Responsive Acoustic Surfaces

Computing Sonic Effects

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Abstract. Acoustic performance is defined by the parameter of reverberation time; however, this does not capture the acoustic experience in some types of open plan spaces. As many working and learning activities now take place in open plan spaces, it is important to be able to understand and design for the acoustic conditions of these spaces. This paper describes an experimental research project that studied the design processes necessary to design for sound. A responsive acoustic surface was designed, fabricated and tested. This acoustic surface was designed to create specific sonic effects. The design was simulated using custom integrated acoustic software and also using Odeon acoustic analysis software. The research demonstrates a method for designing space- and sound-defining surfaces, defines the concept of acoustic subspace, and suggests some new parameters for defining acoustic subspaces.

Keywords. Architectural Acoustics; Performance-Driven Design; Parametric Design; Digital Fabrication.

INTRODUCTION

Many people work, learn, and play in open-plan spaces; however, the users of these spaces often consider the acoustic performance to be poor. (Petersen, 2008) The Distortion 2 project is an experimental research project, designed, built, and tested to create visual and acoustic affects within an open-plan space. This paper shows how, through the specification of geometry and material, a surface can respond to acoustic performance criteria. The findings from this project inform the future designs of acoustically regulating structures for open-plan spaces. This research suggests a general method for designing, simulating, and fabricating sound- and space-defining structures.

The Distortion 2 project was designed for, and has been featured at, two exhibitions: the 2011 Stockholm Furniture Fair, and the 1:1 Research exhibition at the Royal Danish Academy of Fine Arts, School of Architecture. The project was collaboration between CITA, a university architecture research group, Akustikmiljo, a fabricator of acoustic products, Krydsrum, a local architecture practice, and Acoustica, the acoustic engineering division of Grontmij, Copenhagen. The project combines
a research-through-design methodology with the quantitative measurement and simulation methods of acoustic engineering. The goal of the research is the study of the process of design, with the aim of the improvement of this process. The design intent of the Distortion 2 project was the creation of an acoustic surface designed in response to sonic performance criteria, see Figure 1. This project aims to make the soundscape of our buildings an exciting and desirable experience.

**SOUND**

**Sound Design**

This project questions the design strategy of acoustically homogeneous spaces defined by the specification of reverberation time in building codes. Instead it suggests and explores the potentials of acoustically heterogeneous spaces. Acoustic performance is usually specified using a single criterion, reverberation time; however, hearing is a multi-dimensional experience and there are many different ways to evaluate sound quality. Reverberation time is often constant through a space; despite this, we can often perceive different acoustic qualities throughout a space, and these differences have been shown to modify our opinions of the space. (Petersen, 2008)

This research project recognizes this fact and suggests that, if the factors that create differentiated acoustic spaces can be understood and controlled, and then these can be used as a design tool. This research introduces the concept of the acoustic subspace, which we defined here as a zone within a larger space that can be differentiated through its acoustic qualities. This project was designed specifically to probe two acoustic extremes: a sound-amplified zone, and a sound-dampened zone as shown in Figure 2.

The creation of the acoustic subspaces was done through the definition of material, the level of enclosure of the wall, and the geometry of the focusing and sound scattering panels. When measuring the room acoustic impression, the sound source and sound receiver must be very close together to simulate the effect of mouth and ear. The early reflections become very important and therefore the materials of the surfaces close by the listener become noticeably acoustically active. The designed acoustic surface, shown in Figure 3, has a hard and reflective finish of the sound-amplified side and the...
soft and absorbent finish of the sound-dampened side. The reflective panels on the sound-amplified side focus sound to a privileged position to make this zone louder.

**Sound Modeling and Simulation**

To have a functional iterative design-analysis cycle using acoustic performance, the geometry produced in the architectural CAD system needs to be easily imported into the analysis software and the results from the analysis software need to be understood so that they are able to then drive the geometry in the architectural CAD system. Two approaches to acoustic simulation and analysis were used in this project. The first approach used the ODEON acoustic analysis software and used imported geometry. Figure 4 shows the elevations of a digital model and a corresponding analysis diagrams. The analysis diagrams show how reverberation time is relatively constant throughout the space, while sound pressure level varies greatly. The data could be easily transferred from the parametric model to the analysis software, but in order to do this the geometry had to be level separated by material, and be constructed of simple triangular shapes.

