Predictive Auralization of Room Modifications by the Adaptation of Measured Room Impulse Responses

Christoph Pörschmann[1], Sebastian Schmitter[2], Aline Jaritz[3]
[1]*Fachhochschule Köln, 50679 Köln, E-mail: Christoph.Poerschmann@fh-koeln.de*
[2]*windtest Grevenbroich, s.schmitter@windtest-nrw.de*
[3]*Fachhochschule Köln, 50679 Köln, E-mail: aline.jaritz@smail.fh-koeln.de*

Introduction

When optimizing the acoustics of an existing room it is helpful to auralize the implications of an intended constructional change. Especially for the customer who is often not an expert in room acoustics the possibility to hear the impact of a planned room modification is valuable. Even though methods are available which are based on geometrical models and which perform a simulation of the sound field they are for different reasons not commonly used for auralizing the expected results. On the one hand the auralization performance typically deviates considerably from an auralization based on measurements after the constructional change.

In the presented study it is investigated to what extent a measured binaural room impulse response can be appropriately adapted in order to plausibly auralize an intended constructional change of a room. Often the geometric structure is only slightly varied; the main modification affects the absorption of the walls. In such a case the fine structure of a room impulse response is sustained, only the envelope, typically described by a frequency-dependent reverberation time is changed.

In the first section a specific algorithm to perform a modification of a measured binaural impulse response is described. In the second section the results of a psychoacoustic evaluation of the algorithm are being illustrated. For that purpose measurements of binaural impulse responses have been performed in two different rooms before and after a room acoustic modification. In parallel in order to simulate the constructional change an alternative set of impulse responses was generated applying the algorithm to the original measured impulse response of the unmodified room.

Within a psychoacoustic experiment the perceptual differences between the measured impulse responses and the calculated ones is being investigated. Finally, the results of this experiment are presented which show to what extent a plausible auralization of the intended room modification based on measured binaural impulse responses can be obtained.

Algorithm

An algorithm is described which modifies the energy of the binaural impulse response according to an intended room modification.

Such a modification of the diffuse part of a binaural impulse response according to an intended constructional change of a room can be performed without any perceptual differences. The results of several psychoacoustic studies have shown that the diffuse part can be regarded as spectrally shaped noise which frequency dependently decreases in energy [1][2][3]. The reverberation time T_{60} is the appropriate measure to describe this energy decrease.

A plausible modification of the early reflections demands for a more sophisticated procedure. As early reflections have strong influence on the perception of a room, applying a statistically-based modification of these reflections leads to perceptible differences between a measured impulse response and a calculated version. However, in the following such a modification of the early reflections according to a statistical model is investigated. This statistical model treats all reflections in the same way and is equivalent to equipping all the room's boundaries with the same additional absorption.

According to the well-known Sabine's equation [4] it is possible to calculate the room's reverberation based on geometric parameters (volume, total surface area) and the average room absorption coefficient. Originally this equation has been set up for rectangular rooms, but it is widely used for different room geometries.

$$T_{60} = 0.163 \frac{s}{m} \frac{V}{\alpha A} \qquad (1)$$

V: Room volume in m³

A: Total surface of room in m²

α: Average absorption coefficient

Furthermore, this equation can be applied in order to calculate the resulting reverberation time when a constructional change of a room is planned. Therefore in a first step the reverberation time before a constructional change is measured. Applying Sabine's equation the average absorption coefficient α_{pre} is determined.

$$\alpha_{pre} = 0.163 \frac{s}{m} \frac{V}{T_{60,pre} A} \qquad (2)$$

Then the additional absorption α_{add} can be added and the reverberation time $T_{60,post}$ after the room modification can be calculated.

$$\alpha_{post} = \alpha_{pre} + \alpha_{add} \qquad (3)$$

$$T_{60,post} = 0.163 \frac{s}{m} \frac{V}{\alpha_{post} A} \qquad (4)$$

Applying the measured binaural room impulse response and the measured (frequency-dependent) reverberation time a calculation of the binaural impulse response after the constructional change is possible. The following figure shows the basic structure of the algorithm.

