

A Computational Method for Integrating Parametric Origami Design and Acoustic Engineering

An application to a concert hall design

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Abstract. *This paper proposes a computational form-finding method for integrating parametric origami design and acoustic engineering to find the best geometric form of a concert hall. The paper describes an application of this method to a concert hall design project in Japan. The method consists of three interactive subprograms: a parametric origami program, an acoustic simulation program, and an optimization program. The advantages of the proposed method are as follows. First, it is easy to visualize engineering results obtained from the acoustic simulation program. Second, it can deal with acoustic parameters as one of the primary design materials as well as origami parameters and design intentions. Third, it provides a final optimized geometric form satisfying both architectural design and acoustic conditions. The method is valuable for generating new possibilities of architectural form by shifting from a traditional form-making process to a form-finding process.*

Keywords. *Interactive design method; parametric origami; acoustic simulation; optimization; quadrat count method.*

INTRODUCTION

Design for a concert hall includes acoustic engineering and architectural design (i.e. aesthetically pleasing design that satisfies complex architectural conditions, such as concert activities, building regulations, structure, construction processes, budgets and so forth). Usually, computation is often used for generating all possible geometries fulfilling those various architectural constraints. However, the most difficult part of design processes is to choose the best geometric form among the resulting various alternatives.

This paper proposes a computational method for integrating parametric origami design and

acoustic engineering to find the best geometric form of a concert hall. First, we discuss the limitations of conventional collaborations between architects and acoustical engineers. Second, to overcome these limitations, we develop an interactive design method and show its application to a concert hall design project in Japan (the hall will be completed in 2014). The design method consists of three interactive subprograms: a parametric origami program, an acoustic simulation program, and an optimization program. Finally, we describe the advantages of the proposed method, including the ease with

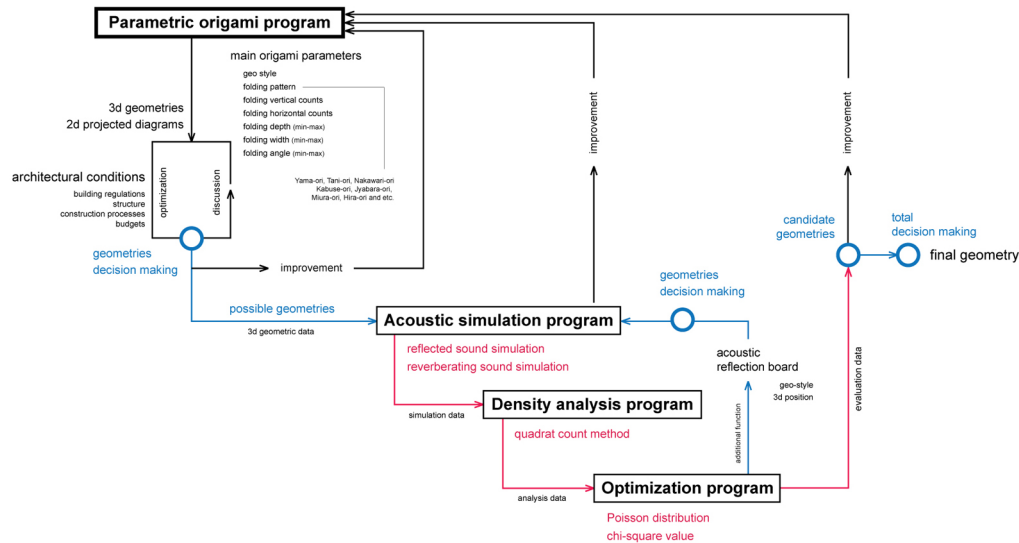


Figure 1
A diagram of the interactive design method.

which it visualizes engineering results obtained from the acoustic simulation program, and a final optimized geometric forms it provides to satisfy both architectural design and acoustic conditions. Because the method efficiently manages fundamental factors underlying architectural forms, it can provide a design framework in which architectural design and acoustic engineering are integrated.

