Room Acoustics in the Architectural Design Process

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Abstract. The basic principles, methods, and digital tools for the analysis of room acoustics are the topic of this paper. Students have been using these analysis and simulation tools during a seminar at Stuttgart University to systematically investigate acoustical situations. Additionally to lecturing on the underlying physics of room acoustics we were trying to convey the impact of geometry on room acoustics and therefore the impact of room acoustics on shapes in architecture. This paper describes the implementation of a real time simulation module for room acoustics within our Virtual Reality System.

Keywords: Room Acoustics; Virtual Reality; Design Tools; Education.

Introduction

The perception of space is realized by a combination of all human senses. Aristoteles said that the most important human sense that helps us to experience physical objects is the sense of touch. But he had also realised that the perception of space could not exist without the sense of vision and the sense of hearing. Nowadays, we know that even scent and taste can take part in our perceiving space. In this paper we will focus on the relevance of hearing to the perception of space.

The designing and shaping of the physical presence of space is the main field of architecture. Architecture joins materials, shape and utilization into a concluded object. The architect is responsible for the overall approach to geometry and the materials. Room acoustics, playing a very important role in the perception of space, is mainly influenced by these two aspects of geometry and material. Conclusively, it is of importance to include room acoustics in the early stages of the planning and the subject of room acoustics should be a part of the curriculum at university.

In this paper the basic principles, methods, and some digital tools for analyzing room acoustics are introduced and discussed. Throughout a number of seminars students investigated acoustical situations and halls using these digital tools. The aim was to not only convey the underlying physics of room acoustics, but also to study whether the actual tools for analysis are useful planning tools for architects. With this seminar we wanted to hone the students’ senses to the coherence of geometry and room acoustics, and to the implicit responsibility of architects to this subject.

“Room acoustics like light is a very important element in design, which helps to guarantee the well-being of each individual, in the sense of physical, psychological and social aspects.“ (Schricker, 2001)
Influencing characteristics

First, the basic relationships between sound, space, geometry, and their perception have to be introduced.

At a temperature of 20°C, sound travels through air at a speed of 343 m/s homogenously in all directions (Barron, 1993). The unit m/s itself already depicts that the phenomena consists of a spatial and a temporal component. The propagation of sound only occurs in a medium such as in air, in liquids or in solids, and the sonic energy decreases the farther the sound propagates through the medium. When a sound wave hits an object, it is normally reflected following the rule that the angle of the reflection is equal to the angle of incidence. The quality of the reflective surface defines the ratio of absorption and diffusion of the incoming sonic waves. The behavior of sound depends on its frequency. This means that the propagation of sound varies at different frequencies. This appears if we look at the dimensions of perceivable sound waves. Based on the equation $c_s = f \cdot \lambda$ ($c_s$: speed of sound, $f$: frequency, $\lambda$: wavelength), the wavelength of a tone at 1000 Hz equals 0.343 m. The length of the sound wave can thus be similar to the dimensions of objects or room elements. In this case the waves are no longer reflected but bent around the objects. This can be observed in the case of the lower frequency ranges, while in the high frequency range the waves behave more like light and are simply reflected. The sound absorption rate of a surface also depends on the frequency and has to be taken into account, too.

Additionally to the physics of sound the functionality of the human sense of hearing is important in order to fully understand room acoustics. Humans are able to perceive sound differing in intensity, space and time. The spatial localization occurs according to the law of Haas. The direction from where the first wave front is arriving is identified as the origin of the sound. The successive sonic energy which has the same content is perceived either as echo or as room volume. The human hearing is capable of a temporal resolution of about 5-10 msec. A significant energetic event after 50 ms is recognized as an echo. Haas used sound at the same energy level during his investigations about the temporal diversification. Due to the longer propagation route the energy intensity of the second signal is usually lower than that of the first signal. This leads to time shifts of up to 80 ms which are not perceived as echoes.

In the evaluation of room acoustics is not only the direct propagation of sound, but also the reflections in their temporal progression and their intensity that are crucial. Room acoustics depends on the room geometry. This seems to be a trivial observation, but it is the main focus of the following systematical evaluation because this is fundamental to the architect’s planning efforts.

The reflections of sonic energy are unique for each room and their sum creates the acoustical impression of the room. For a definition of the acoustical characteristics of a room the following characteristics are considered.