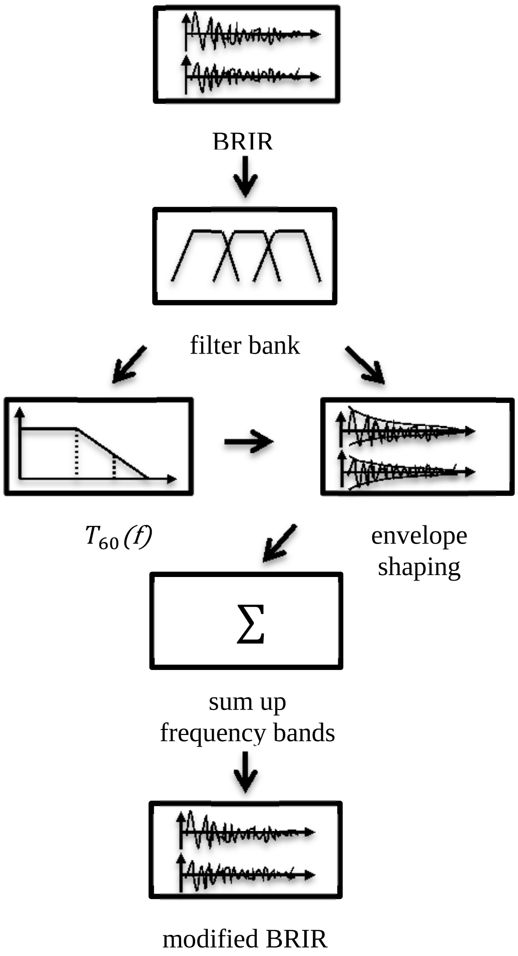

Figure 1: Basic structure of the algorithm. In a first step the BRIR is splitted up in a number of frequency bands by applying a filter bank. For each frequency band the reverberation time is determined and the envelope is shaped according to the intended room modifications. Finally by summing up all frequency bands a modified BRIR is obtained.

The algorithm performs the following steps: First the incidence time of the direct sound is determined from the impulse response. Then the signal is decomposed in several frequency bands (1/3 octave) applying a nearly perfect reconstruction filter bank.

In order to meet the target reverberation time the envelope of each frequency band is adapted. The algorithm reshapes the envelope while maintaining the fine structure of the room's impulse response. The modification of the envelope starts directly (5 ms) after the direct sound peak t_d in the impulse response. The attenuation factor δ_{red} can be calculated to

$$\delta_{red}(t)\,[dB] = -60\left(\frac{1}{T_{60,post}} - \frac{1}{T_{60,pre}}\right)(t - t_d) \qquad (5)$$

The modified binaural room impulse response is gained by summing up all the frequency bands. Of course this simple modification of the room impulse response is not capable of anticipating the exact effects of the constructional change. All estimations are just statistically motivated which means that the energy of all room reflections is reduced in the same way. A more specific modelling of the additional absorption surfaces is not possible in this approach.

However, auralizing the room modifications as described here creates a plausible perception of the intended constructional modification of the room.

Measurements

In order to evaluate the performance of the algorithm, binaural room impulse responses and reverberation times were measured in two different rooms. The measurement procedure for both rooms was the same. However the loudspeaker and artificial heads were different. The recordings of the binaural room impulse responses were done in Room No 1 using an artificial head from Head acoustic (HMS II.3) and the room was excited with a Genelec 1029A. In Room No 2 the measurements were performed with a Neumann KU100 artificial head and an ADFlex 15 loudspeaker from AD-Systems. For each room 6 modifications were assessed to be tested in the psychoacoustic experiment. In each room additional absorption material was implemented in consecutive steps.

Room 1 has a volume of 80 m³ and a total surface of about 119 m². It is located at windtest Grevenbroich and used as a meeting room. Only one type of absorbers was used here. A different numbers of absorbers were implemented; between 1m² and 6m² of the room were covered with absorbers. The reverberation times of the room are shown in Figure 2.

Room 2 (84 m² total surface; 51 m³ volume) is a room in the Laboratory of Architecture at University of Applied Sciences in Cologne and is used for measurements in the area of building acoustics. In order to keep the room acoustically pleasant the room already was equipped with a low-frequency absorber of the size 2.2 m² during all measurements. The reverberation of the room is shown in Figure 3. In Room 2 the sound source and the receiver were positioned at a distance of about 2 m. Here only two absorbers (3.4 m² and 14.3m²) were added in order to modify the room acoustics. Furthermore, different incidence directions (0°, 45°, 90°) were assessed.