THEORETICAL BACKGROUND

In the design process for a concert hall, architects collaborate with acoustical engineers. First, architects develop a geometric form and then acoustical engineers analyze the acoustic efficiency of the proposed form using their simulation program. However, there are relatively few exchanges between them. As a result, in the conventional method architectural optimization and acoustical optimization tend to be rather independent operations, and they are not always coordinated. For instance, acoustic optimization does not always take into account complex architectural conditions or the architects' design intentions, whereas architects do not always utilize informative data provided by the acoustical

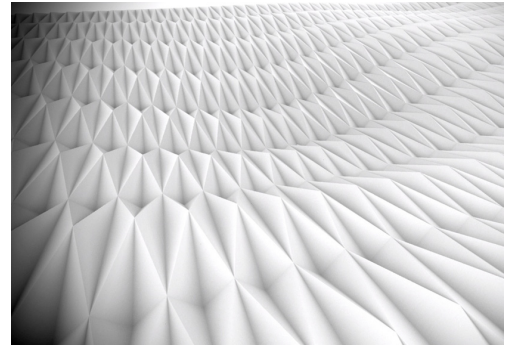
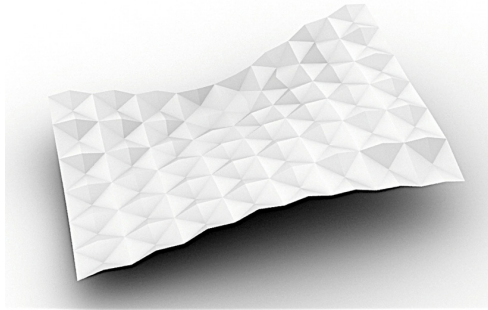
engineers. To bridge this gap, we propose a computational design method for integrating architectural design factors and acoustical engineering factors.

In addition, we want to develop an objective method in which acoustic data derived from a simulation process are efficiently utilized. In this connection, Leach (2009) mentioned as follows: "Within contemporary architectural design, a significant shift in emphasis can be detected – move away from an architecture based on purely visual concerns towards an architecture justified by its performance. Structural, constructional, economic, environmental and other parameters that were once secondary concerns have become primary – are now being embraced as positive inputs within the design process from the outset". Our proposed interactive design method can deal with acoustic parameters as one of the primary design materials as well as origami parameters and design intentions (Figure 1).

With the recent improvement of computer performance, simulation technology has improved significantly. As a result, it has become easy to visualize the state of the acoustic parameters. What makes our method intriguing is that those parameters can

Figure 2

The parametric origami program can transform a flat sheet of paper into a geometric form through various folding techniques: basic techniques (Yama-ori, Tani-ori, Nakawari-ori, Kabuse-ori), advanced techniques (Jyabara-ori, Miura-ori, Hira-ori and so on).



find unpredictable forms which meet both acoustic conditions and design intentions.

EXISTING RESEARCH

In the existing studies, the use of computational methods for designing concert halls is limited to performing two tasks: acoustic simulations and generation of all possible geometries satisfying various architectural constraints. However, there are few methods for choosing the best geometric form among the resulting numerous alternatives.

In this paper, we apply a computational method not only to acoustic simulation and generation of various possible geometries but also determination of the best geometric form satisfying both the architectural design and acoustic requirements.

CONCERT HALL DESIGN PROJECT

In this paper, we apply the interactive design method to a concert hall design project in collaboration with SUEP architects (an architectural office) and

Nagata Acoustics (an acoustical consulting firm). The design method consists of three interactive subprograms: a geometric form-generating program, an acoustic simulation program, and an optimization program.

Geometric form-generating program: the parametric origami program

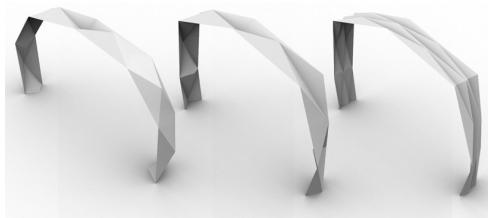
The first subprogram, the parametric origami program, adopts the idea (proposed by the SUEP architects) that a form is generated by folding a sheet of paper—the traditional Japanese art called ‘origami.’ The program can transform any surface into a geometric form using the basic folding parameters of the origami folding system: folding lines, folding depth, folding width, folding angles and so on (Figure 2). These are mutually constraining (i.e., not independent) parameters.

The objective of this parametric origami program is to develop a method for finding combinations of origami parameters which generates geometries fulfilling complex architectural constraints (Figure 3). The computer technology enables us to test every combination of parameters in order to find out possible designs that meet certain requirements. In this process, designers are no longer making single geometry but finding design parameters which determines a final form (Figure 4).

Another feature of this program is: if there is no combination of parameters that meet every requirement, then the program provides an alternative

Figure 3

A diagram of generating architectural form fulfilled complex architectural constraints.