The second approach is to integrate the evaluative tool into the design environment. Figure 5 shows a ray-tracing analysis of a structure mapping the sound level around a structure. This analysis was programmed in the CAD design environment and offered instantaneous feedback about the design option. However, this data was not translated then to an established acoustic parameter, and since the data transfer to ODEON was so simple, this method was only used during the sketch design phase. If this evaluation tool is developed further this could become and increasingly useful tool for designing responsive acoustic surfaces.
To simulate how a person would experience the acoustics at a given position of a room, a technique of mapping of near field amplification, titled Hot Spot Plots were carried out. This technique was developed as part of a research project looking at acoustic conditions in open plan office work environments. (Petersen, 2008) Calculations used a sound source and an ‘imaginary’ receiver 20 cm above the source. The sound source was omni-directional; this type of source was used to minimize the influence of a person’s orientation. The plots in Figure 6 show that there are experienced differences between the various points around the installation. The circles show where there is a strong near field amplification. This analysis shows that the installation shapes the acoustic environment around it.

STRUCTURE

Structural System
The structural system needed to fulfill several criteria: it needed to be as solid and heavy with no holes or gaps in order to reduce sound transmission, it needed to be dismantled and transported, it needed to be self-supporting, and it needed to have the ability to control the orientation of the constituent plates. Similar to other projects done by CITA, customized digital tools allowed us to create the base design and to simulate the performance on its behavior (Deleuran, 2011). The structure’s basic tectonic principle is that of a system made of stiff plates; however, we sought to gain more stability through the introduction of folds into the surface. The structure is a continuous, single-layer folded-plate system that distributes the structural loads through the surfaces and along the folded seams across three dimensions, where different tessellation patterns can achieve different spatial effects, structural conditions, and sonic effects. (Moussavi, 2009) The folded plate structure performs on two levels that are important to acoustic performance: first, the tessellated folded plate components scatter the sound in different directions, and second, the plates can be used to reflect sound from a sound source to a sound receiver.

Structural Performance Logic
One of the fundamental features that defined the folded plate system used was the trihedral corner. The trihedral corner is a structural system where three rigid plates meet at one point, as shown in Figure 7. Trihedral corners are always rigid as opposed to corners with more than three meeting plates which are often non-rigid.
Initial investigations mixed both tetragons and triangles in order to gain more geometric flexibility. The tetragons form trihedral corners and the triangles connect these rigid hexagonal clusters; however, these initial cardboard models showed that this mix was not structurally rigid until a triangular dependency between the adjacent clusters is created. The benefit of this type of structure is its ability to vary appearance as shown in the first three images of Figure 8; however, the disadvantage is how difficult it is to control the geometry of the system. After numerous parametric modeling studies, it was found that the internal geometric constraints made the control system very sensitive to changes in the overall shape. A structural system using only trihedral corners was selected and used. The investigations done showed this system has greater stability than the mixed structure, and because the geometric logic of the trihedral system was less sensitive, it became more flexible.

**Structural Design and Geometric Logic**

The geometry was generated with a parametric system. The folded plate structural system was broken down into a series of repeated components. While the geometric logic of these components remained the same, the dimensional characteristics of each component could change thus allowing the overall structure to have a changing curvature and changing height along its length. A single surface defined the overall form of the installation. This design surface acted as the controller for the overall geometry. On this surface, a triangular grid was placed which was populated with the trihedral folded plate components. These were placed on every other triangle of the grid and the corners connect to each other through the second half of triangles, see Figure 9.

The vertically oriented panels were used for sound reflection. In the geometric model the waves of sound were simplified and regarded as rays; similar to light the ray is reflected where the angle of reflection equals the angle of incidence. (Long, 2006) Based on this geometric rule, every reflector panel on the surface that faces the sound source $S$ can be re-oriented to the optimal reflection angle, see Figure 9. However, due to the re-orientation of the reflector plate, the adjacent panels must also be re-oriented. In order to avoid the reflector plates obscuring the plates behind from the sound, the surface plane of the panel is oriented towards the sound source. This maximizes the surface’s overall area for reflection. To find the position of the three plates an ideal plane $IP$ was created in the middle of the reflector plate and a line from the sound source...
S was created towards the common vertices of the back plates. The intersection between the plane IP and the sound source gives the third point A. This position and the triangular base points are all information needed to instruct the adjacent plates about their rotation.

