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Visualization of low frequency sound fields in rooms

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ABSTRACT
In room acoustic design and analysis the low frequency behavior is an important quality criterion. Especially in small rooms, where the Schroeder frequency lies high above the limits of electroacoustic reproduction systems, the discrete eigenfrequencies of the room are crucial for the frequency response at a listener position. For about five years a software tool has successfully been used in the design process and for the analysis of studios and other rooms for high quality reproduction and recording of sound material. The approach focuses on the practicability of the modeling and the visualization of room modes. Therefore the method uses simplified boundary conditions, which also allows for a high uncertainty of input data and a largely varying level of detail in the planning process. An overview of the method and its implementation is given. The limitations of the tool and accuracy issues due to the necessary simplifying assumptions are being referred to. Measurements carried out for a recent project are evaluated in that regard, attempting a better estimation of these limitations. Exemplary samples of the application for the design of new studios and the analysis of problematic existent facilities are described.
Keywords: Room acoustics, Simulation, Visualization

1. INTRODUCTION
In small rooms, especially in dedicated spaces for performance or reproduction of music or speech e.g. in control rooms and studios, special attention must be given to the low frequency behavior. For room acoustic planning and analysis tasks it is very convenient and common to use tools for prediction and visualization of these characteristics.

Generally the approaches for the computer aided prediction of room acoustics can be divided into geometry-based and wave-based methods. A historical overview is given in [1], implementations and the usage of geometry-based methods are discussed e.g. by Rindel [2] and Vorländer [3]. The lower limit for the applicability of those algorithms is roughly given by the Schroeder frequency, which is an indication for the density of eigenmodes in the room. For small rooms the Schroeder frequency can easily exceed 200 Hz, which is why the modal behavior becomes crucial for the low frequency characteristics of the room. An analysis based on the wave theory needs to be implemented, considering these eigenmodes. A comprehensive review on sound fields in small rooms can be found in [4]. The underlying wave theory has been described in detail, e.g. by Kuttruff [5]. For simple geometries the solutions for the wave equation can be found analytically, but in general numerical methods will be needed. The finite element method (FEM) is frequently being applied. Numerous implementations of this method and studies about their application have already been made. Some

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practical aspects of different variations of the method in terms of complexity are discussed in [6]. A study on detailed FEM simulations using an accurate room model is documented in [7], with focus on the boundary conditions.

However, for the room acoustic planning process and the analysis of small rooms, in many cases a prognosis of exact low-frequency responses is neither practical nor necessary. A lot of details like wall materials, position of speakers and listeners, type of equipment or furniture would have to be defined. Often in the course of projects it is not possible or highly speculative to do so. Furthermore for all the boundary conditions the acoustic data for the lower frequency range needs to be collected with adequate accuracy, meaning measured or calculated with appropriate models. In practice however often the primary need is to identify and localize weaknesses in the low frequency behavior of a room and to geometrically visualize it in order to design measures, rather than to simulate the actual effect of these measures.

In this paper a feasible approach for the efficient analysis and visualization of low frequency issues in rooms will be described. The software tool implementing this approach has been in use for about five years now, successfully helping to analyze problems in a diversity of rooms and to optimize room layouts and acoustic measures. The method uses simplified boundary conditions in order to limit the amount of required input data and the complexity of the simulation. The convenient handling of course is paid for by a loss of accuracy. In this study a set of measurements in an intentionally non-ideal environment has been evaluated and compared to simulations of the ideal conditions. The aim of this study is a qualitative statement about the degree of accuracy, up to which the simulation method provides reliable results. The considerations are concluded by some practical views on the application.

2. METHODS

2.1 Software Tool

The simulation tool is based on the principle, that in closed spaces the wave equation can only be solved for discrete frequencies, the eigenvalues. The corresponding solutions are called eigenfunctions, and the sound field in the room is built by a superposition of these functions. [5]

The implementation is done in Matlab, its principle, illustrated in Figure 1, will be described in the following.