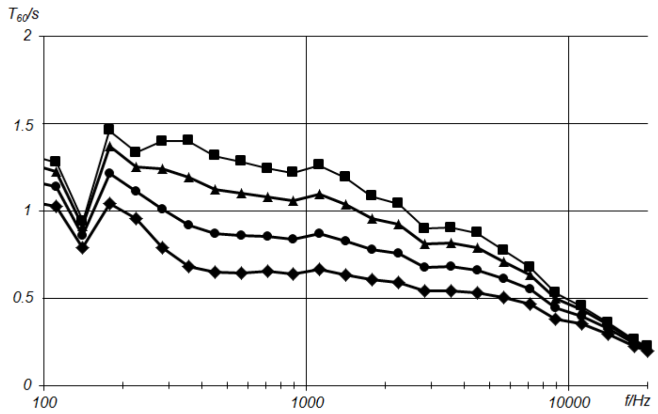

Figure 2: Reverberation times of Room No 1: The room is located at windtest Grevenbroich and is used as a meeting room. In the diagram the reverberation times of the non-modified room (rectangles) and after inserting 1 m², 3m² and 6m² of absorbers (triangles, circles, diamonds) is being shown.

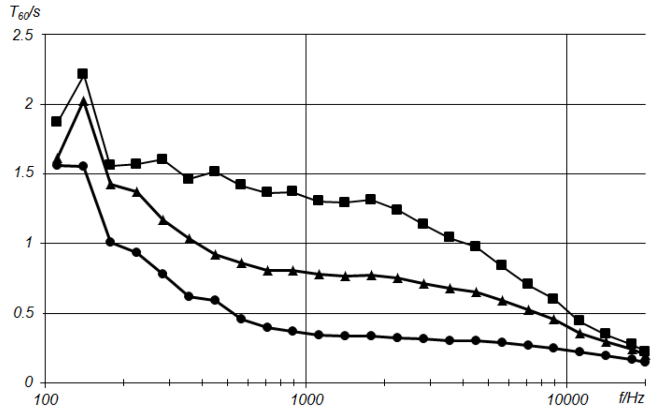

Figure 3: Reverberation times of Room No 2: The room is located at the Laboratory of Architecture at Cologne University of Applied Sciences and is used for performing building acoustic measurements. In the diagram the reverberation times of the non-modified room (rectangles) and after inserting 3.4 m² and 14.3m² of absorbers (triangles, circles) is being shown.

Finally the absorption coefficients of the absorption materials were determined in measurements in the reverberation chamber at the laboratory of Architecture at Cologne University of Applied Sciences.

Psychoacoustic Experiment

In order to evaluate the performance of the algorithm a psychoacoustic experiment according to ITU-R Recommendation BS.1116-1 [5] [7] was performed.

In a first step, outgoing from the binaural impulse responses of the not modified room and the measured absorption coefficients, the algorithm was applied and modified binaural room impulse responses were calculated. Thus two versions of impulse responses after the room modification exist: One which was measured in the respective room after the constructional change (reference), the other one which was artificially created based on the non-modified room.

As stimuli a short broad-band speech sample (German, female) and a sample of a drums sequence were selected. Comparable stimuli have already in previous experiments been identified as optimal for the evaluation of diffuse reverberation [2] [3].

For each room the measurements of six room modifications were considered in the test. Thus for each room 12 test conditions were tested.

Set-up and procedure

In order to evaluate the performance of the algorithm a psychoacoustic experiment according to ITU-R Recommendation BS.1116-1 [5] has been performed. The test was done applying the Software SCALE which has been developed at Cologne University of Applied Sciences for the performance of psychoacoustic experiments [8].

The psychoacoustic experiment took place in the Institute’s anechoic chamber. The sound pressure level in the room was below 30 dB(A). The stimuli were calibrated to equal loudness and were presented at an average SPL of 71.5 dB(A). Thus influences of background noise do not have to be considered.

The experiment started with an introduction phase, i.e. the scenarios were described (in oral and written form) and the set-up of the experiment was explained. Furthermore, the scale and the procedure itself were described to the subjects. At the end of each scenario the subjects were asked to rate the impairment of the stimuli B and C compared to the reference A. During the experiment the subjects knew that either B or C was a hidden reference. The subjects rated the impairment on a continuous rating scale; the categories are shown in Figure 4. Even though most of the subjects were native German speakers the categories were given in English as suggested in [5]. The subjects were asked to give their ratings as intuitively as possible, and not to compare the scores with those of the previous scenarios.

Then in order to give anchors regarding the differences between the stimuli in a training phase the subjects had to rate four examples. The experiment was divided in two sessions of each 12 conditions. Between the sessions the subjects had a pause of about 15 minutes.

Impairment	***Grade***
Imperceptible	*5.0*
Perceptible, but not annoying	*4.0*
Slightly annoying	*3.0*
Annoying	*2.0*
Very annoying	*1.0*

Figure 4: Scale for rating the impairment of the stimuli B and C compared to the reference A according to ITU-R Recommendation BS.1116-1. The subjects rated the impairments on a continuous rating scale.

