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Open measurements of edge diffraction from a noise barrier scale model

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ABSTRACT

Until today, all known simulation methods for the wave phenomenon of edge diffraction are just approximations, based on either Geometrical Acoustics or the numerical solving of the wave equation. Although these methods work fine for simple test scenarios and a certain frequency range, they fail to simulate the effect of diffraction in its whole complexity. This leads to false predictions especially for more complex geometries where the influence of multiple wave diffraction and sound scattering has to be taken into account as well. Consequently, huge effort is currently put into the development of improved simulation methods. Here, a basic need is an all-embracing validation of simulation results, which also includes the comparison with real-world measurements. Unfortunately, there is a lack of such data which is the reason why the Institute of Technical Acoustics (ITA), RWTH Aachen University, Germany, and the Centre for Quantifiable Quality of Service in Communication Systems (Q2S), NTNU Trondheim, Norway, have started an initiative called *openMeasurements*, which is aimed to be an internet platform for free acoustic measurement data of any kind, together with their respective simulation models (CAD-model, detailed information on sources and receivers, material data) and helpful tools. As initial step, various measurement series of a scaled-down model of a noise barrier were carried out. These series aim to give researches, developers, and common application users, the possibility to thoroughly test their prediction models of edge diffraction.

The measurements were carried out in a full anechoic chamber and a turntable was used to rotate the scale-model during the measurements in steps of one degree. The scale-model was constructed with a changeable ground layer in order to massively influence the object's acoustical properties and, thus, create measurement datasets that considerably differ. Here, datasets for five different ground layers were obtained: 3 absorbers, 1 rigid surface and 1 self-constructed skyline-diffuser. A skyline diffuser was chosen as it is a well reproducible geometrical pattern, which enables a simulation of sound scattering in two ways: stochastic and deterministic. In this contribution, detailed information on the measurement setup is given and measurement procedures are described thoroughly. Measurement uncertainties are briefly discussed and first comparisons with simulations are presented. All measurements together with geometrical models of the scale-model (with/without diffuser), detailed information on sources and receivers, material data (absorption- and scattering coefficients) and useful Matlab tools are freely available for download (www.openmeasurements.net).

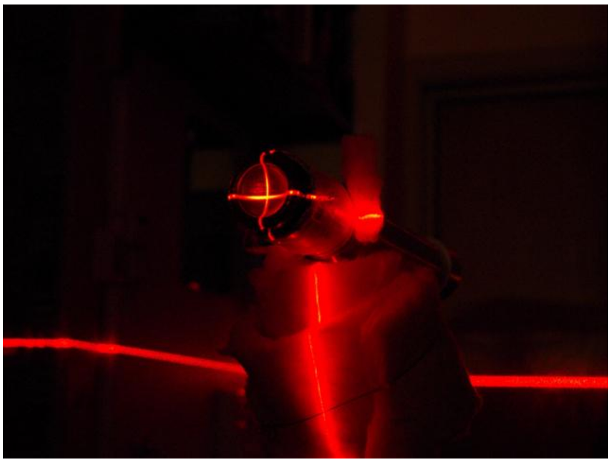
INTRODUCTION

Computer prediction methods need to be evaluated by comparing their results against measurements, and both complicated real-life cases such as auditoria or whole buildings, and specially-made test cases, are needed. In room acoustics, a sequence of International Round Robins was initiated by the third author in 1995 [1] for evaluating geometrical acoustics based prediction software. The modeling of diffraction in room acoustics has been evaluated mainly through simplified cases, [2-4], and the evaluation criteria have varied widely. For the radiation from loudspeakers, that is, the scattering from loudspeaker enclosures, diffraction-based modeling has also been compared against measurements [5, 6]. An obvious test case for diffraction modeling is noise barrier modeling, for which numerous evaluations have been presented. Two examples which used similar modeling techniques as in room acoustics are [7, 8]. Accurate measurements are required for the evaluation, but such measurements are very time consuming. Therefore, the sharing of measurement data might make future method developments much easier. Crucial for the usefulness of such sharing is that the methods and test cases are described well, and that it is made easy to access them. This project aims at such sharing, and also aims at presenting some test cases that have not been available before to the authors' knowledge: the combination of diffraction and scattering reflections. The following sections describe the measurement setups (presented also at BNAM 2010 [9]) and first comparisons with computer simulations are discussed.