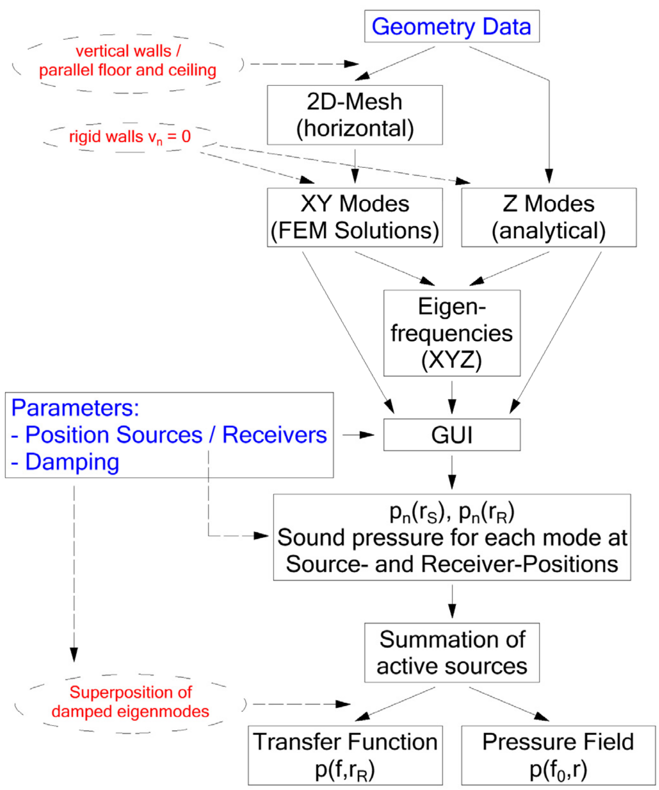

Figure 1 – Principle of simulation method

For the determination of the eigenfunctions of a geometry some assumptions and limitations to the general case are made in order to simplify the calculation. The geometry needs to have parallel floor and ceiling, and walls perpendicular to the floor. The boundary condition for all walls is set as rigid. Due to the orthogonal shape, the problem can be separated into a two-dimensional part in the horizontal plane and a separate formulation for the vertical axis. While the vertical solutions can easily be described by a row of cosine functions, the eigenfunctions for the horizontal shape need to be found numerically. The three-dimensional eigenvalues and -functions are determined as combinations from the two sets of solutions.

At the specified positions for sources and receivers the sound pressure is calculated for all the resulting eigenfrequencies. By superposition of all modes the resulting steady state sound pressure at a receiver position excited by a number of source positions for a frequency vector is calculated, being the transfer function; accordingly the spatial sound pressure distribution is determined for a specific frequency. In case of rigid walls, as assumed earlier, there is no damping of the modes. However in order to get a realistic overlap between the modes and have them make their contribution to the pressure field in a frequency band around the actual eigenfrequency, damping must be introduced. This is done by the parameter of decay time, which corresponds to an average damping.

2.2 Measurements

In context of a project a booth has been surveyed as a possible housing of a monitor room. In the course of this examination dedicated low frequency measurements were performed with regard to a comparison to the corresponding simulations.

The dimensions of the room were 6.45 m x 2.25 m x 2.43 m (LxWxH), which makes a ground area of 14.5 m^2 and a volume of 35.3 m^3. The floor was carpeted with approx. 5 mm of needle felt. The metal ceiling was perforated with an Rd 3-5 pattern. The wall surface consisted of metal panels approx. 1 m wide.

The measurements were performed using a Norsonic Nor 1225 capsule on a Microtech Gefell MV 220 preamp. The measurement system used B&K's Dirac running on MS Windows XP and an RME Fireface 400 audio interface. For the low frequency measurements a logarithmic sweep (degree 20, length 21.8 s) from 20 Hz to 200 Hz was used for excitation through a JBL EON Power15 loudspeaker. Two sets of measurements were performed with this setup, one set with a fixed loudspeaker position and 5 x 6 microphone positions (see Figure 2), a second set with a fixed microphone position and three loudspeaker positions (see Figure 3). All loudspeaker positions were on the floor. As a reference for the respective source position the impulse responses are measured in front of the membrane and in front of the resonance port of the speaker cabinet at each loudspeaker position.