Reverberation Time (RT)

According to the equation of Sabine $RT_{60}[s] = 0.16 \cdot \frac{V[m^3]}{A[m^2]}$ the reverberation time describes the time that has elapsed while the level of an emitted sound has decreased about 60 dB. The room volume is represented by $V$, and the equivalent absorption area by $A$. The RT is the best known acoustic characteristic and a value used to measure the hall-effect. Rooms intended for speeches are designed to have reverberation times of about 0.5 to 1.0 s. Concert halls have ideal RTs of around 1.4 to 2.0 s, and churches often have RTs of around 3-4 s (Mehta, 1999). The RT is a statistical dimension and is valid for the whole room.

Impulse Response (IR), Impulse Diagram

The impulse diagram is the record of the sound pressure level over time, after the stimulating a room with an acoustic impulse. The impulse response and its corresponding diagram are characteristic for each position in the room. The IR diagram allows for
a differentiated overview on the incoming sonic energy at a specific position and time.

**Early decay time (EDT)**

EDT consists of a few isolated early reflections. EDT is sensitive to room geometry since early reflections are coming from identifiable surfaces in the room. Therefore like the impulse response the early decay time has to be considered separately for each position. The EDT is comparable to the reverberation time, but it is comprised only from identifiable reflections in the first phase of sound propagation. The EDT is usually defined at a difference in the sound pressure level of (-)10 or (-)15 dB. The clarity of a room is determined by these early reflections. Reflections during the first 80 ms raise...
the spatially differentiated perception of the field of sound and thereby its transparency. Subsequent reflections convey the impression of a spatial volume, because the signals overlap themselves and a distinguished perception is not possible any more. The sound field evolves and the signals add up.

**Soundfield, soundroses**

The number of reflections increases with an increasing travel time, whereas the energy level of the single signal decreases. The single rays blur to a homogenous sound field. The impression of the sound becomes more voluminous and pleasant the faster and the more homogenous the sound field is. The sound roses in Fig. 2 show the spatial distribution of incoming signals at a single position in a specified time period. The density of single sound events can thereby be estimated.

**Methods of Analysis and Representation**

There are different methods to systematically examine room acoustics. Apart from the individual hearing experience and its evaluation, objective physical parameters exist that can be measured or calculated. The present paper is limited to these objective parameters and ignores the evaluation of their psychoacoustic impacts on human sound perception.

A common and proven method of analyzing room acoustics is the ray tracing method. The manual drawing method follows the path of selected rays. Mainly minima and maxima of the spatial sound propagation are represented. In combination with ground plans and sections a qualitative evaluation of the dispersion is possible. This method gives no information about the signal’s energy level. When examined by people skilled in the art meaningful conclusions can be drawn.

With the capabilities of modern computer systems this method can be improved and more details can be included. It is possible to evaluate digital models 3-dimensionally. Therefore, an almost unlimited number of rays having a specified energy level can be emitted from a virtual source. Modified by the acoustically relevant surface properties like absorption or diffusion, the rays are traced and calculated. The result of this simulation shows each ray with its corresponding energy level. The sum of these rays creates the acoustical impression.

In Fig. 4 different ray paths can be observed, whereby the color represents the energy level of the signal. The calculation of a large number of such rays creates a more and more detailed impression of the acoustical situation.

The output of these simulations are diagrams containing all relevant data as described in the chapter above and which are necessary for the evaluation of the rooms. In addition to the graphical outputs of relevant acoustical events these programs are able to combine the acoustical properties of a room with a specific signal like a piece of music, thereby giving the possibility to listen to a specific acoustical situation. Such auralisations are done by CATT Acoustics (Dahlenbäck), EASE (Ahnert) or Ecotect (Marsh, Raines)

Nowadays these simulations and auralisations can be done in real time. A real time simulation tool for room acoustics was developed at the RWTH Aachen (Lentz et al, 2007). The main focus of the RAVEN (Room Acoustics for Virtual Environment) project is to create a realistic representation for room acoustics in real time. The system is able to
incorporate several sound sources simultaneously. The sound sources may be moved by the user during the simulation and the user can walk through the simulated environment like a natural person and can perceive the actual acoustical situation. Comparing the different situations is not easy, because they have smooth transitions. However, by combining the visual and the acoustical perceptions a plausible representation of the room can be given. When superposing the two perception levels which are similar to the experience in reality, the resulting perception of the room can be evaluated with respect to the congruency of the visual and acoustical room impression.