EDGE DIFFRACTION MEASUREMENTS

This section gives a detailed description of how the measurements of edge diffraction from the noise barrier model were obtained in order to make them reproducible for anyone. This includes information on microphones, loudspeakers, mountings and the test object, as well as information on the applied measurement procedures. All measurement re-

(a) Measurement loudspeaker with omni-directional radiation pattern (ITA).



(b) Laser-aided alignment of the single-driver measurement loudspeaker (NTNU).

Figure 1. Loudspeakers and microphones that were used for the measurement series.

sults and additional data that is required by room acoustics simulation tools, such as material data (absorption- and scattering coefficients) and CAD-models of the noise barrier, is published on the *openMeasurements* website.

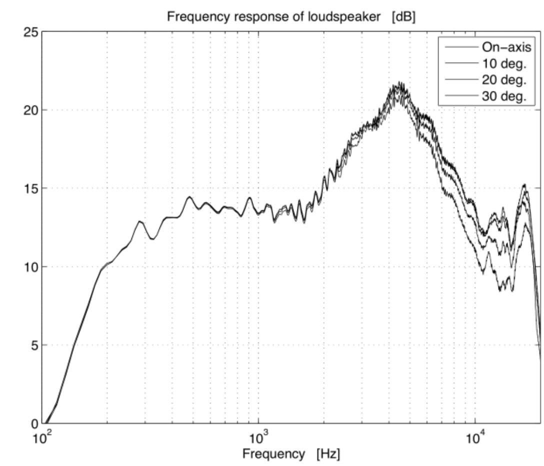
Measurement environment

The measurement setup was installed in the anechoic chamber at NTNU Trondheim, Norway. The chamber is equipped with sound absorbing wedges on all walls and provides free field characteristics down to a frequency of 75 Hz (room dimensions: 7.5m x 5.9m x 5.9m, 260 m^3). For installation purposes, the room features an L-shaped metal grid that is mounted to the floor by circular steel tubes. In this measurement setup, a removable rail system that connects the two platforms of the L-shape was additionally used to carry a Norsonic NOR265 turntable by means of a movable metal sled. The turntable was remote-controlled via an RS 232 interface from a standard PC outside the anechoic chamber. The same PC was used for performing the measurement series by means of the measurement software WinMLS. The tool was used to compute the excitation signal (exponential sweep, 2.73 sec long) that was then played back by a loudspeaker and recorded by two microphones at the same time in order to obtain the respective impulse responses. The measurement system consisted of two Brüel & Kjær (B&K) 4149 free-field equalized ½” microphone capsules with Norsonic 1201 preamplifiers, a Norsonic Frontend 336 microphone amplifier, a LynxTwo soundcard, a Quad 50E power amplifier, and two different measurement loudspeakers.