In order to achieve the correct orientation of the reflector panels the shape of the surface had to change as well; therefore, an iterative routine was introduced to modify the position of the trihedral’s base points. However, as the overall shape of the surface approached that of a parabola in section, the structural integrity becomes compromised. The iterative process to find the node positions became necessary when the structural and geometric rules were overlaid with sonic performance which led to the definition of the folded plate structure.

**DETAILING AND FABRICATION**

**Materials**

Based on previous research project experience (Deleuran, 2011) a composite plate system was developed that integrated the different functions in layers. The layers were: Akustikmiljo’s 50mm Fibrefloat acoustic absorbing panels, 12 mm white-coated MDF, and 3 mm of aluminum-faced composite Di-bond, with bent laser cut steel joints. The MDF face was oriented to the sound-dampened side and this surface was largely covered with absorber. This material cannot bend but can be cut into any shape using the CNC knife cutter. This allowed the customization of the shape of the absorber on the outside where there was the sound scattering facets, and on the inside where there was a laminated textile color.
gradient. This pattern was also engraved in the Di-bond panels. This pattern served both as ornament as well as application guide.

In order to predict and design for acoustic performance using digital simulation techniques two material properties need to be known: absorption and scattering (Rindel, 2010). However, sound transmission is also a critical factor for acoustic performance. If sound transmission is not taken into account, simulations will be invalid. Six different material wall sections were tested for their noise reduction coefficient. A material construction of 12mm MDF and 50mm Fibrefloat was chosen.

**Generative Fabrication System**

Four different digital production techniques used: laser cutting, knife cutting, CNC routing, and metal bending. The fabrication files for all of these techniques were generated out of a customized parametric system. The input for this was the structural panel model. The planar plates are translated from their three-dimensional (3d) position to the two-dimensional (2d) space of the CNC machines and details such as screw holes or assembly related engravings were added, and a similar approach was used for the generation of the gradient pattern for the sound absorbing Fibrefloat, see Figure 10.

Working with 2d representations gave advantages in speed of data processing and construction of geometry. As the geometrical operations were simpler, conclusions from observed material behavior (i.e. changes in material thickness) or fabrication (i.e. tolerances) could be quickly introduced into the system. A 3d representation of the model was not done due to time considerations for programming. The prototyping of physical models gave considerable insights on fabrication and assembly. The ordered geometrical logic of the plate system became confused when it met the system’s edge conditions and with the introduction of special elements (such as stabilizing ground plates top shielding plates). The result was a non-uniform matrix of components. As a result a process was developed that looped through all plates individually investigating their specific set-up. In this way the more than 400 individual part files for fabrication could be generated sequentially, each with its own set of fabrication related parameters.

**Prototyping and Assembly**

As the structure’s sonic performance was determined by the geometry, a precise fabrication was essential. 1:1 Prototypes became a crucial part of the design process. These could be investigated in relation to precision, structural ability and ease of assembly. The first three prototypes were produced in-house with laser cutter, and the fourth prototype was done using the fabricator’s machinery, see Figure 11. The prototypes showed how critical the precision of the joint detail was. The joint is the place where forces are transferred while at the same time being visually very prominent. The use of machine bolts and thread inserts gave high precision to the assembly of the plates as well as creating a re-usable connection. The use of thread inserts avoided
bore holes that would create holes between the front and back of the structure. Prototypes proved furthermore that the exact tolerances of the digital fabrication machinery could translate to the tolerance of the overall structure.

Each of the four materials was finally produced at a different fabricator. After cutting the MDF and Dibond plates, the individual panels were assembled with steel joints attached to the two upper sides. This procedure took around two days. For assembly on site a full-scale ground plan was laid out onto which pre-assembled ground elements were positioned. Then assembly was done plate-by-plate in rows starting from the lower side of the structure. The structure was setup at four times with an assembly time of around 8 hours with three people. Disassembly took less than 3 hours. Screwing machines and simple rolling scaffolding were the only equipment needed.