RAVEN / VA and COVISE/COVER

We were already hosting a virtual reality system at our laboratory. As we were not completely satisfied with the input interfaces of RAVEN / VA and the quality of its visual representation, we decided to combine our COVISE/COVER system and the acoustical simulation.

The required format for the RAVEN/VA system is AC3D from inivis (http://www.inivis.com/ac3d/man/ac3dfileformat.htm). Apart from the format not being according to the ISO standards and common CAAD software not supporting this format, an interaction with users as it is included in the VRML standard is not arranged for.

For the visual interactive real time representation of architecture we are using COVISE/COVER, software solutions that can interpret VRML files. The idea is to combine the visual and interactive abilities of the VRML standard and the sophisticated acoustical simulation of RAVEN/VA.

Conceptual Design

The system works with two models. The first one is a VRML model and is responsible for the visual representation. The second one is an AC3D model which is used in the acoustical simulation. The visual system can handle several thousands of polygons, whereas the acoustical simulation only runs fluently with about 40-80 polygons. This discrepancy is the main reason we decided to use two different models,
because we need more than 80 polygons for a plausible visual representation.

This was overcome by synchronizing the two models. Both models are spatially connected via their spatial origin. The synchronization is accomplished by the tracker daemon. The user positioning data that results from the user’s interaction with the system is transmitted to both modules simultaneously so that both have a concurrent data status.

The drawbacks are obvious. Maintaining two models is a laborious and error-prone task. Changes in one model have to be transferred to the other model. Since geometry changes are currently not possible in a systematic approach, it seemed to be a valid method which could be handled and lead to our goal. For the further development of the system a VRML node in COVISE/Cover should be introduced that can translate the acoustical information from the VRML model to the acoustical simulation module. The problem of having different polygon meshes could perhaps be solved by using something similar to a LOD node. With reduced acoustical geometry information in the background we could provide the acoustical and the visual module with data while hosting only one model.

Using common CAAD tools it was not possible to produce the required file formats. Jörg Scheurich adapted an open source tool called ‘white dune’ for our purposes. ‘White dune’ is now able to import VRML files and export the files to ac3d as well as to the .geo format used by the software CATT. Furthermore, its functionality was improved so that it is now possible to adapt material definitions for acoustical purposes, while emitters and receivers can now be inserted to the CATT system using a graphical interface.

**A case study**

A group of students was asked to investigate a few typical halls. We decided to use the CATT Acoustic Software for the graphical and the offline auralisation. Using the RAVEN/Cover system we were able to see, hear and walk through the rooms in real time. The final target was to build up an existing hall in a digital model and to systematically analyse and evaluate its acoustics.

The first step was to understand the basic principles of sound propagation and the impact of geometry. Halls with simple geometries and comparable volumes were modeled. The absorption of the walls was assumed at 5%, while the floor was modeled with a higher absorption of 30%. The main goal was to show, supported by their own hearing experience, the relevant parameters of room acoustics to the students. Through their systematic experiments they learned to listen. The dimensions where acoustically relevant events occurred became tangible. The acoustically comfortable areas could be explored. The impact of geometry and material to the acoustical outcome became obvious.

After these exercises the students were able to investigate real room situations. They were now able...
Figure 6
Room 02, calculation of the IR by CATT, Volume 17,400m³

Figure 7
Room 03, calculation of the IR by CATT, Volume 18,000m³

Figure 8
Overlay of the IRs of the three rooms.
to simplify and abstract a real setting for the models and to estimate the acoustical properties for the surfaces, whereby we have to admit that this was the hardest part of the simulations. Even though the interactive models are not suitable for a paper publication, Fig. 9 shows an impression of a student’s model of the Mozartsaal in the Liederhalle in Stuttgart.

Conclusion

The results described in this paper are first of all a qualitative estimation of the acoustical situation. In order to get a more realistic acoustical representation of the rooms the definition of the used materials has to be more precise. However, the method is successful to get the feeling for the impact of geometry on the acoustic behaviour of a room and to give the students a realistic hearing experience. The differences between the methods used for analysis became obvious. The auralisation and the comparison of different situations that were heard need trained or experienced ears. The interpretation of the graphical outputs and the diagrams is also a demanding task. The comparison with defined limits is possible, but a recursive process to define geometry or the constellation of a room is difficult.

References

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