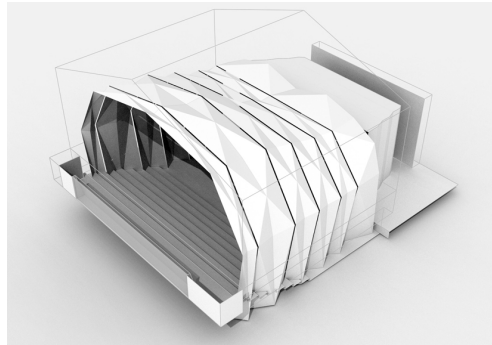
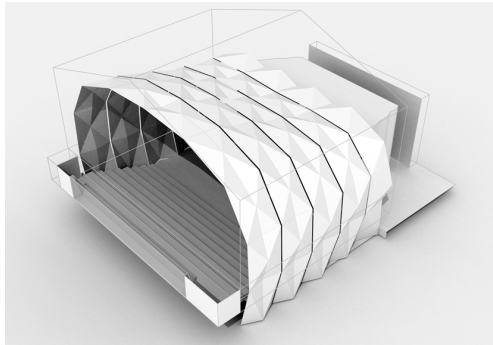


Figure 4
Possible form variations.

combination. In the literature, a few studies deal with computational origami methods for architectural design. Most of them follow a strict origami rule such that a single sheet of paper is fold into a given polyhedral surface without any cut. However, in architectural design processes, this rule sometimes disturbs design intention or other architectural performances. To overcome this limitation, the method enables us to balance parameter weights in an optimization process. That is, the method allows us to cut a sheet of paper or loosen architectural constraints, in the process of balancing between origami rules, acoustic performances and design.

Acoustic simulation program

The second subprogram is an acoustic simulation program, which deals with geometric acoustics, i.e.

sound propagation in terms of straight rays.

There are some existing software packages which can simulate sound propagation and geometric forms interactively. However, it can simulate only the distribution of direct sound, which is not enough for sound optimization of a concert hall. To overcome these limitations, we developed an acoustic simulation program which visualizes sound propagation in a three-dimensional space over time in three ways: by arrows originating from a sound source at an arbitrary point in a hall; the distribution of reflected sound; and the distribution of reverberating sound (Figure 5).

These two subprograms, the acoustic simulation program and the parametric origami program, run interactively in the following manner.

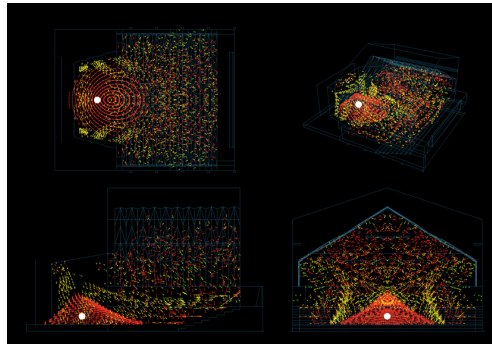
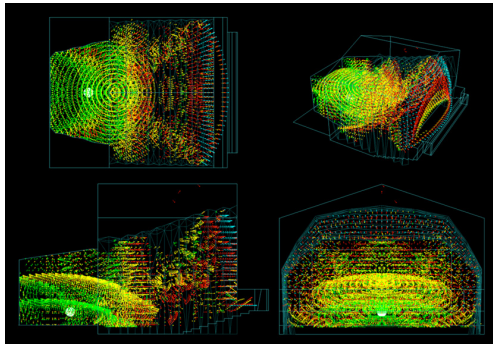
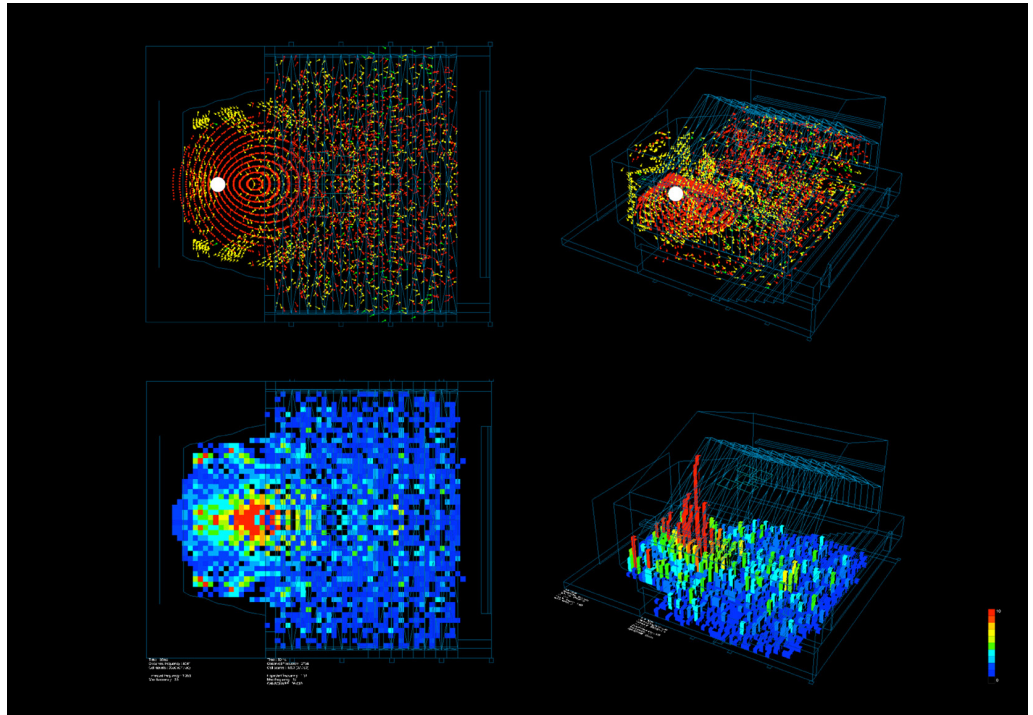