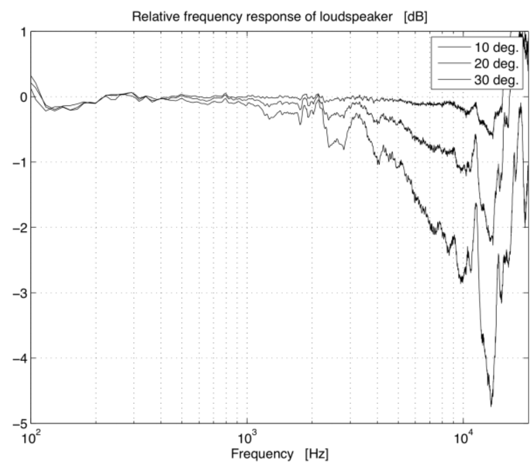
Measurement loudspeakers

Two loudspeakers with strongly differing directivities were used for the measurement series. The first series was carried out with the high frequency unit of a three-way measuring loudspeaker system with omni-directional radiation characteristics (see Figure.1a). The speaker was developed at the Institute of Technical Acoustics (ITA) and is designed as a PVC-sphere of 10 cm diameter equipped with 12 tweeters. The small cabinet is made possible by means of center-magnet drivers featuring neodymium with an overall diameter of only 36 mm. The unit radiates omni-directionally up to 5 kHz but has little output capability below 1 kHz. Above 5 kHz the loudspeaker directivity loses its spherical characteristics as it gets more and more dominated by the radiation pattern of each driver. More information on this high frequency unit together with a detailed description of the whole three-way loudspeaker system can be found in [10].

The second measurement series was carried out using the measurement loudspeaker developed by the acoustics group



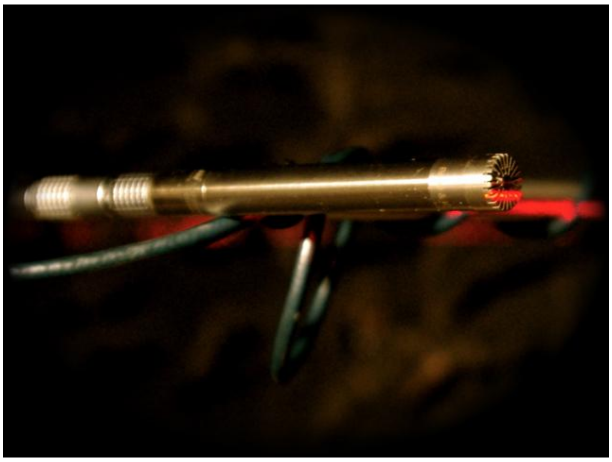
(a) Frequency responses for angles up to 30 degrees off-axis.



(b) Same as in Figure 2(a) but relative to the on-axis response.

Figure 2. Frequency responses of the single-driver NTNU loudspeaker, for angles up to 30 degrees off-axis.

(a) The stand is made from steel rods with polished surface making laser-aided alignment easy.



(b) The centers of the two microphones are in plane with the axis of the top rod.

Figure 3. T-shaped microphone stand with two microphone mounts and additional laser pointer device.

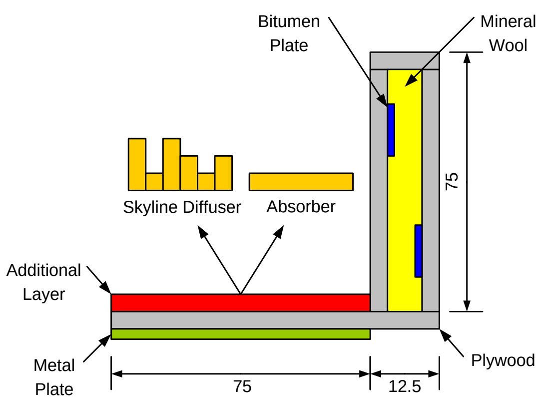
at NTNU. The unit consists of a single two-inch driver (Aurasound NSW2-326-8A-120) that is mounted at the end of a 37 cm long, 5 cm diameter PVC tube where the other end is closed. This loudspeaker covers a much broader frequency range than the previous one, from 200 Hz up to 20 kHz, caused by the larger excursion abilities of this two-inch driver, together with the smoothly increasing directivity of the single driver. However, the single driver system also demands for a very precise positioning to be able to model the directivity with high accuracy. For this reason, the loudspeaker features also a removable aiming device that functions like an iron sight of a rifle, but with a second notch instead of a bead. This enables an easy and very accurate adjustment of the loudspeaker along a laser ray that is shot from a target position (see Figure 1b). The directivity of the single-driver speaker is indicated by the frequency responses for various angles shown in Figure 2. For the specific scattering objects used in this study, radiation angles up to around 28 degrees off-axis will hit the object, but most parts of the scattering objects will be within angles up to around 15 degrees off-axis. Therefore, it can be seen that up to 5 kHz, the narrow-band level is within 0 to -1 dB. For slightly more relaxed requirements, the level is within 0 to -2 dB up to 8 kHz.

