Robotic Methods in Acoustics

Analysis and Fabrication Processes of Sound Scattering Acoustic Panels

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This research explores the design, fabrication and testing of acoustic panels in the context of architectural acoustics. A method of fabricating curved acoustic panels with locally diffusive geometry will be presented. A novel method of testing the sound distribution of a panel in 3-dimensions will also be presented, which uses a robotic arm to position a microphone along a hemispherical toolpath. My aim is to present a theoretical process by which one could start to correlate geometry and sound scattering in a multi-dimensional design space, and how this might fit into the context of architectural project, as shown in Figure 1.

Keywords: Architectural Acoustics, Digital Fabrication, Robotics, Empirical Testing

INTRODUCTION

Contemporary concert halls employ custom acoustic treatment which are mass-customised to respond to differing acoustic conditions across the auditorium, whereas in the past standardised products would have been used. These custom acoustic treatments can display differentiated acoustic qualities including absorption, scattering and diffusion; also known as ‘hybrid surfaces’ due to their ability to perform within multiple acoustic criteria (Cox and D’Antonio 2016, p. 313). The ability to create differentiated building elements using digital fabrication makes it possible to vary acoustic qualities throughout a space (Bonwetsch et al. 2008, p. 365). These treatments are often integrated into the wall or ceiling, as opposed to being distinct features, which allows the treatment to blend in with the architectural style. However, because the treatments are custom made for the project they do not come with the testing data that would come with a standardised product, which means we cannot accurately simulate the acoustics of a space in a digital model with these treatments present.

These treatments are often made from a gypsum composite and previous solutions to their fabrication often involves the use of CNC milling to either mill an EPS foam mould for GRG (glass reinforced gypsum), as in the case of Guangzhou Opera House (Exton 2011, p. 121) or to mill the gypsum fibreboard panel directly, as in the case of the Elbphilharmonie Concert Hall (Koren and Müller 2017, p.127). As part of this investigation, custom robot arm end-effectors have been created, including a hot wire cutter and hot knife cutter. This paper will propose a method of fabricating panels using a multi-axis robotic arm with these tools to create EPS foam moulds for GRG.
Current solutions for testing custom acoustic treatment involves empirically testing prototypes with specialised equipment or using software to digitally predict the performance of the panel prior to fabrication. When testing these treatments empirically a reverberation or anechoic chamber with a specific apparatus is required, depending on the aspect of performance being tested. However, access to this type of space and equipment is not always readily available. This paper proposes that if multi-axis robotic fabrication is to be used in the fabrication process then why not take further advantage of this tool and use it to position a microphone when testing the panel. This provides a more accessible way to test panels post-fabrication and could help to create a closer loop between the fabrication and testing of acoustic panels. This test could be used to analyse if a panel has an equal distribution of sound in all directions or that a panel might intentionally reflect sound in one direction more than others. The data from testing these panels can then be used correlate geometry with sound scattering properties (Reinhardt et al. 2017, p. 156).

The investigation will present the combination of a design, analysis and fabrication method, the results and discuss the potential of these methods.
METHODS

Tools for fabricating EPS moulds have been created including a large hot wire cutter and small hot knife to be used as robot arm end-effectors, shown in Figure 2. A two-step method has been employed which firstly uses a large hot wire cutter mounted to the robot arm to create the curvature of the global surface, shown in Figure 3, which is intended to direct reflections and scatter sound due to convex curvature; then using a hot knife to carve out the local surface condition, which is intended to scatter sound further. This fabrication method could allow us to create free-form moulds faster than CNC milling, due to the ability of these tools to cut a finished surface in one pass, whereas a CNC may need multiple passes to achieve a similar result (Clifford et al. 2014, p. 8). The foam used to create the moulds can even be fully recycled if a thin latex sheet is used to protect the mould while casting (Clifford et al. 2014, p. 13).

A tool for attaching a microphone to the robot arm has been fabricated. It is designed to have a minimal surface area so that it will not cause unwanted reflections that disturb the measurement (Ibid., p. 93). This testing method is based on the 3D goniometer which outlined in the AES-4id-2001 and ISO 17497-2:2012 standards. The setup, shown in Figure 4, uses the guidelines for performing the test in a non-anechoic room (Ibid., p. 91). The tool is used to take measurements along a hemispherical toolpath at 61 planes of measurement. Multiple microphones are not required as a single microphone can be positioned by the robot and measurements can be taken sequentially. A loudspeaker plays test tones and the SPL (sound pressure level) of the reflection is measured at each plane. Using this data, a polar balloon is constructed to represent a multi-dimensional understanding of sound reflections. A polar balloon is a 3D version of the polar pattern which is a mode of representation to describe the radiation pattern of microphones, loudspeakers and acoustic panels.