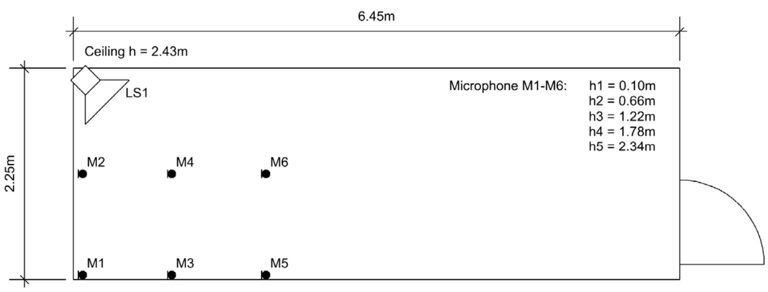

Figure 2 – Measurement positions (Set 1)

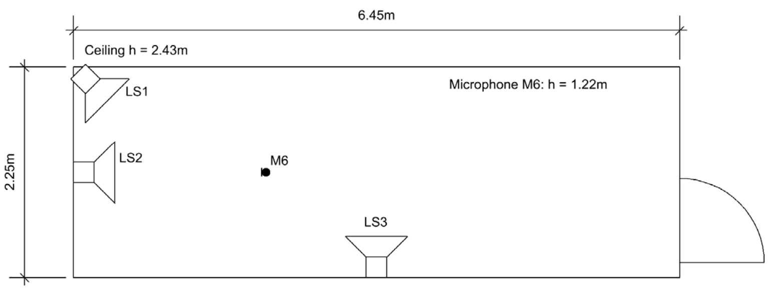

Figure 3 – Measurement positions (Set 2)

In addition conventional broadband room acoustic measurements were performed with a Norsonic Nor 276 dodecahedron and a logarithmic sweep (degree 19, length 10.9 s) for 2 x 8 combinations of speaker and microphone positions.

3. RESULTS

From the broadband room acoustic measurements decay times were determined. Table 1 shows the averaged values for the third octave bands from 50 Hz to 200 Hz and the standard deviation of the averaged positions.[2]

Table 1 – Decay times

3rd octave band [Hz]	50	63	80	100	125	160	200
T_{30} [s]	0.48	0.44	0.38	0.47	0.58	0.67	0.69
Std Deviation [s]	0.09	0.04	0.07	0.05	0.06	0.05	0.07

Apparently the room boundaries cause a significant damping in the low frequencies. The metal panels building the wall surface supposedly act as membranes, and the perforated ceiling will do its work at least from the low mid frequencies upwards.

The frequency response at each microphone position is referenced to the frequency response at the respective speaker position. Neglecting the dimensions of the speaker cabinet, this is interpreted as the transfer functions between pairs of source and receiver positions. Geometry and positions are fed into the simulation tool, along with an average decay time of 0.5 s. The results for a selection of measurement points are shown in Figure 4. Each graph contains the measured transfer function (blue) from the loudspeaker position (LS1) to the respective microphone position and the corresponding simulated curve (green). The results are chosen from the first set of measurements according to Figure 2. On the left side of Figure 4 the six horizontal positions at a height of 1.22 m are evaluated (labeled L1_M1_H3 - L1_M6_H3), on the right side the five levels are evaluated for position M4 (labeled L1_M4_H1 - L1_M4_H5).

[2] The frequency range considered is by definition at least partly situated below the Schroeder frequency, so curved decay slopes have to be expected, depending on the distribution of damping constants over the frequency range as well as strong spatial fluctuations of the sound field. [4] So the values listed here shall not be read like the statistical reverberation, but rather allow a cautious estimate of the average damping within a frequency range.

