A PHYGITAL FORM-FINDING METHOD FOR BODY-SCALE SOUNDSCAPE INSTALLATION WITH FLEXIBLE MATERIALS

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Abstract. Body-scale spatial installations with flexible materials effectively shape the soundscape in micro-environments. Design directives for such installations primarily rely on digital simulations and physical experiments. However, common acoustic software often fails to authentically replicate real experiential effects in compact installations. In contrast, physical experiments offer precise insights into the relationship between material forms and acoustic outcomes. Thus, a combined approach using virtual simulations and physical experiments across various scales is essential to determine the morphology and distribution of the flexible material. This research proposes a progressive design method for prototypes of soundscape installation, amalgamating phygital experimentation-based reasoning. It aims to validate the pivotal role of diverse experimental data and explore their integration within architectural design processes. The methodology involves software simulations, scale-down physical experiments, and full-scale tests, providing incremental design conclusions and facilitating the gradual realization of architectural design solutions. This approach was successfully applied to the "Natural Speaker" installation, presenting an innovative, shared experiential dataset and fostering fresh insights for soundscape design.

Keywords. Urban Soundscape, Phygital Experiment, Flexible Material, Form-finding Method, Architectural Design

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1. Introduction

1.1. BACKGROUND

The concept of soundscape was introduced by R. Murray Schafer in the 1970s (Schafer, 1993) to encompass the amalgamation of all sounds within a specific location or environment. Subsequently, Kang Jian proposed the concept of urban soundscapes in 2007, focusing on the formation of soundscapes within cities(Jian, 2007). A well-crafted soundscape can elevate spatial experiences and shape people's perceptions and emotional responses to space. Conversely, unfavorable soundscapes might have adverse effects on the health and psychological well-being of humans and other organisms(Fritschi et al., 2013). Consequently, numerous researchers have endeavored to shape favorable soundscapes through the design of sound propagation.

Materials possessing unique acoustic properties have garnered attention, with particular emphasis on flexible materials, such as textiles(Fridh et al., 2019). Besides, to enhance the acoustic characteristics of specific spaces, designers commonly employ body-scale spatial installations for acoustic design(Fusaro et al., 2018). These installations, characterized by their small size, adjustability, and mobility(Steele et al., 2019), can adapt to diverse urban environments, actively engaging in the shaping of urban soundscapes(Cerwén, 2016).

However, the design of body-scale spatial installations encounters challenges. Due to their compact size, body-scale installations often overlap with the spatial areas influenced by user behavior. It's necessary to consider the differences in acoustic performance caused by body positions. This complexity demands a more refined simulation and validation concerning soundscape. However, for the common acoustic design software, such as EASE (Enhanced Acoustic Simulator for Engineers), they often focus on larger spaces, making it challenging to accurately reflect the real experiential effects of body-scale spatial installations. Hence, in the process of optimizing the form and materials of body-scale spatial installations, a combined approach using different scales is necessary to determine the form and distribution of flexible materials, thereby enhancing the efficacy of body-scale spatial installations.

1.2. LITERATURE REVIEW

Numerous scholars have extensively researched the design methods for soundscape installation, with a primary focus on digital simulations. The integration of APBD (Acoustic Performance-Based Design) (Badino et al., 2020)allowed for the early identification of dependencies between design features and acoustic performance. Projects like the Smithsonian Institution Courtyard Enclosure and Manufacturing Parametric Acoustic Surfaces (Peters, 2010) demonstrate the potential of using sound simulation parameters. Genetic algorithms and APBD have been repeatedly employed in prior research projects for the form-finding of acoustic shells. The Aalborg Acoustic Pavilion (Foged et al., 2014), utilizing evolutionary computational strategies, achieves direct feedback between form, material and acoustic performance through comprehensive simulations. Similarly, projects like Soundforms (Foged et al., 2012) and RES (Resonant Strings Shell) (Mirra et al., 2018) exhibited researches akin to exploring diverse topological structures using acoustic predictions. In these cases, the optimization are usually based on Grasshopper plugins like Galapagos.

Contrary to digital simulations, physical experiments have also been incorporated into acoustic performance design considerations. An exemplary case is RES(Mirra et al., 2018), notable for its cyclic mechanism involving yearly fabrication experiments and on-site measurements during outdoor music festivals. This approach leverages machine learning for acoustic design, compensating for the lack of utilization of actual measurement data in the design process and validating the accuracy of the Aeolus plugin (Mirra et al., 2023) in early reflection predictions for musical scenarios.