It is important to distinguish between diffusion and scattering, diffusion is how uniformly distributed sound is reflected; whereas scattering is the ratio of sound reflected in a non-specular way. The diffusion coefficient is used to define the quality of a panel; however, the scattering coefficient tends to be used for acoustic simulation to define the quantity of sound that is scattered (Cox and D'Antonio 2016, p. 87). The diffusion coefficient is calculated using a goniometer which measures the direction of reflections and it requires up to 37 microphones, arranged in either a semicircle or hemisphere depending on whether the test is 2D or 3D. If a panel scatters sound in multiple planes then a 3D setup must be used (Ibid., p. 89).
DESIGN EXPERIMENTATION

The design of the panels has been explored based on the limitations of the tools. The hot wire cutter can only create ruled surfaces and therefore cannot offer free-form surface creation comparable to CNC milling. In order to create more complex geometries, a hot knife tool was created which features a rigid piece of metal with high resistivity which can be shaped with different profiles. The method is defined by a directional sweep of a profile through foam and is distinct from CNC milling which is non-directional due to its spinning drill-bit (Clifford et al. 2014, p. 8). The large hot wire cutter tool is first used to ‘rough’ the foam block, removing the bulk of the unused material and creating a negative of the global surface which can be used in the moulding process subsequently. A hot knife tool is then attached in order carve out locally diffusive surface geometry. A curved profile has been utilised at different sizes to create a grid of convex nodes, the size of these nodes was varied on different panels to see how this affected scattering. After the EPS foam moulds have been created they are cast with a gypsum and glass fiber mixture. At scale the glass fibers give the panel a greater shear strength and allow much thinner depths of material.

The panels are measured using sine wave test tones at 7 frequency bands from 125 Hz to 8 kHz. The panel is irradiated with sound using a stationary loudspeaker which is designed with a flat frequency response and has a frequency range of 54Hz - 30kHz. When the sound stops the reflection from the panel is recorded using an omni-directional acoustic testing microphone which is also designed with a flat frequency response and has a frequency range of 15 Hz to 20 kHz. The planes of measurement are constructed along a hemisphere centred on the panel and the microphone is positioned normal to the hemisphere to measure the directionality of the reflection most accurately.
RESULTS
Three panels have been fabricated using the process outlined: a panel which is globally curved with no local surface carving, one which has been carved with the hot knife tool using a 20mm curved profile and another with that has been carved with a 50mm profile, the latter two are shown in Figure 5. These samples were designed to represent a variety of surface conditions that might be used as an acoustic treatment. The measurements shown in Figure 6 were taken while playing a 1kHz test tone, which represents a key frequency for both vocal and musical acoustical conditions. The data is converted from an impulse response to frequency response using a Fourier transform, and the SPL is used in the representation of a polar cloud, as shown in Figure 7.

- The panel with no local surface carving was found to have the strongest reflections, especially on the incidence angle from the loudspeaker, which could be due to the lack of locally diffusive geometry and could also be caused by a focusing effect from its global curvature.
- The panel with 20mm radius convex nodes featured weaker reflections than the previous panel with a similar overall distribution, potentially due to their similar global curvature.
- The panel with 50mm radius convex nodes was found to have the most evenly diffused distribution, showing the least high SPL reflections compared with the other panels. The more equal distribution could be explained by the 50mm convex node radius, because it is acknowledged that the scattering of higher frequencies is influenced by the width of geometry (Koren and Müller 2017, p.126).

DISCUSSION
A method of fabricating acoustic panels and a novel method of testing them has been shown. We are currently in the process of identifying problems with the testing method, such as the environmental noise caused by performing the test in a robotic lab, specifically ventilation and mechanical sounds, and attempting to mitigate these issues.
The room is reverberant, as opposed to anechoic, this is not a problem in a 2D goniometer setup which use boundary microphones to remove the floor boundary, however, with a multiple plane method this solution does not apply. In this setup there are potential unwanted reflections from the floor and walls which can invalidate the measurement if not properly acoustically treated. In terms of evaluating the results, polar clouds were produced in this investigation, however, to truly evaluate the performance of the panels then diffusion, scattering and absorption coefficients must be calculated. Methods of understanding these areas of performance are being studied in more recent investigations. Another consideration is the design of the panels, as the samples were designed to present a variety of surface conditions, however, if they were optimized first in the digital model then their acoustic performance could be much greater. This would also reduce the costs associated with a trial and error approach. We hope that further studies will be able to create stronger correlations between geometry and sound. By studying global surface direction and local surface geometry, more acoustic tendencies can be identified, then larger scale prototypes can start to test differentiated qualities across a surface. This study is the first step toward an empirical and localised understanding of multi-dimensional sound scattering using a robotic arm, with further development this could start to inform how large scale acoustic treatment is created in a hybrid digital and analog design space enabled by robotics.

REFERENCES