Adding Performance Criteria to Digital Fabrication
Room-Acoustical Information of Diffuse Respondent Panels

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In this research project we explore the defined design and application of digitally fabricated wall panels for room-acoustical architectural interventions. In particular, we investigate the room-acoustical criteria applying to everyday used spaces. We present a digital design and fabrication process developed to create non-standardised panels and two case studies which apply this process on the acoustical improvement of a specific room situation. Our aim is to find correlations between digitally fabricated surface structures and sound-aesthetical characteristics, in order to utilise these for the architectural design.
1 Introduction

In recent time the question of performance in architecture as a key factor for the design has come into the interest of professionals and architects (Kolarevic 2005; Hensel and Menges 2008). With advanced digital fabrication and manufacturing technologies at hand the question arises, what performance issues can be added to architecture besides just realising complex forms? In the research project presented in this paper we explored the design of acoustical active wall panels making use of an additive digital fabrication process.

Apart from spaces designed for a special function and whose profile require a high acoustic specification, e.g. auditoriums, concert halls or recording studios, room-acoustics is a largely neglected issue in architecture (Schafer 1977; Böhme 2001). Nevertheless, acoustical characteristics have an impressionable influence on the perception of space (Handel 1989). The subjective feeling of acoustical comfort can be extremely diverse and a diverse set of design approaches are needed in order to customise specific spatial situations. In this research project we concentrate ourselves on spaces for everyday use (i.e. residential and office space).

In room-acoustical design alongside acoustical absorption, the subject of diffusivity has gained some importance (Tarnoczy 1991; Haan and Fricke 1997). Diffusion is described as the process of spreading or dispersing the acoustic energy emitted by a source in preferably random directions so that it is less direct or coherent. This creates an even distribution of the sound energy in space and is regarded to have a positive effect on the acoustical perception, the space is considered to sound better (Marshall 1967; Barron 1971). Negative noticeable spatial resonances resulting from unfavourable sound reflexion, i.e. room modes as a result of standing waves, which is an acoustical characteristic often found in small and medium sized rooms, can be avoided. Especially, the speech intelligibility can be improved through diffusion of sound, because in contrast to absorption no energy is destroyed. Surprisingly, apart from the work of Beranek until now only little quantitative research has been conducted on diffusivity (1962, 1996).

In order to obtain diffusivity of a building element an aperiodicity of the surface structure is necessary. Using a standardised production this can only hardly be achieved. A single element can offer a non-periodic surface structure, but the addition of several elements, to for instance clad a wall, again result in an overall periodic surface. In contrast, special customised measures which are applied for concert halls are not economically viable for residential or office buildings.

Digital fabrication offers the opportunity to produce non-standardised elements, which have the potential to create rooms with a specific acoustical characteristic and are economically feasible. Besides the possibility to produce individual non repeating building elements digital fabrication opens the possibility to gradually change the acoustic performance along a spatial boundary and thus create differentiated acoustical characteristics within a single space.

2 Specifications

For this case study a room the size of an average living room, respectively a small to medium sized office served as the test environment. The room had a square footprint of 5 by 5 meters and a height of 2.90 meters. The ceiling already featured permanent installed acoustic absorbers, but these were not sufficient to create a pleasant atmosphere. One side of the room was open to the façade, whilst the three other sides could be used for an architectural intervention to alter its acoustical characteristic.

2.1 Design and Diffusivity

In order to design a diffusing surface it is necessary to be able to make certain predictions on its scattering effect. Cox and D’Antonio give a thorough insight into the characterisation of diffusing surfaces and also discuss the limits of computational prediction methods (2004). To ensure a diffusion effect we set up certain specifications as design guidelines, although there is no recipe that guarantees a predictable degree of diffusivity of a surface structure. First, we defined that the element would consist out of a single material and therefore the scattering effect is a result of the shape and not the difference in material.
(i.e. difference in absorption). In general the applied material should have only minimal absorption properties. Secondly, the surface structure should feature compartments of highly differentiated depth, but with a comparable surface. The depth of the structure has to be greater than half the wavelength in order to be effective for a certain frequency. As our main focus lies on optimising the comprehensibility of speech, were the frequency of 1000 Hz is most important, a depth of roughly 20 centimetres is needed. Furthermore, the structure should not be permeable, meaning that all impinging sound energy should be reflected. Regarding its two-dimensional expansion the resolution of the structure should be in-between 2 and 20 centimetres and be homogeneous on a macroscopic level of approximately 30 centimetres. Finally, the structure should by no means exhibit periodicity in any direction.

