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Uncertainties caused by source directivity in room-acoustic investigations

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Abstract: Although deviations in the measurement of acoustic parameters should be lower than the subjectively perceivable change in the corresponding parameter measured, this study reflects that directionality of sound sources could cause wide audience areas to break away from this criterion at high frequencies, even when using dodecahedron loudspeakers which meet the requirements of the ISO 3382 standard. The directivity of four different acoustic sources was measured and the influence of its accurate orientation spatially quantified in five enclosures for speech and music. By means of simulation software, the number of receivers affected by uncertainties greater than difference limens was established.

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1. Introduction

The directionality of a sound source has a significant effect on the results obtained for acoustic parameters derived from the impulse response, especially at high frequencies. This is found to be true even for dodecahedron loudspeakers meeting the requirements of the ISO 3382 standard¹ regarding the directional patterns of sound sources. Results obtained from different sources can differ substantially, so much that it could lead to misleading evaluations of the acoustic attributes at the same source–receiver position. Even for two random–specific orientations of the same source, results may differ by more than the subjectively perceivable change—one just noticeable difference(jnd)—of the corresponding parameter.²

Up to now, research on uncertainties due to source orientation has been limited to, as well as by, measurement procedures. The peculiarity of the phenomenon, which appears solely at higher frequencies, seems to suggest that simulation software—whose main limitation is ray tracing at low frequencies—is not a limiting tool. It may enable us to test the “source orientation” variable spatially in a time-saving way, in sharp contrast to the use of measurements. In addition, as can be seen in this work, present display facilities implemented by developers of the programs are a great aid for interpreting results.

By means of simulation software, this study has set out to determine the effect of the directivity of sources—which meet the requirements of ISO 3382—on the results of acoustic parameters in enclosures for speech and music where such a standard is applied. Four different *omnidirectional* types of sources were surveyed and tested. Three of them, S1, S2, and S3, were different commercial dodecahedron sources while S4 was the source developed at the Institute of Technical Acoustics in Aachen, Germany.³ This last source consists of a three-way measurement loudspeaker in which a subwoofer is used to achieve the required sound power at low frequencies and two specially designed dodecahedron speakers with different diameters are made use of to improve the omnidirectional sound radiation in comparison with the one obtained through conventional singular dodecahedron measurement devices. So as to simulate the directional pattern of the four sources, the radiated fields were measured in an anechoic chamber. By means of a computer-controlled measurement procedure, a half-sphere of measured data in 5° angular increments between adjacent points was obtained. The full sphere was built by applying symmetry rules. Odeon[©] room acoustics software was used during the simulation procedure.

Table 1. Basic data of the halls.

| Hall, location | Volume (m ³) | Seats | $T_{30 \text{ mid}}^a$ (s) | Shape | Rays/oct |
|---|--------------------------|-------|----------------------------|---------------|----------|
| Sarasate Theatre, Pamplona (Spain) | 4 000 | 480 | 1.0 | Rectangular | 3 600 |
| Bretón Theatre, Logroño (Spain) | 6 300 | 988 | 1.3 | Rectangular | 7 000 |
| Elmia Hall, Jönköping ^b (Sweden) | 11 000 | 1100 | 2.2 | Fan | 15 000 |
| Baluarte Concert Hall, Pamplona (Spain) | 20 000 | 1568 | 1.9 | Rectangular | 30 000 |
| Mozart Concert Hall, Zaragoza (Spain) | 25 800 | 1992 | 2.9 | Semi-surround | 18 000 |

^aFrom measurements according to ISO 3382 for “normal coverage.”

^bReference 4.

2. Measurement and simulation procedures

The reliability of a room acoustical simulation varies according to a range of calculation parameters: geometry data, absorption and diffusivity coefficients of surfaces, number of rays, length of the calculated impulse response, etc. For an accurate prediction of room acoustic parameters the modeling of surface reflections often needs to be polished through the aid of measurements. This has been the case of the present research work. A complete set of measurements was designed for the prior characterization of the halls to be evaluated. They were made in unoccupied conditions and with a number of measurement positions chosen under “normal coverage” based on ISO 3382 standard requirements. The measurement technique of room impulse responses based on logarithmic sweep sine excitations was resorted to.

