufficiently secure.

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