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FROM ARCHITECT'S VISUALIZATION TO ACOUSTICIAN'S AURALIZATION

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1. INTRODUCTION

It is necessary for both architect and acoustician to be able to render their work to the client. Sketches, detailed renderings, drawings and models are tools which can be used to allow the client to fully understand and prefer the solutions suggested by the architect, Wade [1]. Up until quite recently, acousticians have been at a disadvantage in their ability to render their suggestion in such a form that they are comprehensible to both the general client and the architect.

In part this is due to the lack of a commonly accepted language in the description of aural sensations. The semantic difficulties encountered in discussions on acoustics between, for example, musicians, acousticians, and architects, are well known. Since the aural sensation is individual, and no formal education is available to help verbalize common aural impressions, it is necessary to include an educational/instructive section in the presentation to the client. One also has to realize that it may be difficult for the client (and the architect) to distinguish sufficiently between the artistic and recording qualities of the programme material and the properties of the acoustical qualities. This problem can be reduced by listening to a sufficient amount and variety of programme material. The more knowledgeable the user, the more information can be extracted from a visualization, whether architectural or acoustical.

Through the use of new computer aided design technology, it is now possible for both architect and acoustician to give the client much better insight into the properties of the intended building. Usually, these computer aided design systems require large computational facilities or long computation times. However, many types of simple demonstration possibilities exist which only require quite small outlays. These can give effective insight into the acoustic properties of various types of auditoria, as they are perceived by the listener. New hardware which may be used for acoustic visualisation, "auralization", makes it possible to apply a more interactive approach to auditorium design, while still keeping both computational costs and times low. This technique is still in its infancy, and the authors believe that there will be considerable progress in the field of auralization within the next decade. New systems for virtual reality will make it possible to merge architectural (visual) and acoustical computer aided design models.

In contrast to the computer aided design renderings used for visual prediction, the computer aided design renderings used for aural presentations require larger effort in order to obtain the necessary impression or illusion. Not only is it necessary to calculate the steady state distribution of sound energy but also the transient response. Light waves move approximately 1,000,000 times faster than sound waves in air. The "reverberation time" of light in an auditorium is only of the order of microseconds, while that of sound is usually of the order of one or two seconds. Since the integration times of sight and hearing are approximately the same, Lindsay & Norman [2], we can perceive the transient nature of sound in auditoria but not the transient nature of light. But in any case most light sources emit steady state "noise signals", whereas speech and music are transient signals.

The steady-state distributions of both light and sound may be calculated using radiosity models. For sound these models are only valid at medium to high frequencies. For low frequencies wave models have to be used here as well. The transient response of the room can be calculated using a number of methods, each having its advantages. Several methods will have to be used to cover the entire frequency range of hearing.

2. ARCHITECTURAL AND ACOUSTICAL VISUALIZATION

2.1 Graphic Sketch & Sound Field Simulation

The preliminary design work is usually illustrated by means of sketches. The sketches, whether drawn with pencil, ink, or crayon, are often the first form of visual presentation used by the architect to illustrate thoughts to colleagues or clients. Although colour may be used in this stage the sketch usually employs only black and shades of gray with various textures to convey a first impression of the space to be built, Branzell [3]. In these sketches the illusion of visual depth is essential to convey the impression of volume. Even though several sketches are made of various views of the space there is no possibility of having the impression of "being there". The representation is too coarse. However it will be possible from the sketches to have an impression of the shape of the space. Using sketches of details it is also possible to illustrate intended surface structure, etc. The sketch will also illustrate how humans relate to the space, whether as performers or listeners.

From an acoustical viewpoint the intended volume, space and seating capacity are essential to the resulting quality of an auditorium. In an analogue way to the architect's sketch it is possible to achieve an acoustician's sketch. The architect's sketch transmits an impression of shape and space, volume, to the viewer. By using the same input data, dimensions, volume, surface treatments, seating capacity, etc., it is possible to calculate the basic measure of room acoustic quality, the reverberation time. Through the use of for example an electronic reverberation unit, suitable programme material, headphones or loudspeakers it is possible to listen to how various reverberation times will influence one's impressions of the programme. It is essential however that the sound levels at which one listens are correct to obtain the correct aural impression of reverberation time.