With the aim of selecting an adequate recreation of typical conditions in enclosures for speech and music, four different halls—all of them located in northern Spanish cities—were chosen. At the same time, a hall well known by acousticians was included in the assessment. The geometrical, absorption, and diffusivity data of the Elmia Hall in Jönköping, Sweden, were forwarded to the participants at the Second International Round Robin on Room Acoustical Simulation.⁴ Moreover, this hall along with calculation parameters used by Odeon was provided by the manufacturers to their users as demo data on purchasing the software. The theatres and concert halls selected are listed in Table 1 along with basic information on each. They have reverberation times within the range of 1.0–2.9 s at midfrequencies, their volumes ranging from 4000 to 25 800 m³ and three different shapes, i.e., rectangular, slightly fan-shaped, or semi-surrounded.

The calculation parameters were picked taking into account previous work⁵ and recommendations of the program. In general, the length of the impulse response should be similar to the reverberation time of the room and in our case the number of rays was established following the criteria consisting of at least one direct ray per square meter in the most distant receiver from the source. This led to values from 3600 to 30 000 rays per octave depending on both the size of the halls and the location of the audience zones. When unknown, absorption coefficients were selected from the library provided by the software used or literature. Diffusion coefficients of 0.1 and 0.7 for smooth and rough surfaces respectively were applied. These coefficients are specified for the middle frequency around 700 Hz. Then the software expands them into values for each octave band according to typical conditions for materials.

In order to determine the effect of the source orientation on the results of various acoustic parameters, 72 simulations were carried out with each source. A full 360° rotation was covered in 5° steps. For the spatial analysis, a grid of receivers — one receiver per m²—was placed all over the audience zone excluding balconies. Over 3000 receivers, each one “measuring” seven parameters— T_{30} , EDT, C_{50} , C_{80} , T_s , G , and LF—at eight frequency bands for each simulation and source, were finally utilized. Over 50 million data had to be carefully evaluated by means of MATLAB technical computing software.

3. Results and discussion

The first question to be tackled was the reliability of the simulations. With the help of the measurements conducted for the characterization of the halls, absorption coefficients of surfaces were slightly adjusted in order to fit the values of reverberation times in several test points with those obtained through simulation. Definitive simulated values differed less than 5%—jnd of T_{30} —with respect to the measured reverberation time in each evaluated position. Furthermore, the bearing of the source orientation on measurements was also assessed by considering one source–receiver position for each hall at the central part of the audience and turning the source in 5° steps.²

Mm. 1. shows the results obtained for source S2 at the Baluarte Concert Hall. Sound pressure level of solely the direct sound at 2 kHz octave band is represented for each one of the 72 orientations successively. The SPL_{direct} value is subject to the lobe shape of the dodecahedron loudspeaker, i.e., whether a maximum or a minimum of the source directivity is facing the receiver. Furthermore, the corresponding octave-band directivity balloon plot of the source along with a graph containing measured and simulated values in the test receiver—which is highlighted inside the grid map—can also be observed. Both measurement and simulation values follow a similar pattern.

[Mm 1. (Color online) SPL_{direct} for S2 at 2 kHz while turning the source. (Top-left hand window) Directivity balloon plot of the source. (Bottom-left hand window) Measured and simulated values in the test receiver, highlighted. Room: Baluarte Concert Hall. This is a file of type animated “gif” (3.6 Mbytes).]

To establish a final verification of simulation reliability, variations on the C_{80} parameter are shown in Mm. 2. The same source, concert hall, and receiver test are displayed; however, in this case, 4 kHz octave band is the frequency chosen for representation. The mean value for C_{80} in the highlighted receiver is in the vicinity of -2 dB but the variation of the parameter value ranges from -3 to -1.2 dB. When we evaluated the direct sound along with the whole impulse response, we also found that the coincidence between measured and simulated values favored the simulation software and its ability to accurately predict even minor changes in measurement conditions.

[Mm 2. (Color online) C_{80} for S2 at 4 kHz while turning the source. (Top-left hand window) Directivity balloon plot of the source. (Bottom-left hand window) Measured and simulated values in the test receiver, highlighted. Room: Baluarte Concert Hall. This is a file of type animated “gif” (3.6 Mbytes).]