2.2 MATERIAL AND FABRICATION

Derived from the prerequisite to build up highly customisable structures of large volume and to use a material with a low degree of absorption, we chose to apply an additive fabrication technique using polyurethane foam as a build up material. Polyurethane (PU) results from a chemical reaction between diisocyanate and a polyol, as well as optional additives. Depending on the formulation polyurethanes cover an extremely wide range of stiffness, hardness, and densities. They are used in insulation, surface coatings, adhesives, solid plastics, and athletic apparel (Seymour and Kauffman 1992).

In our case we used PU that results in stiff foam with a hard nonporous surface to obtain good reflection properties. For the fabrication process the mixture was composed such, that during the curing process we got a balance between inherently stable foam and the expanding effect of the polyurethane as it reacts with carbon dioxide out of the air. On the one hand we had to assure that each layer of polyurethane gives a good foundation for the layer above, on the other hand the increase in volume ensures an economical build up process.

To fulfill the requirement of aperiodicity, each element had to have a different surface geometry. Consequently, we applied an additive fabrication process, where the dispensing
of the PU directly forms the final product and no additional mould or formwork is necessary. In order to deposit the layers of polyurethane in the desired geometry, the dispensing head is hooked up to a six-axis industrial robot (Fig. 1). The movement of the robot is directly controlled by the design data of each element. The designs had to incorporate two important parameters derived from the fabrication process. First, the speed of the robot, which directly affects the amount of material deposited at a certain location and also affects the centrifugal forces acting upon the deposition material. Secondly, the sequence in time the robot will follow the specified movement paths, as the crossing of paths produces different heights dependent on the curing state of the polyurethane. A change in these parameters produces completely different outcomes for one and the same input geometry.

3 Digital design Tools

The main complexity arising from the combination of the chosen material and the digital fabrication technology was the impossibility to virtually model a process like foaming. The evaluation of the designs became possible only through an iterative loop of design scripting and production which involved analysing the material properties and the behaviour of the PU during the foaming process and feed this information back into design. We set up a customised design system within a standard digital modelling software, were simple path data (i.e. the movement of the robot) is extended by the above mentioned fabrication parameters (i.e. speed and sequence). Combined, this data constitutes the digital design parameters of the process (Fig. 2).

The fabricated results got analysed for their effects that emerge out of the fabrication process and the material properties, which then got isolated to be applied for future designs. For example, small pockets created in a first pass accumulate material deposited in a second pass and thus define areas of growth. Mushroom like structures evolve, varying in height depending on the amount of material which is gathered in each pocket. In contrast, where the deposition nozzle crosses an already cured area, the PU runs down creating very fine lines (Fig. 3). Through incorporating these observations into the designs complex structures were generated, that could not have been preconceived. As complex and random these products might appear they are nevertheless at any time reproducible.

4 Case studies

The research was interlinked with two student design workshops. During the first part the focus was on exploring the material and fabrication process, while in the second part the topic of acoustics got introduced. The gathered experience was put to test to design diffusing panels for the above mentioned spatial situation. Two exemplary projects were developed, fabricated and installed on site.

The first project follows an integral approach. A puzzle like structure based on the building grid covers the complete wall surface and gradually dissolves towards predefined acoustic “hot spots”. A so called “hot spot” being a position in space were a maximum level of acoustical diffusion is achieved. The design incorporates two basic, well proven diffusion structures known as the “Schroeder diffuser” and the “skyline diffuser” (Cox and D’Antonio 2004). A height variation in the structure is distributed through random functions with an increase in strength and height towards the aforementioned “hot spots” (Fig. 4).