Measurement microphones

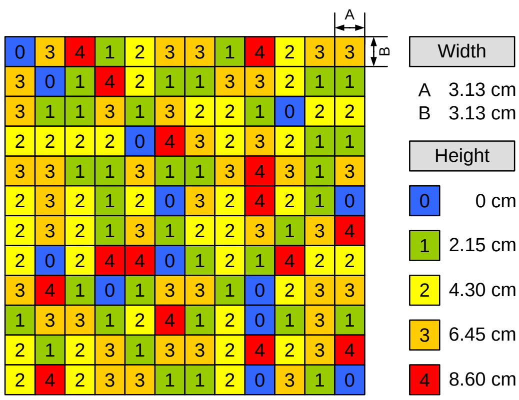
Two microphones were used to measure the respective impulse responses behind the noise barrier model. The microphones were calibrated to 94 dB at 1 kHz using a B&K 4231 calibrator. A special T-shaped microphone stand (see Figure 3a,b) was constructed to measure at two positions at the same time consisting of two steel rods where the top rod was perpendicular to the other rod and offered microphone mountings on each side with a total distance of 1 meter in between. In addition, a laser device was mounted on top of the stand, centered between the two microphones and pointing in parallel to their direction. The great benefit of this type of construction is that it enables an accurate alignment of the stand by means of both, a cross laser device that points from the target position to the top center of the stand (see Figure 3a) and the top-mounted laser device that points from the stand to the target position.

Scale model of a noise barrier

A 1:4 scale model of a simple noise barrier was constructed as test object. The model was basically a box with a perpendicular ground layer on one side, with both parts made from 15 mm plywood (see Figure 4a for a detailed construction plan). The box was filled up with mineral wool and 2 mm bitumen patches were attached to the box's inner faces to reduce vibrations. The outer faces were filled, sanded, primed, painted, and polished in order to maintain rigid and smooth surfaces. Additional layers were mounted on the ground layer in order to change the object's acoustical properties to a large degree and thus being able to generate measurement series that differ considerably.

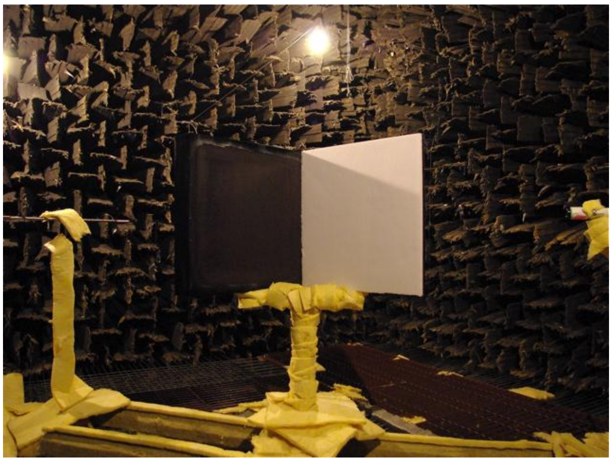


(a) Construction plan. Dimensions in cm.



(b) Column-pattern of the skyline diffuser.

Figure 4. Scale model of a simple noise barrier.



(a) Model with absorber as ground layer (white polyurethan foam slab).

(b) Model with skyline diffuser as ground layer.

Figure 5. Example measurement setups.