Once the simulations were validated for all rooms by means of measurements—except for the Elmia Hall, which was tested with the aid of the demo data provided by the manufacturers—the task was to find a way of processing the vast amount of data available. On identifying the standard deviation including the effect of the source orientation— STD_S —as the parameter that characterized the dispersion of the results observed in each receiver when carrying out the 72 corresponding simulations on each source, it was possible to draw up grid plots such as those shown in Fig. 1 covering the different halls. Relative STD_S with the jnd of the respective parameter as a reference was preferred for depiction. Thus, apart from displaying the results on a sole scale for all parameters, the value of relative STD_S was also representative of the change in subjective perception that the uncertainties could produce. The jnds Bork⁴ used in the Round Robin—estimated from the data of Cox *et al.*⁶ and Bradley *et al.*⁷—have been made use of. As can be seen in Fig. 1, there are several variations depending on the position within the hall. The use of a gray scale for the diagram enables us to locate the most affected zones. Central areas may be more affected by the directivity of the source. The proximity of a wall and subsequently the arrival of a reflection from others may help to compensate for the uncertainty which arises as a result of the difference of levels from the direct sound. If we use ITDG—the time gap between the arrival of the direct sound and the first sound reflected from the surfaces of the room—as an indicator of the receiver positions and plot STD_{S_2} at 4 kHz for all receivers, see Fig. 2(a), we will be able to detect a tendency of higher deviations when ITDG increases.

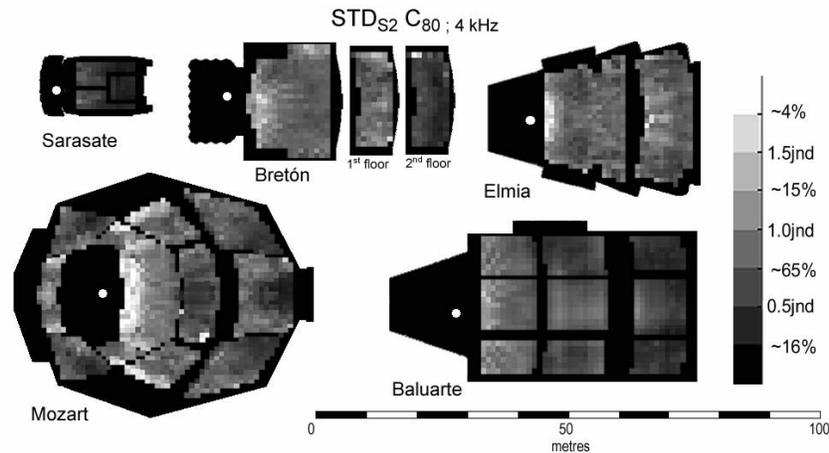


Fig. 1. Relative STDs for C_{80} parameter obtained for S2 at 4 kHz for all rooms. Reference: 1 dB—jnd for C_{80} . At colorbar, the percentage of receivers whose STDs remain within an interval of half a jnd is also displayed.

A different representation of the influence of the source orientation on acoustic parameters, particularly on clarity C_{80} , is shown in Fig. 2(b). Standard deviations STD_S within the hall are plotted again with jnd as a reference and the rate of receivers affected as well. This plot also casts light on the magnitude of the problem being analyzed. When measuring acoustic parameters, uncertainty should be lower than the subjectively perceivable change in the corresponding parameter measured. Using STD as the parameter that characterizes the deviation of the results in a measurement and stating the related 95% confidence interval, the maximum permissible difference limen should be twice the STD of the measurement apparatus. Hence, the STD should not be larger than half the jnd of the parameter under discussion. At 8 kHz octave band, this criterion is not fulfilled in over 85% of receivers in the case of S1, S2, and S3, and 18% of receivers when using such a specific source as S4.

Finally, Fig. 3(a) shows the percentage of receivers affected depending on each one of the sources in the five halls under study. For low frequencies, source directivity had no effect at all on the simulated parameter and there were similar findings for all orientations. Sources S2 and S3 delivered satisfactory results up to 1 kHz, while S1 and S4 increased this limit up to 2 and 8 kHz, respectively. At the highest frequencies, 4 and 8 kHz octave bands, the criterion of tolerance established was not met in over 80% of the receivers for the three commercial loudspeakers. Moreover, at 1 and 2 kHz octave bands, which are more common when resorting to