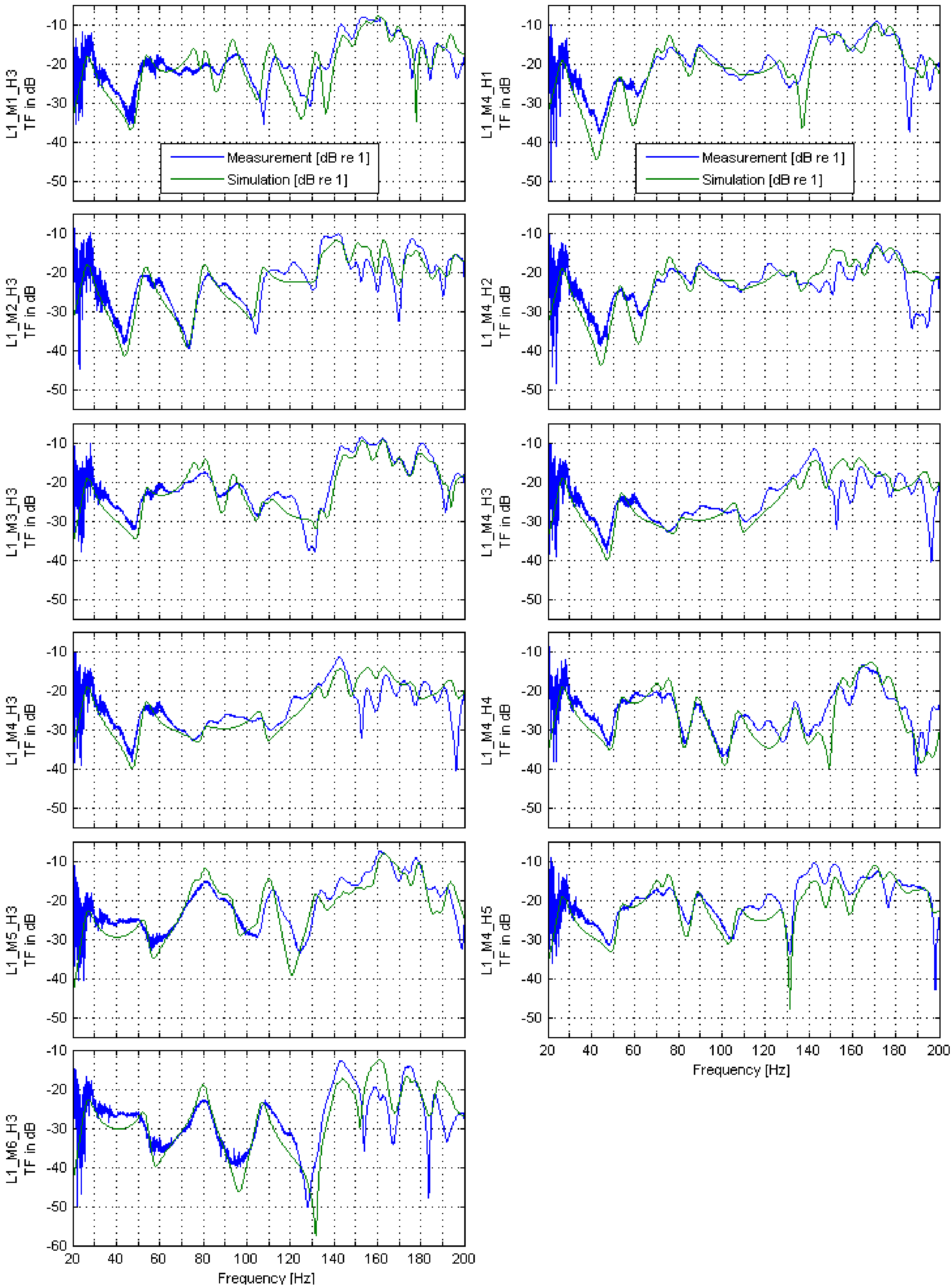

Figure 4 – Transfer functions measured (blue) and simulated (green), measurement set 1 (LS1)

Left: positions M1 – M6 at height h3 = 1.22 m

Right: position M4 at heights h1 – h5 (see overview in Figure 2)

4. DISCUSSION

The simulated transfer functions can mostly reproduce the basic shape of the measured curves. Until about 100 Hz many of the modal details are matched. Here the damping in the simulation seems to be slightly underestimated. For the upper half of the frequency range however the deviations become more significant, and maybe more importantly, their randomness. Some segments show good correlation also at high frequencies, whereas in some parts the peaks differ by 10 dB or more. Even opposed deflections must be observed at some points. However the envelopes still show good agreement also for the upper part of the frequency range.