However, for soundscape installations with flexible materials, numerical simulation or physical experimentation alone may not be applicable to the design of small soundscape installations with flexible materials. Research by Alvise Morandi and Carol Monticelli (Morandi & Monticelli, 2023) isolated flexible materials from secondary features of acoustic reflection installations, initially validating the effectiveness of membranes and their forms in noise control. Previous acoustic simulations have used an approximation in which the surface of the installation was considered to be a plane that reflects sound waves. The impact of this approximation on the simulation of flexible structures still needs to be verified Therefore, although previously physical experiments were mostly used for validation and localized testing in the later stages of design. However, it is particularly needed in the pre-design of flexible materials where the behavior in the acoustic environment is not yet known.

Moreover, prior practices largely focused on music performances and conference scenarios, abstracting most receivers as defined-height receiving planes (Foged et al., 2014) or defining spherical ranges(Morandi & Monticelli, 2023). The Aeolus plugin (Mirra et al., 2023) enabled rapid generation of 2DSPL diagrams. However, for the research related to body-scale soundscape installations, consideration of receiver bodily behavior becomes essential. Thus, the extension of acoustic prediction tools into 3D spaces warrants real-world acoustic environment integration.

In summary, while computational power enables traditional digital software to offer a basis for spatial form through multi-objective optimization, real physical experiments intuitively and effectively establish relationships between specific materials and acoustic properties. Combining digital simulation and physical experiments in the design process of body-scale soundscape installations would be a valuable research direction.

2. Proposal

This research proposes a progressive design methodology for body-scale soundscape installations based on the integration of digital and physical experiments. It aims to validate the guiding role of multi-source experimental data in the design process and explore its alignment with architectural design process. This method deconstructs the design process, identifying specific design problems at each stage and translating them into digital or physical experimental methods by controlling parameters. Designers use the experimental data generated at each stage as a basis for design conclusions, applying them in subsequent discussions, gradually derive architectural design solutions.

Specifically, the method consists of three cyclical stages:

(1) Digital simulation. Designers simulate the initial form of the installation by using acoustic software to obtain rough topological and shape information.

(2) Scale-down physical experiments. To address uncertainties in digital software, designers conduct physical experiments on various derived forms of the installation, acquiring more accurate data and scientifically formulating acoustic strategies.

(3) Full-scale physical experiments. The data derived from scale-down experiments cannot be directly related to the human experience. Therefore, full-scale physical experiments are included in the design methodology as an important validation.

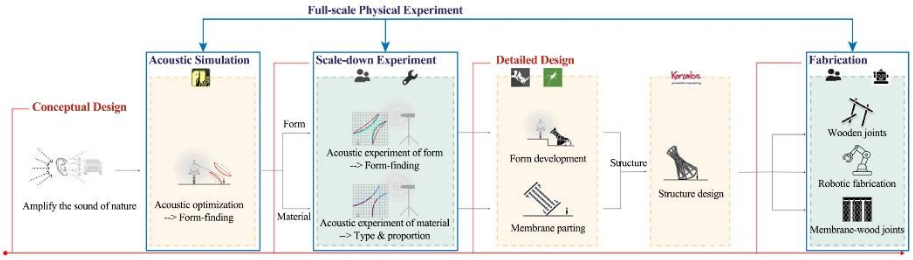

Figure 1. An illustration of the method proposed

3. Case study

This methodology was demonstrated in the design process of the "Natural Speaker", a body-scale soundscape installation. Within this project, the initial design process was divided into four stages: form generation, form elaboration, material selection, and material distribution. A combined approach involving software simulations and physical experiments was adopted to complete the design reasoning for each stage.

3.1. EXPERIMENTAL SETUP

This section predominantly focuses on the preparation of software, physical model and variable design for scale-down physical experiments. For the software, Grasshopper plugins for acoustic simulations were involved. Hardware requirements include: (1) components for physical models such as aluminum alloy frames, wooden boards, acrylic sheets, and hand tools. (2) equipment for measuring sound effects, including sound sources, a source controller, sound level meters, and tripods; (3) materials for testing, comprising fabrics and membranes. Materials and tools for full-scale physical experiments will not be discussed at this stage due to its complexity.