The second project aimed at exploiting the material’s self organisation capacity as a means to achieve the height field variation required for diffuse reflection. Instead of clad-
During the complete wall surface, a couple of single elements were applied to distinct areas of the room. The sizes of these elements ranged from 2 by 1.5 meters up to 3.5 by 1.7 meters. The effect of height variation was achieved through overlapping paths in the fabrication process. This effect was used in conjunction with the very basic geometry of spirals, which through overlaying generated the required variation in pocket depth and size. In plan the simple geometry is still visible but while moving along the objects the height variation becomes the predominant visual appearance (Fig. 4).

5 Evaluation
The architectural interventions were assessed both qualitative and quantitative and in each case compared to the characteristics of the original bare room. The qualitative assessment was performed in form of interviews with test subjects emphasising on their perception of the space. The evaluation of these interviews will be part of a separate research paper focussing on the psychoacoustical effect of the designed elements. Summarised, the test subjects reported a great difference before and after the intervention. Acoustical phenomena that were observed as unpleasant, like flutter echoes and standing waves, were eliminated. Overall, the space was perceived as being “warmer” and more comfortable.

The quantitative measurements support the psychoacoustical perceptions. The scattering properties of the diffusing panels were measured applying a modified approach described by Farina (Farina 2000). In particular, we utilised the industrial robot to move along the panels and measure the multiple impulse response. In the sampled images the line to the left visualises the arrival of the direct sound, followed by the first reflection of the hard surface respectively the panel. We can see that the diffusing panels are softening the temporal behaviour of the first reflection drastically. The hard reflection from the ceiling of the robotic cell which appears on the far right of the visualisation vanishes completely (Fig. 6).

In addition, measurements on reverberation time and the degree of absorption were performed, as diffusion is always combined with an absorption effect. They show a considerable decrease in reverberation time. The differences in the reverberation times between the various microphone and speaker positions observed in the empty room nearly vanish in the panelised room, which indicates a more homogenous or diffuse sound field (Fig. 7). Especially, the measurements of the single panels performed under ideal conditions in an echo chamber display a constant high absorption in the frequency range between 500 Hz and 2000 Hz, which has most impact on speech comprehensibility (Fig. 8). Although, we chose a material with a high degree of reflection, the relatively high degree of absorption could be explained with small hole-like structures in the overall geometry of the panels and overhangs resulting from the foaming process of the polyurethane, an effect that has already been observed by Commins et al. (1988). The difference in values for the room measurements and the reverberation chamber are due to the fact, that in the reverberation chamber we only measured the “hot spot” panels. These feature a greater height variation and are more scattering, thus they have a greater effect on the low frequencies. For
the greater absorption of the higher frequencies measured in the room, we assume that because of the scattering at the walls more sound energy is deflected towards the ceiling were in the specific situation permanent acoustic absorbers were located.

6 Conclusion
The research shows the potential of applying digital fabrication processes to the design of acoustical active diffusion panels and how the performance of such elements can be increased and thus the overall quality of space. As digital fabrication technology is more and more available it becomes an implicit factor in architectural design and the focus shifts back towards architectural questions of functionality and spatial quality. In our case the necessity to design an aperiodic structure makes full use of the possibility to produce customised, non-standard elements, inherent to digital fabrication. More, through incorporating parameters derived from the fabrication process into the design novel structures and forms emerge that challenge our visual and aesthetic perception.

As the architect begins to design within a fabrication process he also is in need of new design tools. Until now only the fabrication parameters were incorporated into the design. A next step would be to integrate the performance parameters in a more specific way. The feedback of the performance data into the design can be done using the acquired measuring data of the physical prototypes or through a combination with computational simulation programs, although these are still very costly and until now no objective evaluation criteria exist. Exploiting the same machine for the fabrication, as well as the quantitative evaluation of the measured results within the fabrication process within a given design framework.

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7 References