To some degree, and increasingly with frequency, the deviations and contrary peaks could be caused by the fact that the loudspeaker used for the measurements is not at all a point source, as assumed for the calculations. The cabinet has spatial dimensions, the reference measurements have been performed at a certain distance of the membrane and the port, which themselves have dimensions and frequency responses with phase differences. These are basically boundary conditions, which are not considered in the simulation.

The other major cause for the differences between measurement and simulation is assumed to be the simplification of the boundary conditions for the room surfaces in the simulation as described along with the method. The surfaces in the measured room are not rigid, but have a complex reflection factor, which will shift the spatial characteristics of the discrete modes. The damping that was assumed uniform for the addition of modal components, in reality is different for each eigenmode. Through the complex superposition of modes, whose number increases with frequency, the fluctuations of the sound pressure at a specific point differ from those simulated.[5]

As described earlier, both of these shortcomings of the simulation method have been chosen for practical reasons, namely the simplification of the 3D model by ignoring details like loudspeakers or furniture in general, as well as the reduction of boundary conditions by assuming uniformly rigid walls respectively a uniform damping. Despite these shortcomings, the results achieved with this method are accurate enough to extract the desired characteristics of the wave field in a given geometry, like the pronounced low frequency modes, or the characteristic course of the transfer function towards the Schroeder frequency for a particular receiver point.

5. PRACTICE

As mentioned before, in practice the most important information attained from the simulations will be the identification of single peaks in the lower part of the considered frequency range, their extends and their spatial characteristics, and in the upper part of the frequency range the course of the transfer function due to cumulation of modes. In both cases the visualization is a central aspect of the application for the design and placement of appropriate measures. So in addition to the results discussed before, a short example will be constructed from the case analyzed by the measurements.

Let's take position M6 at a height of 1.22 m, which is about a possible listening position for the monitor room. In the corresponding plot in Figure 4, the last graphic in the left column, one can see the strong fluctuations in the sound pressure up to 140 Hz, which are caused by the discrete low order modes, which have little overlap and therefore leave wide dips in between.

Figure 5 shows the wave field at 80 Hz for excitation at the loudspeaker position LS1 as measured (left), and for simultaneous excitation at three positions (right).[3] The spatial distribution of the pressure can be seen, and thus the maxima on the room surfaces. This is where room acoustic measures for this frequency can be most effectively positioned. Also shifting source and receiver towards minima or maxima of a particular frequency can be a way to manipulate field and transmission. Furthermore additional sources can be positioned to alter the excitation of the wave field. This is done as an exemplary modification of the original situation. In Figure 5 on the right the generated field is illustrated for 80 Hz. By creating symmetric excitation and positioning additional sources close to the minimum of the main mode, the overall excitation of the mode is reduced drastically.

[3] Each picture contains the mapping for the xy plane at receiver height and in z direction at the receiver position. The receiver is marked as a circle, the excitation points are visualized as star shaped markers.

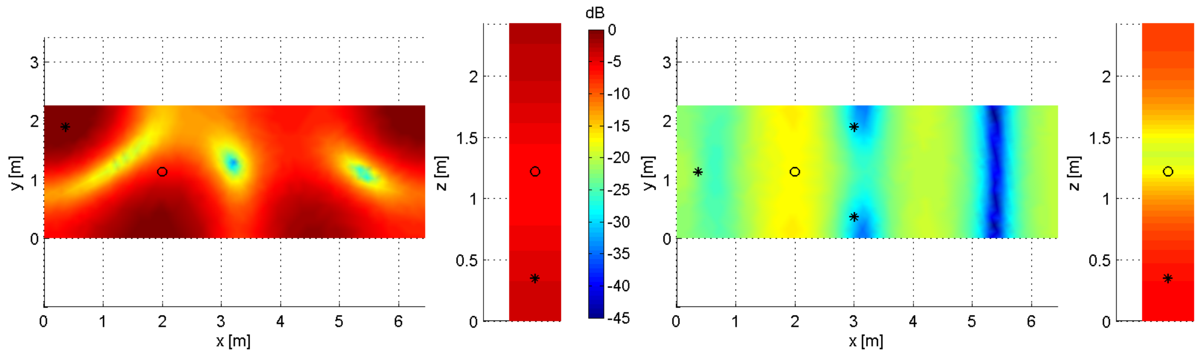

Figure 5 – Wave field horizontal and vertical at 80 Hz for excitation points LS1 (left) and LS2-4 (right)

The next frequency to be considered could be 97 Hz, where the original frequency response for source position LS1 has a severe dip. The reason for that can be observed in the mappings in Figure 6 on the left. The receiver is situated in the minimum of the horizontal pressure distribution. Through simultaneous excitation at the three source points as introduced above, the wave field can be shifted completely, so the receiver now lies close to a maximum.