Figure 2. Equipment and materials for the experiment

In terms of physical model design, it consists the frame, the material under test, and the sound detection equipment. The frame was used to fix the material under test. A scaling ratio of 1:50 was used for the experiment, so an aluminum alloy frame with slots of 1300*900*1200mm dimensions was used. Meanwhile, wooden and acrylic boards were embedded in the frame to block the sound diffusion. The wooden and acrylic boards come with grids in order to fix the material in proportional segments. In order to focus on the experimental object, the profile morphology was extracted and used as the main object of study for the experiment. Thus, the tested materials are mainly the two parts that make up the profile. The material was fixed with the help of wooden strips placed between the wooden and acrylic boards.

The experiment comprises four types of variables: forms of section, types of the materials, proportions of the materials, and the location of acoustic equipment. Based on the digital simulation results. Nine profile forms are proposed. To simplify the experimental steps, forms A, B, and C are selected as representatives. The composition of the materials encompasses three types: pure fabric, pure membrane, and a composite of fabric and membrane material. There are three variations in the assembly position for both upper and lower materials, resulting in nine assembly methods denoted as A-1, B-1, C-1, A-2, B-2, C-2, A-3, B-3, and C-3. For the location of acoustic equipment, when testing the effects of bird sounds on people, the sound source was placed on the axis of the profile, simulating the location of the birds in the design. The sound level meter was placed at the human ear location. When testing the effect of human sound on the bird, the positions of the sound source and the sound level meter were switched.

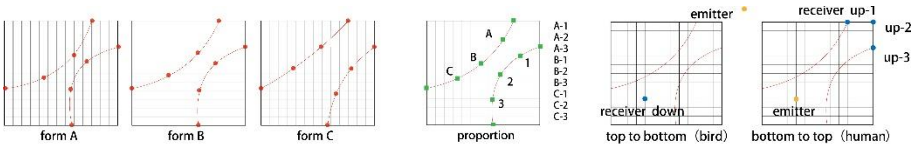

Figure 3. Definition of variables for the experiment

3.2. EXPERIMENTAL PROCESS

The experiment has two goals. On the one hand, the experiment can instruct on how to amplify the bird's voice, so that people can hear the birdsong more clearly. On the other hand, the experiment can instruct how to reduce the human voice so that the human voice does not disturb the bird's normal stay as much as possible. In terms of experimental arrangement, initially, multi-objective optimization of the overall form of the installation was conducted using acoustic-related digital plugins. Subsequently, the material distribution of the installation was obtained through a scale-down physical experiment. Lastly, an evaluation was conducted through full-scale experiments to validate the accuracy of the aforementioned stages.

3.2.1. Digital Simulation experiment

In the software simulation phase, the study utilized the Pachyderm Acoustic plugin in Rhino-Grasshopper for acoustic simulations. To replicate real-world scenarios within the design environment, the simulated sound source was positioned at the height of tree. Before the simulation process, an initial installation form was designated. Through continuous feedback from acoustic simulations of sound reflections, parameters controlling the form would be iteratively adjusted. Eventually, an optimal solution for parameters was obtained. It implied a best form of surface for sound propagation.

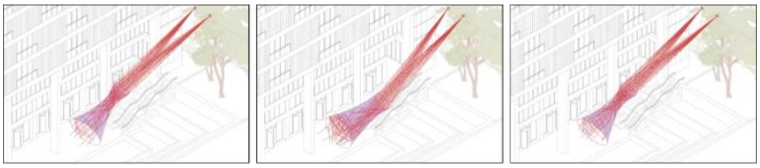

Figure 4. The process of digital simulation of acoustic performance

3.2.2. Scale-down physical experiment

Form	Material	Dividing Location	Receivers' Locations	Stage
/	none	/	up-1 up-2 up-3 bottom	stage 0
form A form B form C (3 types)	membranes textile+membranes (2 types)	none (1 type)	bottom (1 type)	stage 1 = (6 rounds)
form B (1 type)	membrane(up)+membrane(bottom left)+membrane(bottom right) membrane(up)+textile(bottom left)+membrane(bottom right) membrane(up)+textile&membrane(bottom left)+membrane(bottom right) membrane(up)+membrane(bottom left)+textile(bottom right) membrane(up)+textile(bottom left)+textile(bottom right) membrane(up)+textile&membran(bottom left)+textile(bottom right) membrane(up)+membrane(bottom left)+textile&membrane(bottom right) membrane(up)+textile(bottom left)+textile&membrane(bottom right) membrane(up)+textile&membran(bottom left)+textile(bottom right) (9 types)	× B-2 (1 type)	up-1 up-2 up-3 (3 types)	stage 2 =(27 rounds)
form B (1 type)	membrane(up)+textile&membran(bottom left)+textile(bottom right) (1 type)	A-1 A-2 A-3 B-1 B-2 B-3 C-1 C-2 C-3 (9 types)	up-1 up-2 up-3 bottom (4 types)	stage 3 =(36 rounds)

