Uncertainties in measurement of single number parameters in room acoustics

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Single number parameters are often used to describe the acoustic conditions in auditoria. ISO 3382 describes a procedure to conduct room acoustic measurements and defines quality requirements on the measurement equipment. This study deals with the influence of the source, namely dodecahedron speakers, on the measurement result. The characteristics of different loudspeakers in the same measurement condition will be presented. The influence of the speakers’ directivity on single number parameters such as Clarity, Definition, EDT and $T_{30}$ etc. will be evaluated. Besides uncertainties in the high frequencies that can be derived from deficiencies in the directional pattern of the source, differences in the single number parameters were also found in the lower frequencies. This is quite surprising as it is often expected that the dodecahedron speakers have a fairly good directional radiation pattern at these frequencies. The differences between single- and multi-way dodecahedron loudspeakers and their behaviour in this respect will be discussed in detail.

1 Introduction

The ISO-3382 standard [1] is frequently used when it comes to quantitatively describing the acoustics in concert halls or other auditoria. Besides specifications on measurement conditions and measurement procedures the standard also contains a guideline to professionally analyse the data and definitions of well-accepted room acoustical parameters. Furthermore the standard contains requirements sound sources have to meet in order to be considered omni-directional in terms of the standard.

2 Requirements for Sound Sources

In its origin the requirements for sound sources were logically derived from the ISO 140 [2] standard series about the measurement of sound insulation in buildings. In ISO 140 as well as in ISO 3382 the maximum acceptable deviations from omni-directionality – when averaged over “gliding” 30° arcs in a free sound field – are given. Considering that the diffuse sound field of a laboratory test facility for building acoustics is hardly comparable to the sound field in a concert hall the maximum acceptable deviations from omni-directionality as defined in ISO 3382 are more restrictive than the requirements for sound sources in building acoustics. The critical acoustician will never the less annotate, that the measurement procedure of the gliding arc allows the use of particularly critical or uncritical arcs. In order to keep the efforts for such a gliding-arc measurement at a practical level it is appropriate to assume that an arc of the equatorial plane will be used most of the time for an assessment of the sources directivity. Such an equatorial arc, however, does not pass through a lobe of a dodecahedron speaker and, hence, does not mark a critical arc of the speaker. Despite all that it can be shown that all established dodecahedron measurement loudspeakers meet the demands of the ISO 3382 standard.

Effective sound radiation at lower frequencies is a sensitive topic with dodecahedron speakers as it requires large volume velocities which generally are achieved by large amplitudes and large surfaces of the loudspeaker membranes. Large cabinet sizes also support low frequency radiation as they reduce the compliance of the enclosed air volume and consequently lower the resonance frequency. The size of the loudspeaker cabinet, however, also has disadvantageous effects, as a uniform directionality of the sound source can no longer be guaranteed. In order to use the advantages for low frequency sound radiation and, at the same time, avoid the problems of a high frequency directivity, a multi-way dodecahedron speaker system can be used.

Although it is known that the directivity of the sound source has an influence on the result of the room acoustical single number parameters it is desirable to know the characteristics of different speaker systems and derive the advantages and disadvantages of the different measurement philosophies. As a result it will become evident how the different parameters are affected by deviations from omni-directionality and also for which frequencies the error is negligible.

With this goal different dodecahedron sound sources were used for measurements in a large lecture hall of RWTH Aachen University.
3 Measurements

The assembly hall of RWTH Aachen University is a rectangular lecture room with the approximate dimensions of 22 m x 28 m x 10 m (WxLxH) and a volume of some 5500 m³. The auditorium seats about 650 listeners on the main parquet (ca. 500 seats) and a circumferential side and rear balcony (ca. 150 seats). The usage includes besides lectures also movie screenings and concerts of the local students orchestras.

Figure 1: General assembly hall of RWTH Aachen University – On the turntable the ITA dodecahedron speaker is set up in its auralisation-configuration (A)

In accordance with ISO 3382 six microphone positions were chosen; five of which are located on the main parquet and one on the rear balcony. Figure 1 shows how a dodecahedron speaker was set up on a turntable which was placed at a stage position that is regularly used by lecturers. For each of the four in Figure 2 depicted loudspeakers and for each of the six microphone positions 36 measurements were conducted. After each of the 36 measurements the turntable was rotated by an angle of 10°.