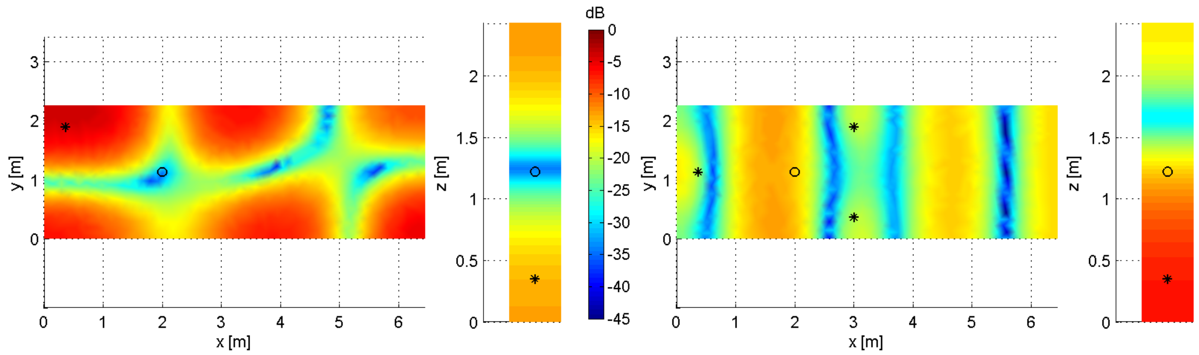

Figure 6 – Wave field horizontal and vertical at 97 Hz for excitation points LS1 (left) and LS2-4 (right)

In Figure 7 the simulated transfer functions can be compared, the original situation (blue) and the exemplary modification with three sources (green).

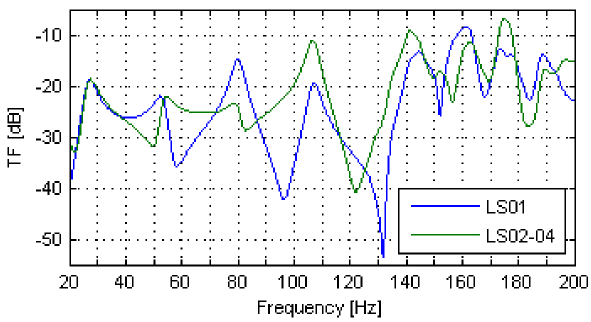

Figure 7 – Transfer functions for excitation points LS1 (blue) and LS2 plus LS3-4 (green)

Up to approximately 100 Hz the frequency response has become smoother. Around this frequency the multiple excitation, implemented simply by subwoofers on the floor, would be crossfaded to the monitors, which now could be considered separately. Although the acoustic treatment of the room often needs to be independent of the exact layout to some degree, as the case may be, after considerations such as described before, one can more or less focus on the weak spots that remain.

6. CONCLUSIONS

An approach for the simulation and visualization of low frequency sound fields in rooms has been described, which over several years has proven to provide a practicable method for analysis and design tasks in room acoustics. An overview of the software implementation has been given, and the measures of simplification in favor of usability and efficiency have been looked at in terms of resulting limitations. Measurements with intentionally non-ideal conditions have been evaluated regarding these shortcomings. The results have shown certain frequency depended deviations, and they can be used to increase the awareness for the application of the method. But once again, the idea was to identify and localize weaknesses in the low frequency behavior of a room and to geometrically visualize it in order to design measures, not to simulate the actual effect of these measures. Considering this, one could rather state the degree of stability of the method regarding the simplifications made. In this practical context the closing chapter offered a short look at the usage of the visualization tool for room acoustic analysis and design tasks.

ACKNOWLEDGEMENTS

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