Four different layers were additionally attached during these measurement series: 3 absorber plates and 1 self-constructed skyline-diffuser. The absorbers were made from 25 mm and 50 mm slabs of polyurethan fibres, and fibreglass wool, respectively. The skyline-diffuser was designed to scatter uniformly in the frequency range from 2000 Hz to 5500 Hz. A single diffuser unit was assembled from 131 massive columns with the same quadratic cross section (3.13±0.05 cm edge length) and material (oak) but different heights (13 pieces of 0 cm, 38 pieces of 2.15 cm, 38 pieces of 4.30 cm, 40 pieces of 6.45 cm, and 15 pieces of 8.60 cm height, with an accuracy around 0.05 cm). This resulted in a 12 by 12 matrix with a total edge length of 37.5 cm following a special pattern that is shown in Figure 4b. To cover the whole ground layer four identical skyline diffuser units were constructed and mounted side-by-side with an overall weight of about 18 kg. Due to the large weight difference between the different cases, a 4 mm thick metal plate was mounted to the rear side of the ground layer for the non-diffuser cases in order to keep a balanced weight distribution across all cases.

Measurement procedures

The measurements were carried out in two subsequent phases. At first, the turntable, loudspeaker and calibrated microphones were installed inside the anechoic chamber using laser devices for accurate positioning. All mountings were covered with fibreglass wool strips, which were fine-tuned by analyzing trial measurements and reducing of unwanted reflections that came from certain reflecting parts.