Figure 5
Left: reflected sound simulation, Right: reverberating sound simulation.

Figure 6
Distribution of sound density.



Optimization program by the quadrat count method

First, the parametric origami program generates all possible geometries of a hall according to the parameters derived from the architectural conditions (resulting from building regulations, structure, construction processes, budgets and so forth), the folding parameters determined by the architect's aesthetic sense and allowable parameter values derived from the origami folding system. Then, for each possible geometric form, the acoustic simulation program visualizes sound propagation and the distribution of sound reached at each audience member's seat (Figures 6 and 7). Given the outcomes of each possible geometry, the optimization program judges which is the best combination of parameters that satisfies both the architectural design and acoustic requirements. Acoustic requirements (proposed

by the Nagata Acoustics) include: first, the sound is distributed evenly over the hall and audience seats in 30 to 90 ms; second, there is no echo or flutter echo; and third, there is no sound focus. To examine whether or not sound is uniformly distributed over the hall, we applied the quadrat count method with the Poisson distribution. The program automatically calculates the chi-square value for testing uniformity in each form, given by:

$$\chi^2 = \sum (O-E)^2/E,$$

where O denotes observed values and E denote expected values (Figure 8).

Another notable aspect of the optimization program is that it can easily change the conditions of acoustic requirements which vary according to collaborators. Such flexibility produces various architectural designs in accordance with collaborators.

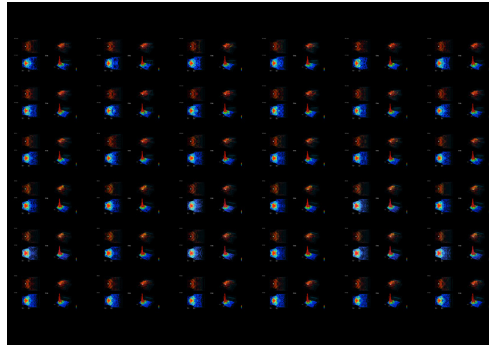
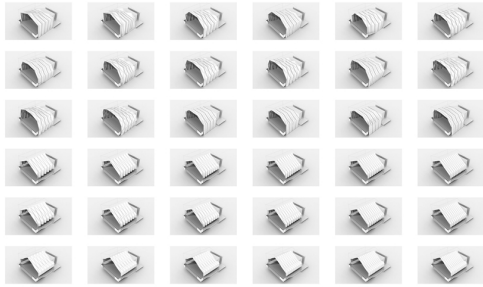


Figure 7
The part of various possible geometries of a hall according to the parameters derived from the architectural conditions, and the results obtained by the acoustic simulation program.

The results of the project

The concert hall design project is part of the design project for a cultural-arts complex in Ureshino-shi, Saga-ken (southern part of Japan). SUEP architects designed this whole project under the design concept of a folding roof. In collaboration with them, we considered that the following three conditions should be satisfied.