In the architect's sketch there is depth. How can one transfer this impression of depth in the acoustician's sketch? The aural illusion of depth is achieved through the addition of audible direct sound, Blauert [4]. Through the variation of the ratio of direct to reverberant sound, variation of the distance in time between the direct sound, and the onset of reverberation, it is possible to vary the impression of depth (and to some extent volume). If one studies the sketches in figure 1, one can see how the visual depth and volume will correspond to the acoustical depth and volume. The cloud in the figure illustrates the concepts of volume and the distance from the center of the cloud to the performer the depth.

In a sense there is also correspondence between the way in which we perceive visual colour and tonal quality. It is common to describe tonal quality in semantic differentials such as warm-cold, blunt-sharp, dark-light, dull-brilliant. By varying the levels and reverberation time with frequency it is possible to convey various impressions on the semantic scales. This is much the same way as one can change the visual characteristics of a space by the appropriate choice of colours in the sketch.

In the same way as it is possible for the architect to produce more detailed and "accurate" drawings, it is also possible for the acoustician to achieve more detailed and accurate sound field simulations. Since they are more informative, they can make the proposed space more understandable to the client. By using a more complex type of reverberation unit it is possible to obtain a better sound field simulation. This type of reverberation unit not only features simulation of the reverberation, but also sound corresponding to that reflected off walls and other reflecting surfaces in early stages of propagation. Such sound field simulations can be imagined to be based on drawings which feature sizes and positions of various reflective surfaces without any

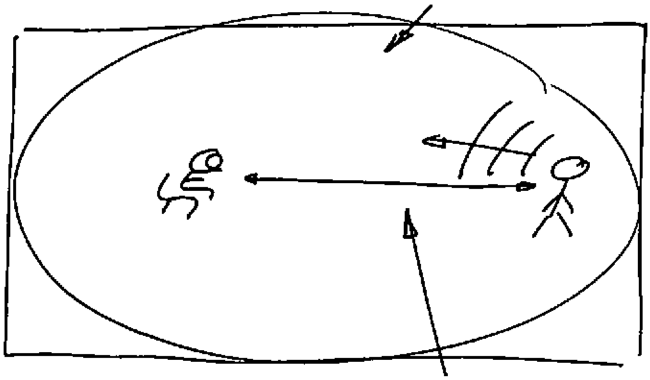

Figure 1. Visual and acoustical depth and volume.

great detail, for example some 10 or 20 surfaces. Similar sound field simulators have been used in acoustical consultancy for quite some time, Veneklasen [5].

The basic function of one sound field simulator is shown in figure 2. This sound field simulator, primarily intended for home hifi use, can be used effectively to better describe to clients and architects how various sound field properties influence our hearing and aural perception of space. Its cost is only marginally higher than that of simpler reverberation units. The typical unit, for example Yamaha DSP1000, features semi-fixed sound field settings. These correspond to a rough approximation of the typical sound fields of some twenty different spaces such as various concert halls, operas, churches, outdoor venues etc. These approximations are based on measurements. To some degree these may be varied with regard to for example volume, reverberation time, level of direct sound, onset of reverberation, etc. The unit outputs six channels and requires a "triple" stereo setup. Two channels are needed for direct sound. Four channels are needed for envelopmental sound, front and rear (side) early wall and ceiling reflections. Late reverberation is radiated from four of these channels. At Chalmers, we use a similar unit in our course on room acoustics, to illustrate various properties of room acoustics and their interaction, good or bad, with our hearing. Response from the students has been extremely positive.

Lending such a unit to musically inclined clients, who have access to an electronic instrument, such as a synthesizer, should increase their interest and sensitivity to acoustic qualities considerably.

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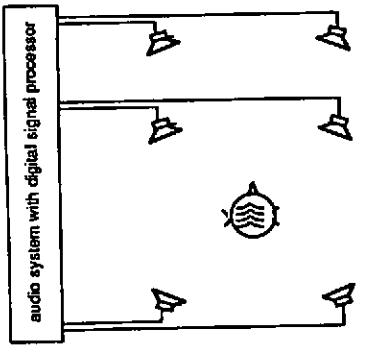

Figure 2. Basic sound field simulator.

2.2 Detailed drawing - Rendering - Auralization
To present ideas more effectively to the client it will be necessary for the architect to present the client with more complex and detailed drawings. These will be to scale, may be isometric, may feature perspectives, include human figures to give more life and relation to the space. Form will be more defined as will surface characteristics and various details. This may be in the form of a rendering with semiphotographic qualities. It is easy to include detail in a rendering, it is much harder to include detail in a model, and still harder to define detail in such a way as to be able to use it for construction. In a graphical rendering it is common to express foreground elements in great detail in order to emphasize depth. In auralization it is necessary to use high detail not only with regard to surfaces close to the listener but also with regard to the surfaces close to the orchestra.