The ITA dodecahedron speaker was measured in three sequences in order to allow a comparison between its different configurations. As it can be seen in Figure 2 the left loudspeaker consists of three parts. In its auralisation configuration (A) all 3 ways are used simultaneously [3]. A digital DSP-controller is used to divide the input signal (sweep) into three bands and, at the same time, equalise the measurement system to provide a flat frequency response and an overall linear phase response. As in this setup the acoustic centre of the high-frequency tweeter does not coincide with the mid-frequency dodecahedron the system was also used in its measurement configuration (S). Here the low- and mid-band speakers are used during a first measurement simultaneously and, in a second measurement, the mid-band dodecahedron is replaced by the high-band unit and for a second measurement the low- and high-band speakers are used. As part of the data analysis both measurements are added and hence represent a measurement where the acoustic centre for all frequency bands is exactly at the same position. Of further profit is the fact that the subwoofer is used twice, yielding to an extra 3 dB in terms of SNR in the critical low frequencies.

4 Data Analysis

4.1 Time-windowing and filtering of responses

A short glimpse is to be taken at the method of analysis of the measured room impulse responses. ISO 3382 generally allows two methods how the impulse response may be analysed. Ideally the impulse response is time-windowed before any filtering. This way the influence of the filter delays is minimised. Problematic about this approach is, however, that the group delay of the sound source is not considered. Usually the loudspeakers group delay for lower frequencies is higher than for higher frequencies. By first time-windowing the impulse response some signal energy of the low frequencies may not be due considered when calculating energy ratios.

In order to calculate the single number parameters many software programs only consider the filtered impulse response. Here the impulse start is determined for each frequency band separately. While this method correctly accounts for the delayed impulse start due to filter and loudspeaker delay correctly only few programs adapt the integration interval by half the filter delay time to consider the “blur” of the filter.
For this study the complete data analysis is done in two ways: On the one hand the broad-band impulse response is time-windowed and then filtered and in contrast to that the impulse response is filtered and the integration intervals are kept constant (not considering the extension by half the filter delay).

4.2 Assessment of the loudspeaker influence

Firstly a comparison between the different loudspeakers should be drawn. To do so the analysis of the measured data is done in two steps. For step one the single number parameters, which were measured in the 36 single measurements, were used to calculate the arithmetic mean. This way the influence of the sources directionality is reduced and the parameter shows a result as it is measured by the different loudspeakers. In order to assess how the results of the various loudspeakers differ from each other the absolute error is calculated. Reference value is the mean of the results as measured by the individual speakers.

In a second step it is to be studied how the single number parameter is affected by the directional pattern of the sound source. With this goal the results of the 36 measurements are compared with each other by calculating the standard deviation $\sigma$ of the individual measurements from the arithmetic mean. The standard deviation $\sigma$ shows – assuming the deviation is described by a normal distribution – which difference is not exceeded by 68 % of the 36 measurements. This analysis was done for C80, D50, LF, EDT, and T30.

5 Results

5.1 Influence of the Directionality of the source

Here the parameters are calculated by first time-windowing the impulse response and then applying the filter. In Figure 3 the results of the first step of the analysis for a representative microphone position can be seen. The behaviour of the curve for the other measurement positions differs from the shown manner only in detail. Table 1 shows the results of this figure for all single number parameters in a compressed form. As before, the standard deviation $\sigma$ identifies the absolute error that is not exceeded by 68 % of the measurements.

In order to study the effect of the directionality the results of the second step of analysis are presented in Table 2. As the results above and below the 1 kHz-Octave differ significantly from each other the standard deviation $\sigma$ is calculated separately for both frequency bands. The ITA-A column shows the results of the dodecahedron speaker that was developed at the Institute of Technical Acoustics in its auralisation configuration. ITA-S represents the added results of the ITA loudspeaker in its measurement configuration. The results of the other sound sources are presented anonymously.