The signals were presented by a set of closed AKG K271 MKII headphones. The subjects were allowed to listen to the stimuli as often as they wanted. 28 subjects aged between 23 and 64 participated in the experiment, four female and 24 male. All persons indicated that they had normal hearing ability. Only 25 % of them had experience with psychoacoustic experiments.

Results

The results are described according to the suggestions from [5]. Figure 5 shows the absolute mean grades for the calculated stimulus and the hidden reference. It can be observed that for the drums stimuli the impairment was higher than for the speech stimuli. As the observations cannot be regarded being statistically independent no confidence intervals can be given here.

ITU-R BS.1116-1 recommends the difference between the grades given to the hidden reference and the test stimulus as the appropriate input for statistical analyses as shown in Figure 6.

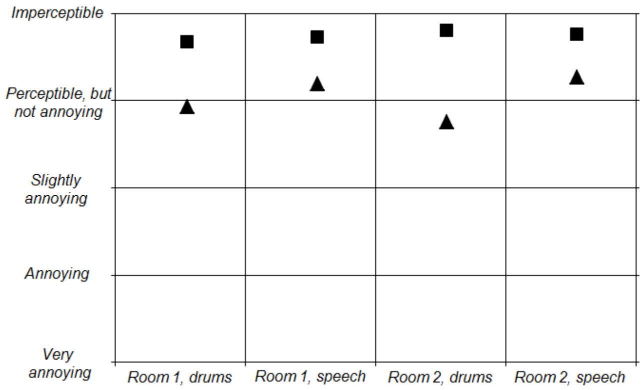

Figure 5: Absolute mean grades for the calculated stimuli (triangles) and the hidden reference (rectangles). Shown are the values for the two rooms separated for the drums and the speech stimulus.

Again the data is presented separately for the two stimuli types and for the two rooms. It is obvious that the differences were lower for the speech stimuli. A comparison of the conditions by means of a t-test showed that the differences between the loudspeaker stimuli and the voice stimuli are significant ($p > 0.95$). Comparing the two rooms significant differences were observed for the drums stimuli while the speech stimuli were not significantly different ($p<0.9$).

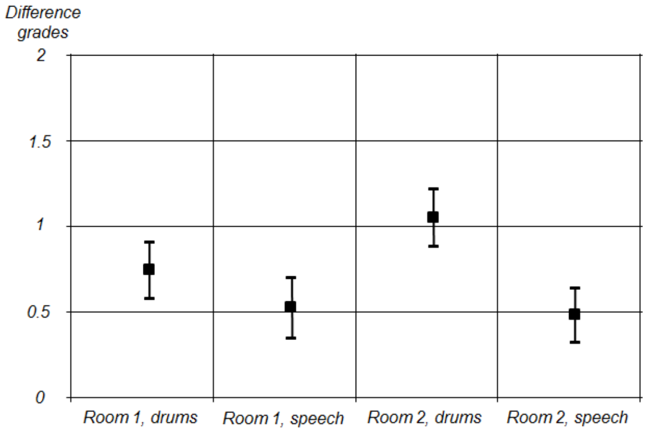

Figure 6: Differences between the grades of the hidden reference and the calculated stimuli. The values are separated for the two rooms and for the different stimuli types. Shown are the average values as well as the 95% confidence intervals.

Further investigations of the results were performed. In a first step it was tested based on the results of Room No 1 if a higher degradation can be observed with increasing additional absorption material. This seems to be plausible as the algorithm performs a stronger modification of the measured impulse response if the added absorption is higher. However no significant influence could be observed in this psychoacoustic experiment.

Finally it was tested, based on the scores of Room No 2, if the direction of sound incidence plays a significant role. No confirmation of this hypothesis could be found based on the data of this experiment.

Looking more generally at the results it can be observed that the differences between the scores of the estimations for the hidden references and the test stimuli are relatively low. Furthermore, most of the subjects commented the test as being very difficult and the differences between the stimuli were considered being small for most of the stimuli.

Conclusions

A specific but simple modification of the reverberation envelope of a binaural impulse response allows for the plausible auralization of an intended room modification. Not surprisingly the psychoacoustic experiments have confirmed that significant perceptual differences exist between the measured and the simulated stimuli. However, these differences which were measured based on the ITU-R BS.1116-1 [5] are relatively small and according to the subjects' comments a plausible perception of the modified room was achieved.

One interesting application of the developed algorithm is to give a customer the possibility to hear the impact of a planned room modification. Another application is to reconstruct the acoustics of historical rooms that have been modified over the years.

The results of this experiment form a starting point for further research in the field of the auralization of room modifications. A corresponding Research Project funded by the German Federal Ministry of Education and Research is proposed to start in summer 2013.

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