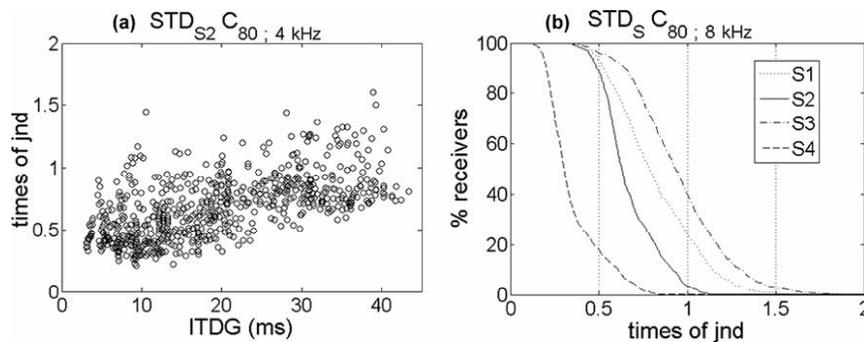


Fig. 2. Relative STDs for C_{80} parameter (a) for S2 at 4 kHz vs ITDG and (b) for all sources at 8 kHz vs percentage of receivers affected. Reference: 1 dB—jnd for C_{80} . Room: Baluarte Concert Hall.

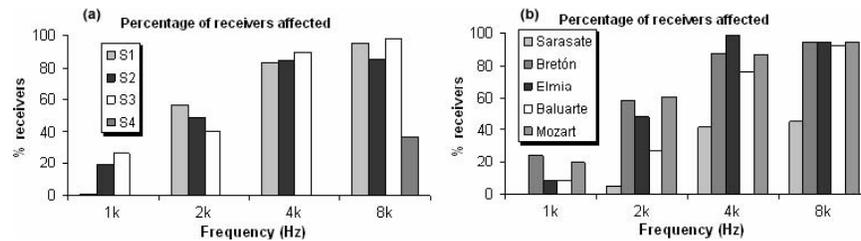


Fig. 3. Percentage of receivers with STDs for $C_{80} > 0.5jnd$ (a) for all rooms and (b) for the three commercial dodecahedron loudspeakers.

average figures to define the acoustic properties of a room, a deviation any higher than half the jnd of the parameter would be expected in at least 15% and 40% of receivers, respectively, when measuring with sources S2 or S3. The described S4 measuring system has a better performance at higher frequencies and only at 8 kHz does sound radiation become perceivably directional. By setting aside that source which is only common for highly specialized measurement purposes and attempting to globally analyze the findings obtained by means of loudspeakers with common directivity patterns, we came up with the differences found in the test rooms [see Fig. 3(b)].

STD_S figures for the rest of the simulated acoustic parameters were analyzed and results similar to these reflected here for C_{80} were collected although the magnitude of uncertainty changed somewhat. Such as was stated in previous research by measurement procedures,² C_{50} turned out to be the most sensitive parameter, while reverberation times, whose calculation usually requires a complete integration along the time scale, were the least sensitive to the directivity of the source.

4. Conclusions

Enhanced computing power enables the acoustician to test a vast array of variables efficiently, thus making it possible to come up with configurations which would otherwise be unfeasible solely through measurement procedures. The use of simulation software could aid us in diminishing the complex procedures required when spatial distributions within halls are analyzed. In this research, a first attempt to predict uncertainties in the measurement chain of room acoustic parameters was made by means of simulation techniques. More specifically, spatial variation of uncertainty due to source orientation was analyzed. Simulated results seemed consistent with those obtained through measurement procedures.

The loudspeakers which were tested delivered satisfactory results up to 1 kHz. Below that frequency band, the bearing of source orientation is negligible for all acoustic parameters. As frequency is increased, sound radiation becomes more directional and the effect on the parameters cannot be neglected any longer. Variations on parameter figures depend on the source, the frequency band, the way those parameters are derived, as well as the position within the hall where they are going to be measured. The use of typical commercial dodecahedron sources could lead to high deviations in wide areas of audience zones of common enclosures for both speech and music. At 1 and 2 kHz octave bands, the percentage of receivers affected with uncertainties higher than the subjectively perceivable change exceeds 15% and 40%, respectively. Furthermore, at higher frequencies, a deviation greater than half the jnd of the parameter could be expected in at least 80% of receivers. Source rotations through three angular positions and the posterior averaging of subsequent measurement results—ISO 3382 requirement if the source directivity is found to have a significant effect on measured acoustic parameters—should not be discarded even in the case of dodecahedron loudspeakers having the ISO standard qualification. If the aim is to make it possible to compare measurements among different teams and equipments more accurately, the standard probably relaxes omnidirectional requirements at higher frequencies. A far-reaching aim would be to consider alternatives for assessing source omnidirectionality such as those proposed by Leishman *et al.*⁸ since authors suspect that the

ISO 3382 classification method may lead to misguided conclusions about omnidirectional performance owing to its implementation by using single-plane measurement arcs.

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