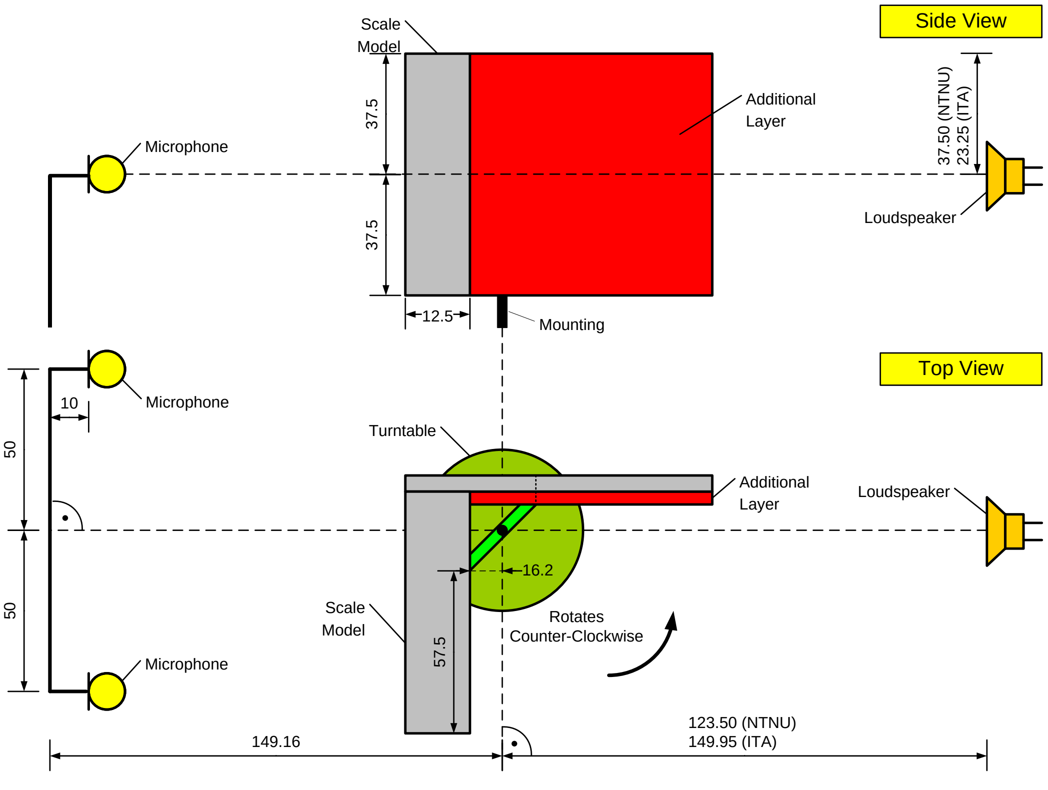
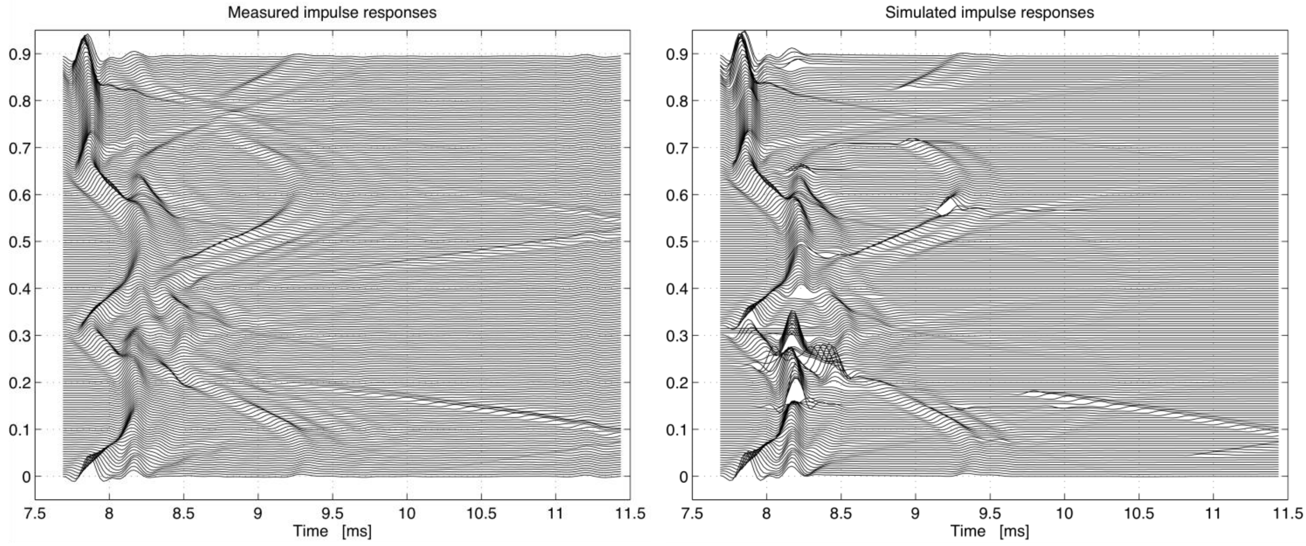


Figure 6. Assembly plan for the measurement setup. All dimensions are in cm.



(a) Measurements (b) Simulations, taking up to third-order diffraction into account.

Figure 7. Measured and simulated impulse responses, bandpass filtered between 282 Hz and 7.08 kHz, corresponding to the 1/3 octave band range of 315 Hz – 6.3 kHz.