Figure 5. Experimental process of the scale-down physical experiment

The previous step of digital simulation led to a theoretically optimal form. However, for body-scale installations, it demands more precise and reliable data guidance for sound effects. Thus, scale-down physical experiments were conducted. This process contained three progressive steps: (1) A best form would be selected according to the result of acoustic pressure testing with different forms. (2) The type of the material of the installation would be determined through acoustic pressure testing results. (3) The distribution of the material would be determined through another set of acoustic pressure testing experiments.

At the beginning, the experiment measured sound propagation in the absence of materials. Subsequently, the reasoning experiments for the form and material started. The aim of the experiments was to derive an optimal shape to maximize birdsongs reaching the human ear. The experimental tested the differences in acoustic performance at the human ear position with the 3 different forms of A, B, and C under identical material conditions. The materials used in experiments were unified as membrane or a composite of membrane and fabric. In the experiment, materials were set to predetermined lengths, fixed onto the aluminum frame. The sound source was mounted on a tripod fixed in the location of the axis of the section of the installation. Controlled by a sound source controller, it emitted pink noise. The sound level meter was positioned beneath the cross-section, simulating the location of the human ear.

Comparing data from two sets of experiments, the sound pressure level exhibited the best performance in LAF at Form B. Consequently, form B was selected as the morphology of the installation.

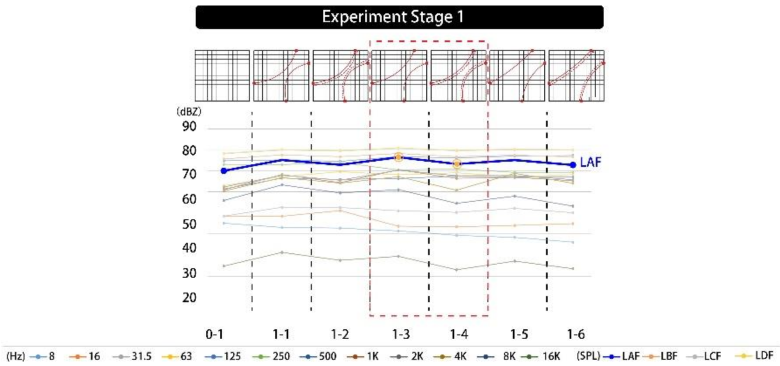

Figure 6. Results of the stage 1 of the scale-down physical experiment

After the morphology was determined, the experiment attempted to deduce the type of the material of the installation. The purpose of this set of experiments was to test under which material composition human voice could be maximally absorbed by the installation, thus not disturbing birds. In the experiments, the form remained a fixed parameter of form B, while materials were successively replaced with different types. Considering that fabrics do not have the ability to reflect sound in a way that would adversely affect the transmission of bird sound, the material above the two components of the cross-section was considered to be membranes. Conversely, the materials in the lower parts of the cross-section were individually replaced with three types (pure fabric, pure membrane, and a composite of fabric and membrane), yielding a total of 9 experimental scenarios. The sound source, simulating human voice, was fixed close to the top of the installation near where a user's mouth would be. The sound level meter was placed at 3 different positions at the top of the axis of the cross-section, mimicking the sound perceived by birds.

Comparing the results of the experiments, it was found that when the upper section of the installation was membrane and the lower section was a composite of fabric and membrane, the propagation of human voice was minimized for birds. Consequently, this material type was chosen for the installation.