The data as it is presented above marks to a certain degree a rather surprising result. The most remarkable feature, that can be seen in Figure 3, suggests that there is a frequency independent deviation between the
Table 2: Standard deviations s of the single number parameters and sound sources

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Loudspeaker</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ITA A</td>
<td>ITA S</td>
</tr>
<tr>
<td>σ C80 [dB]</td>
<td>0.08</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>0.38</td>
<td>0.27</td>
</tr>
<tr>
<td>σ D50 [%]</td>
<td>0.46</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>2.58</td>
<td>1.82</td>
</tr>
<tr>
<td>σ EDT [s]</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>σ T30 [s]</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>σ LF [%]</td>
<td>0.52</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>2.45</td>
<td>1.94</td>
</tr>
</tbody>
</table>

The results of the five loudspeakers. For the 62.5 Hz octave band the reason for the large differences in the results is likely be a low Signal/Noise-Ratio. Even with 16 coherent repetitions of the sweep (degree 17, i.e. 3 s) some speakers only achieve a level of 20 – 30 dB above the noise floor.

At frequencies that are of relevance for the ISO 3382 standard, namely the bands from 125 Hz to 1000 Hz, a difference in the results of the different loudspeakers is also measurable. This is unexpected in the light of the data presented in Table 2 which shows that the influence of the loudspeakers directionality on the parameter is rather low at frequencies of 1 kHz or smaller. Measurements in the anechoic room indicate that the sound pressure level of the loudspeakers is well within the requirements of the 3382 standard. Considering the findings of de Vries [6] it is not really plausible that a significant parameter variation of the parameter can be contributed by a microphone that was moved between the different measurements. Especially for frequencies below 1 kHz the wavelengths are of such a magnitude that it does not present a challenge to place the microphone with a reasonable accuracy.

5.2 Influence of signal processing on the parameter

A detailed analysis of the influence of different algorithms on the determination of the room acoustical parameters has been done by Lundebey [7]. The focus of this analysis is how a group delay that is not constant at all frequencies influences the calculated single number parameter. The influence, however, is not the same for the two algorithms of data analysis. When the impulse response is time-windowed before any filtering the group delay of the loudspeaker is the dominating factor. Figure 4 shows the group delay of the loudspeakers that were used in this study. Apart from some minor deviations it is pleasing to see that all speakers have a fairly flat group delay. Although some information at the lower frequencies is lost due to a necessary time-windowing operation it still can be seen that the group delay increases towards the lower frequencies. This delay has a negative effect on the results for the lower frequencies as the actual impulse starts later than the start of the time-window and hence some energy of the early impulse response is not properly considered.

If in contrast the impulse start is calculated for the filtered impulse response the difference can be seen in Figure 5. It is evident that the parameters of temporal energy ratios systematically consider more energy in the early parts of the impulse response when a time-windowing is not carried out.
intervals are chosen correctly. The delay of the impulse start as a function of frequency for the different speakers is presented in Figure 6.

![Figure 6: Impulse Start as delayed by the filtering and the loudspeaker](image)

Here it can be seen that impulse start is retarded by about half the group delay of the filters. Besides this it becomes also apparent that the different loudspeakers delay the impulse towards the lower frequencies themselves.

The fact that the impulse is only delayed by roughly half the group delay of the filter confirms the importance to increase the integration intervals in order to correctly analyse the impulse response.

6 Conclusions

Considering the data it is evident that different effects on the results have to be separated. Firstly the directionality of the source – especially at higher frequencies – has a significant influence on the single number parameters. All studied dodecahedron sources have, however, only a minor directional pattern below 1 kHz. As ISO 3382 conform averaging for different frequencies is done exclusively at bands ranging from the 125 Hz to 1 kHz octave all sound sources can be used for measurement purposes in room acoustics. Above 1 kHz, however, it is to be expected that the measurement result is afflicted with a noteworthy measurement error. For auralisation purposes, which become more and more significant, it is hence of importance to use a suitable source with an omni-directional pattern over large frequency bands.

Secondly it has to be stated that the measurement results are also affected by other influences the speakers differ in. The deviance of the single number parameters is sometimes of the magnitude of perceptibility.

The comparison of different algorithms for the data analysis revealed that the increment of the loudspeakers group delay at the lower frequencies has an influence on the parameter. While the algorithm of time-windowing the impulse response before any filtering does not consider such effects it reduces the influence of the filter-delay to a minimum. In contrast refraining from time-windowing correctly considers a delayed impulse start at the cost of a difficult to assess influence of the filters. The previous analysis confirmed the importance of considering the group delay of the filters when determining the integration intervals for the parameter calculation.

Although a longer group delay towards the lower frequencies is not the argument to solely explain the difference of the parameters a source equalisation is a helpful tool to keep the group delay constant for all frequency bands and is therefore beneficial for a correct data analysis.

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References