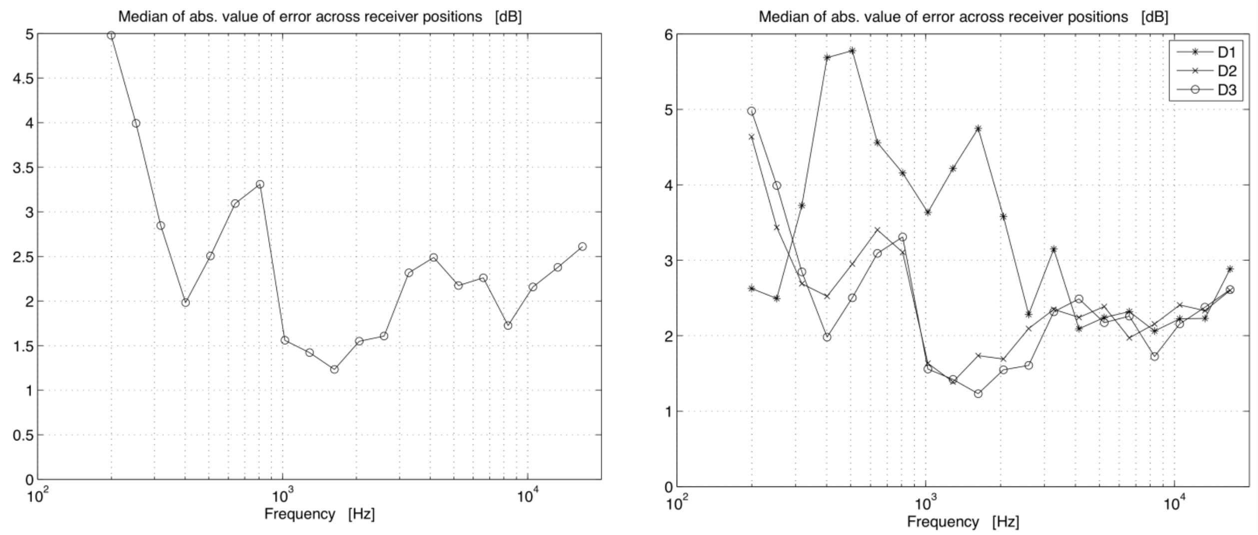
These measurements were also used for an additional check-up of the setup by comparing level and time of the first arriving impulse (direct sound) at both microphone positions. As the distance from the loudspeaker to both microphones was equal, these impulse responses had to be very similar. After optimizing the setup, 'free field' measurements were carried out for both loudspeakers in order to construct inverse equalization filters that are required for removing the influence of the loudspeaker response from the measurements. Then the scale model was attached to the turntable using a special mounting that provided a balanced and stable revolution around the model's rotation axis. Fibreglass wool was additionally wrapped around this mounting to reduce unwanted reflections. An assembly plan of the measurement setup is shown in Figure 6.

During phase two the actual measurements of scattering/diffraction from the scale model were carried out. The measurements were divided in 2 main series, one using the ITA loudspeaker and one using the NTNU loudspeaker. Each main series consisted of 5 sub series with different model setups: (1) no additional ground layer (rigid surface), (2-4) absorbing ground layers (soft edges), and (5) scattering ground layer (skyline diffuser). Figure 5 shows two measurement setup examples, one with an absorbing ground layer and one using the skyline diffusers. The turntable rotated the model counter-clockwise in steps of one degree with a pause of 10 secs between each measurement to ensure that the model had reached a stable position. This resulted in 360 measurements for each microphone per sub series, where the model's initial position (0 degree) is shown in Figure 6.

EXAMPLE OF COMPARISONS WITH SIMULATIONS

The measurements described above were compared with simulations as a test example of how this set of benchmark measurements might be used. Simulations were done using the Edge Diffraction Toolbox [11] in Matlab. In a first simulation series, the all-rigid case with no additional layer was studied. The room temperature was measured to 17 °C and the speed of sound was set accordingly in the simulations. The source and the microphones were modeled as omnidirectional and specular reflections together with diffraction up to third order were included in the simulations. Simulations were made for rotations steps of two degrees and consequently generated 180 impulse responses for a full-circle-rotation. Measured and simulated impulse responses were then compared, as presented in Figure 7. These diagrams show bandpass filtered IRs, in the range of 282 Hz – 7.08 kHz, corresponding to the 1/3-octave band range of 315 Hz to 6.3 kHz. The IRs are plotted in a stacked fashion where each IR is displaced vertically in order to create a view where individual wavefronts can be observed, in a similar way as in [4]. Generally, the simulations are close to the measured responses, but a few problematic areas can be observed. These problematic areas typically arise where higher-order diffraction would have been needed. In addition, the numerical implementation of the higher-order diffraction is such that singularities cause numerical problems whenever a source or receiver is aligned with the surface that connects two edges. Furthermore, the presence of the mounting stand in the measurement setup led to some scattering and modified the diffracted waves of the lower edges even though it was covered with absorbers. The stand was not included in the computer model and consequently, some deviations between measurements and simulations are caused by this.