- To shorten the processing time for finding variations of origami folding patterns fulfilling architectural constraints.
- To find out a geometric form satisfying not only acoustic performance but also designer's intention. Because following the advice of acoustic engineers often results in a cave-like form (which is acoustically effective) but such a form does not always meet architectural design intentions.
- To discover unexpected geometries which optimize for both acoustic and design conditions.

Quadrat analysis

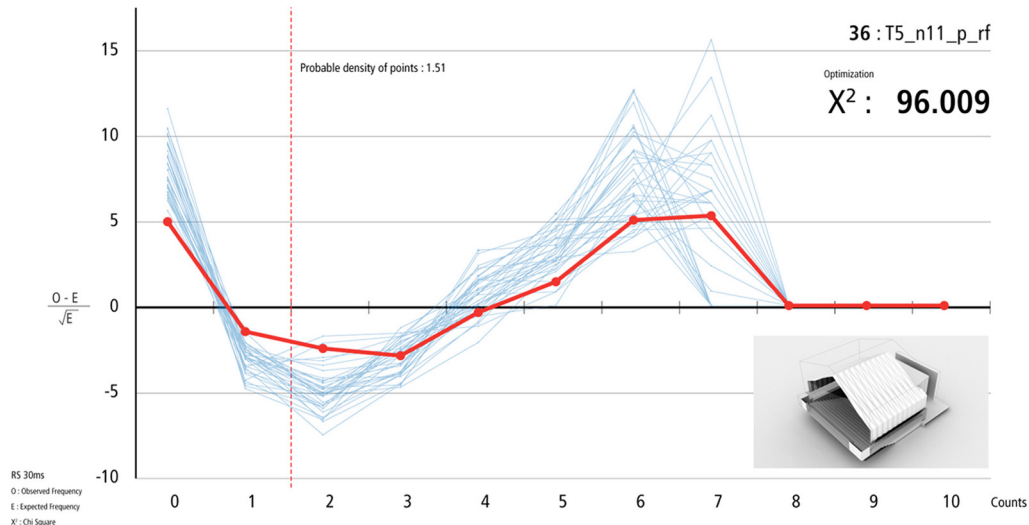
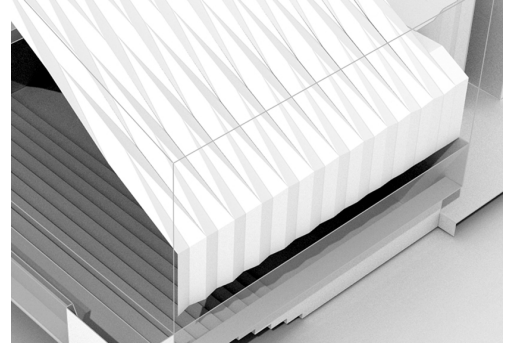
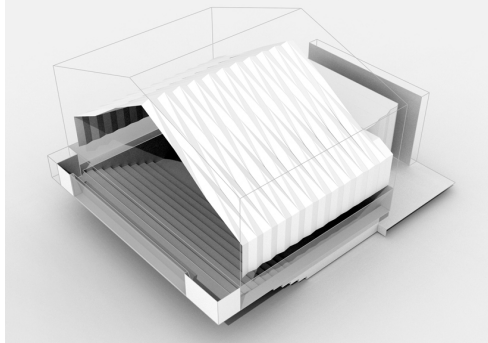


Figure 8
The results obtained by the quadrat method

Figure 9

Left: the final model of the concert hall generated by modified Miura-ori taking account of various folding parameters. Right: Details of the final model of the concert hall.



With the proposed computational method, about two hundred possible geometries were generated, among which the final geometry of the concert hall was chosen through the optimization process.

The folding pattern of the final geometry is based on Miura-ori, consisting of concave polyhedral surfaces. At first glance, the final geometry looks simple but it is complex in the sense that the folding depth and angle are delicately controlled (Figure 9).

CONCLUSION

This interactive relationship enables us to choose the best combination of parameters satisfying both architectural design and acoustic requirements among numerous possible forms. Parametric design is often used to explore complex geometries, but in this method it is used to promote complex interactions of collaborators.

Terzidis (2006) mentioned about a form-making process as follows: “architects and designers believed that the mental process of design is conceived, envisioned and processed entirely in the human mind and that the computer is merely a tool for organization, productivity, or presentation”. However, the computational form-finding process allows us

to take account of acoustic parameters as one of the primary design materials as well as designer’s sense.

Computational technology is not only useful for improving or automating design processes, but it is also valuable for generating new possibilities of architectural form by shifting from a form-making process to a form-finding process.

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