For the acoustic simulation there is a conflict in the representation of detail. While it is possible to calculate the path of a sound ray with great exactness, this is not sufficient to provide accuracy. The concept of sound rays is a simplification of the physics of sound propagation that is only permissible under certain conditions. The frequency range of interest in auditorium acoustics is enormous compared to that of interest in visual systems. In practical work with auditorium design, the concept of sound rays is reasonably valid over 0,5 kHz. Speech and music often have their maximum energy at 1-2 kHz and this also corresponds to the region of maximum sensitivity of human hearing. At lower frequencies the accuracy of computer models based on the ray or image source concept falters. At frequencies higher than a few kHz most surfaces are irregular enough to produce diffuse reflections that are computationally hard to include in personal computer programs. By using various forms of extended computation techniques it is in principle possible to take most of the frequency range of hearing into account in a subjectively acceptable way. The auralization of computer aided design models usually uses much digital signal processing, particularly filtering often described as convolution. Presentation of auralization can be done using headphones or transaural techniques. The latter feature more realism.

Consider a simple architectural rendering that is done in black, white, and greys. This is obviously less realistic than a rendering which uses colour. Colour enhances the rendering not only in itself but also because it can convey extra dimensions such as materials, etc. The same type of step in realism is present in auralization as well. Auralization which does not take the frequency response of the sound source and its directivity as well as the frequency response of reflections off surfaces is without "colour".

By adding features such as human figures, musical instruments, etc., to the drawing one adds elements of life. Such "perturbations" or "visual noise" that are added to the drawing have their counterparts in the acoustic visualization. Just adding some background noise, for example air conditioning noise, to the auralization will make the auralized environment much more real. One also has to remember that people are 'noise', not only do they talk, they breathe, cough, sneeze, whisper, etc. While these actions are at times quite distracting they make the difference between a dead and a live environment.

2.3 Architectural & Acoustical Scale Model

The use of architectural scale models is not without problems but features a realism that cannot be achieved in graphical rendering. The model is attractive in itself due to its toylike miniaturization. It is hard however to achieve correct scaling of all details. It is also difficult to envision what it is like to be shrunk into the model to have a correct view. Model 3-D photography could eliminate these problems and would be similar in concept to auralization using an acoustical scale model. Computerized 3-D rendering can probably reduce both problems.

Acoustical scale models have been used for auralization of auditoria for several decades but with limited appeal. New signal processing equipment can alleviate many of the problems earlier encountered in auralization. The use of special analysis techniques to avoid noise and non-linear signal distortion can make this visualization technique popular once more. A small sound source can be inserted into the model and, by using a miniaturized binaural recording head, correct signals may be obtained for full scale auralization. These signals are impulse responses of the auditorium, which can be convolved with speech and music to obtain audible samples of the sound quality of the auditorium.

The acoustical scale model technique has the advantage of being acoustically correct over the frequency range of interest since it takes into account the diffraction and scattering of sound waves. The minimum scale that can be used is currently 1:10. This differs from the preferred architectural scale of 1:50 which also can be used for acoustical measurements but not for auralization due to transducer problems.

3. THE AURALIZATION SYSTEM AT CHALMERS UNIVERSITY OF TECHNOLOGY

The auralization system developed at Chalmers is configured as shown in figure 3, Kleiner et al [6]. A 486 PC-compatible computer is used for all functions in the system. The data from drawings or other sources is entered into a computer file. The image source/ray tracing model program calculates the generic impulse response for the room in a number of octave bands. The model also takes into account first order scattering. The late part (sound arrivals typically 100 - 160 milliseconds after the direct sound) is treated separately by a semistatistical model. The output from this module is then used in another module to calculate the binaural impulse response at the desired seat. This impulse response is then convolved with speech or music in real time using a Lake FDP1+ digital signal processor, which is connected to the computer. Up to 2 seconds of impulse response can be convolved at compact disc and digital audio tape data rates. The real time nature of the convolution process makes it easy to compare different types of source material as well as different types of hall combinations. Listening can be done either via headphones or via loudspeakers. In the latter case a simple transaural filter is used to compensate for inter-ear signal leakage, 'cross-talk'.