A quantitative analysis was done by Fourier transforming the impulse responses, and computing 1/3-octave band levels for the measurements and simulations alike. Only the displayed part of the IRs, i.e., a length of 3.7 ms, were used for the FFT. Thirteen 1/3-octave band levels were compared for the 180 receiver positions. This leads to a distribution of errors, or deviations, that can be presented and analyzed in various ways. As a single-number accuracy indicator, the median values of those deviations are presented below. The median is chosen rather than the mean value since there are a number of positions where there are very large deviations, and this leads to a very non-symmetrical distribution of the level deviations. Median values are better representatives than mean values for such distributions. Figure 8 (a) shows the median deviation between measurements and simulations as a function of frequency. The frequency range of 1- 2.5 kHz reaches the closest correspondence between simulations and measurements with a median level error around 1.5 dB. The error increases significantly for the lowest frequency bands of 200 Hz and 250 Hz, and this is primarily due to a lack of higher orders of



(a) Simulations included diffraction up to third order.

(b) Parameters D1, D2, D3 indicate the maximum diffraction order in the simulations.

Figure 8. Median value of the absolute value of the deviation between measurements and simulations as function of frequency.

diffraction. The influence of the order of diffraction is illustrated in Figure 8(b), where it can be seen that the inclusion of second-order diffraction order has a substantial effect on the accuracy of the simulations. Interestingly, from around 4 kHz, diffraction orders above first order have little influence in general. It should be pointed out that while the median value gives a good indication of the general performance, there might be receiver positions where higher diffraction orders would improve the accuracy also at high frequencies. Prior to the comparison of measurements and simulations, it was checked whether the intended angle of zero degrees in the measurement setup lead to the minimum deviation (between measurements and simulations). It was then found that the best fit resulted when there was a one degree shift, that is, the intended angle zero in the measurement setup was actually closer to -1 degree. A comparison like this is very useful for developing simulation software – for identifying potential bugs, numerically problematic areas, and areas where algorithms need improvements.

THE OPENMEASUREMENTS WEBSITE

The initiative *openMeasurements* is aimed to be an Internet platform for free high-quality acoustic measurement data of any kind that could be helpful for researches, developers, and application users. The platform provides not only the measurements themselves, but also detailed information on how measurements were carried out, additional data such as CAD-models and their respective material data, and useful tools for simulation, analysis and modelling purpose. The website is hosted by the first author and everyone is encouraged to contribute to this project.

As initial step, the following data will be available on launch day, which is scheduled for summer 2010:

- Measurements of edge diffraction from a noise barrier model as described above. This includes also CAD-models of the setup, material and temperature information, and Matlab scripts for generating skyline diffuser geometries and analysing measurement data.
- The Edge Diffraction Toolbox by Peter Svensson [11].
- Measurements of scattering coefficients of everyday furniture such as tables and chairs [12].
- Data on directional patterns of dummy heads and natural sound sources. These datasets are stored in the OpenDAFF format [13] where a detailed description of the data format together with Matlab/C++ import functions will be available on the website.

SUMMARY & OUTLOOK

In this contribution a series of measurements of edge diffraction from a noise barrier scale model was described. This included detailed information on the applied measurement equipment, the scale model and a description of the measurement series. All data presented here, as well as helpful tools and additional setup information such as absorption- and scattering coefficients of the used materials, are available online on the *openMeasurements* website as an initial step. The initiators encourage everyone to contribute to this project with their own measurements in order to create an all-embracing online source for acoustical measurements.

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