RESULTS
The measured results discussed here were taken when the project was installed at the Royal Danish Academy of Fine Arts, School of Architecture. The project was tested for acoustic and structural performance. Acoustic parameters were measured and compared to the simulation and the structure was laser scanned.

The ability of the acoustic surface to create acoustic subspaces was tested with a head and torso simulator (HATS), see Figure 13. The parameter Voice support, STV is defined as the reflected sound minus the direct sound (from mouth-to-ear). (Garcia, 2011) STV is for one channel only. The difference between left and right channels can be used describe the amplification and attenuation of the structure. As the HATS was facing along the structure, one ear faced out into the room and the other ear faced into the structure, a new parameter, STV IA-diff, was used to denote the inter-aural difference between the channels. Figure 12 shows the results from this investigation for positions 3, 7 and 11. These positions cover three conditions: far away from the structure, close to the structure with left ear, and inside the structure with right ear close to the structure wall. The results show that a STV IA-diff value of close to 0 when far away from the structure, a positive value of 3-4 dB with left ear close to the structure, and a negative value of 2-4 dB with right ear close to the structure. Therefore there is a significant attenuation of the reflected sound because of the structure.

The relative sound strength, G, and the reverberation times, EDT and T30, were studied at each of the three positions shown in Figure 12. These measurements were calculated for the reverberant
sound energy only, so the strong influence of the direct sound is ignored. The results of this are shown in Figure 13. The G-values are higher close to the structure. This is most likely because there are more sound reflections from the surfaces when close to the structure, when further away, there is mainly the response from the large room. The EDT values of the reverberant sound energy give quite a good description of the experienced room impression. Similar to the simulations, see Figure 5, the T30 values do not vary much depending on the position. It can be seen that the structure creates the impression of a sound-damped room when close to the structure.

A laser scan of the assembled structure revealed that while the panels and local geometry of the final structure follows precisely the planned geometry, the structure bends under its own weight at the highest point, see Figure 14. This performance was similar to what was observed with the cardboard models in the design phase, thus re-affirming the value of working with physical prototypes. An investigation of the scanned point cloud shows that while there is some bending in the plates, the bulk of the deformation can be traced to tolerances within the joints. The structure has a maximum deviation of only 5 cm in the vertical and 14 cm in the horizontal at the structures highest point of 315 cm.

**CONCLUSIONS**

The consideration of acoustic performance is important in the design of open-plan working and learning spaces. The Distortion 2 project has shown that sound can be an area of creative design potential. Designing for sound is a challenging as it is a time-based phenomenon that changes with the position and qualities of sound sources and sound receivers and the social/cultural situation in which it is experienced. Through responsive geometry and material, architectural surfaces can create acoustic conditions. In order to design for sound performance an evaluation system must be part of the design process and measurable acoustic performance criteria must be set to correspond to the design intent. Designers must be able to contemplate design options through these evaluative feedback mechanisms. Feedback on acoustic performance can come from through acoustic simulation studies. This project has demonstrated the phenomenon of the acoustic subspace. Acoustic surfaces can create differentiated acoustic conditions within open-plan spaces; however, the reverberation time (T30) does not capture this impression. The parameters of EDT, G, and STV IA-diff, were found to be more useful to define and measure the acoustic subspace.

Parametric modeling techniques were central to the design process as they allowed the creation a model that could be modified to achieve the performance criteria. Material properties were mapped in relation to acoustic performance and geometry was adjusted meet performance requirements. It was found that file exchange with the acoustic analysis software was easiest using DXF file with simple triangulated shape geometry. The parametric model was linked to fabrication machinery. However, the
linking of form, performance, and fabrication requires letting go of some design ideas, because of competing demands from these the three systems, a balance must be achieved.

This project demonstrated the trihedral folded plate system as a structurally strong system with design flexibility. To integrate the behavior of sound, the geometric logic of the folded plate, structural considerations, and the assembly logic into the performance equation establishes a feedback loop that creates a new understanding of architectural assemblies. The project was realized and performed as predicted because of the high degree of precision that was achieved through digital fabrication.

REFERENCES