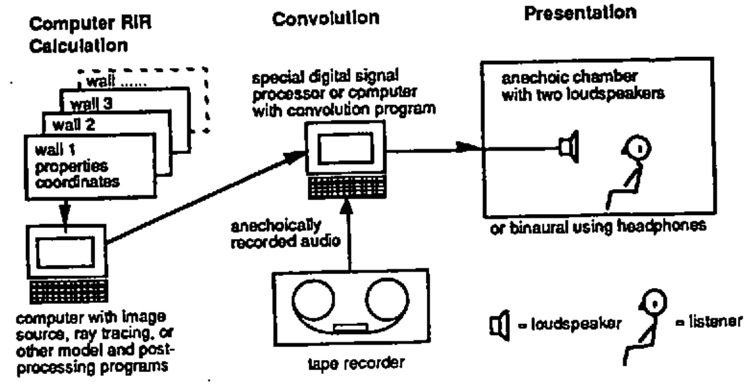

Figure 3. Basic auralization using acoustical computer model and convolution.

One of the advantages of the present system is that it allows parametric variation of room boundaries and other surfaces. It is easy for example to do design studies where room shape is changed. Instead of having to change a large number of surface descriptions only a few descriptors are changed.

With the present system it is also possible to listen to the sound fields in real halls in such a way that they are comparable to the auralized models. In this way it is possible to study differences between auralized and real halls to improve the auralization process. Another way of using the system is in the study of the aural perception of changes to halls caused by geometry, materials, seating, etc. This will be important when old auditoriums are to be renovated or rebuilt. Influence of background noise may also be studied.

4. EXAMPLES OF AURALIZATION

The system developed at Chalmers is new and has until now been used primarily for design studies, teaching, and research into auditorium acoustics. Some examples of its use are:

1. Studies of preference for hall shapes
The preference of listeners for various hall shapes was studied in a pilot study, Kleiner et al [7]. In this study three different hall shapes were studied: fan shape, shoe-box, and reverse fan shape. The audience area was kept constant as well as the reverberation time as calculated by the program. This is a type of study that could not have been made in real halls. The volume was adjusted slightly between the different cases in order to yield the same reverberation time. The results showed a slight preference for the reverse fan shape.

2. Studies of perceptibility of changes in room acoustics
In this study five different types of changes to the acoustical conditions were studied, Dalenbäck et al. [8]. These were:
- Community hall - changes in hall shape and absorptive treatment.
- Concert hall - proper and improper installation of a public address system.
- Music rehearsal room - with and without reflectors and adjusted absorption

- Variations in basic hall shapes - fan shape versus reverse fan shape
- Office room - with and without absorptive treatment

These cases were presented to a mixed group of listeners. These were asked to grade the auralized spaces along semantic scales with regard to reverberance, clarity, and source width. The results indicate that the changed conditions are quite perceptible even to untrained listeners. Some cases are markedly easier to recognize than others. Even the more difficult cases could easily be differentiated by trained listeners but the semantic scales chosen could in some cases not be used to describe the aural perception in an adequate way.

3. Sound amplification and reverberation enhancement
The goal of these tests was to investigate the possibilities of designing a reverberation enhancement system for a hall which would simulate a particular hall, Kleiner et al [9,10]. Auralization was used to study if it was possible to achieve the same aural impression in a hall with reverberation enhancement system as in the simulated hall. It was also studied if it was possible to study the properties of various reverberation enhancement systems from the standpoint of feedback instability and sound coloration. The results show that it is probably very difficult to reproduce the exact properties of a particular large hall in a small hall using a reverberation enhancement system. The attractive properties of the fine-structure of the reverberation of a large auditorium are hard to achieve with a reverberation enhancement system.

4: Future uses for auralization
Other uses for auralization include:

- Training of architects, acousticians, musicians, blind people
- Factory noise prediction
- Noise and sound quality assessment
- Studies in psychoacoustics
- Studies of coupling and interaction effects between aural and visual perception of space
- Studies of environmental noise propagation in cities.

5. CONCLUSIONS

The integration of acoustical "visualization" (or sketching) with the architect's graphical rendering will improve the architect's possibilities of presenting to the client the characteristics, both visual and aural, of a new auditorium and the consequences, both visual and aural, of changes in an auditorium. Auralization is a new term used to describe this acoustical "visualization" in analogy with conventional visualization. There are comparable steps in auralizing to the steps used in graphical sketching and rendering. Even the same type of terms may be used in the descriptions. New computerized design techniques allows effective auralization using personal computer systems.

Pilot studies using auralization on sketched rooms show that the method can effectively reveal changes in the acoustical conditions in these rooms. Auralization can also function as a very useful tool in the training of architects and acousticians.

6. ACKNOWLEDGEMENTS

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