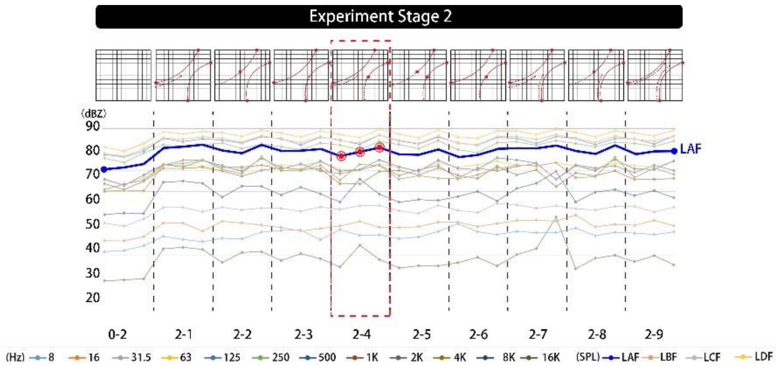

Figure 7. Results of the stage 2 of the scale-down physical experiment

In order to derive a more specific distribution of the material, the experiment conducted sound pressure measurements by varying the proportions of the material combinations based on the aforementioned materials. The purpose of this experiment was to obtain a material distribution ratio that would optimize the composite indicator of bird and human sounds. The experiment selected four equally spaced points on the cross-sections, totaling 9 sets of scenarios. The sound source was placed both up and down, measuring the acoustic performance of both birdsongs and human voices.

In the comprehensive comparison, the optimal effect in sound propagation was observed when the material junction points of the upper and lower cross-sections were respectively located at positions A and 2. Consequently, this proportion of the material was chosen for the material design of the installation.

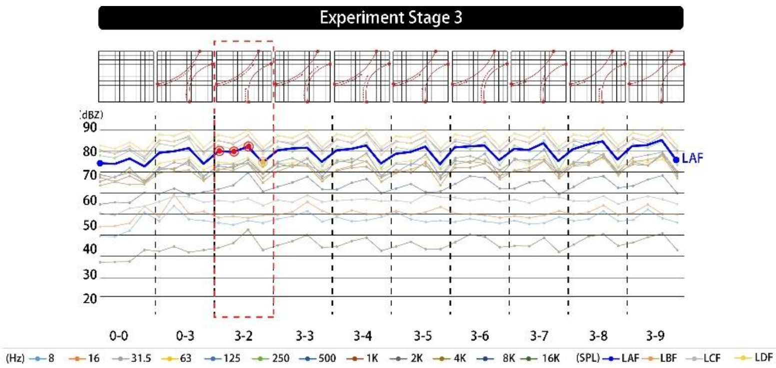

Figure 8. Results of the stage 3 of the scale-down physical experiment

3.2.3. Full-scale physical experiment

Although scale-down experiments provide highly intuitive data regarding sound propagation effects, they were insufficient to form reliable judgments regarding human experience. Therefore, a full-scale physical model becomes crucial as it allowed for the evaluation of whether previous experimental data and design strategies were truly effective and meaningful in terms of subjective experiences.

A full-scale experiment in a spacious outdoor location in Shanghai. The installation was positioned facing a tree frequently inhabited by birds, serving as the source of sound emission. Constructed primarily using pure membrane material as the enclosure structure and wood as the sup-port structure, the installation was divided into 50*50*50cm spatial grids during the experiment. Measurements and assessments of sound pressure at grid points within the spatial framework and human perception of bird sounds were con-ducted. Ultimately, it was observed that locations where bird sounds measured higher sound pressure levels also elicited stronger human perceptions of bird sounds (higher scoring in subjective assessments). This observation indicates that the outcomes guided by previous experiments have good guiding significance for real experiential perceptions.

Figure 9. Images of the process of full-scale physical experiment

4. Discussion

Despite the effectiveness of this general method, there remains improvement in the actual installation design process. For instance, in the scale-down experiments, cross-section was used to simplify design reasoning. However, in reality, the three-dimensional state of the physical installation would provide more data information than the two-dimensional profiles, enabling guidance for both the design of the listening position for humans and the resting location for birds.

5. Conclusion

The utilization of body-scale installation with flexible materials is considered an effective method for soundscapes. However, due to the higher demands of body-scale spatial installations for embodied experiences, digital acoustic simulation often fails to meet the data requirements for design.

This research explores the soundscape installation design process from an architectural perspective and introduces a progressive design method that combines experimentation with design. Through a three-stage process involving digital simulation, scale-down physical experiments, and full-scale physical experiments, the form and material design of the installation is derived. In this process, multisource sound data from both software simulation and physical experiments are integrated into the installation design process and serve as crucial foundations for design advancement.

This method is validated in the design process of the "Natural Speaker" soundscape installation. The results demonstrate the effectiveness and generalizability of the proposed method. Additionally, the study has generated experiential data that will be shared on GitHub. Furthermore, the research contemplates utilizing the experimental data of acoustic performance to establish a general correspondence among form, materials, and soundscape. This initiative aims to foster new inspiration and contemplation in soundscape architectural design for future reuse, potentially opening new avenues of thought in this field.

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