Optimization of Natural Frequencies for Fabrication-Aware Shape Modeling

Christian Hafner* Przemyslaw Musialski* Thomas Auzinger* Michael Wimmer* Leif Kobbelt†
*Vienna University of Technology †RWTH Aachen University

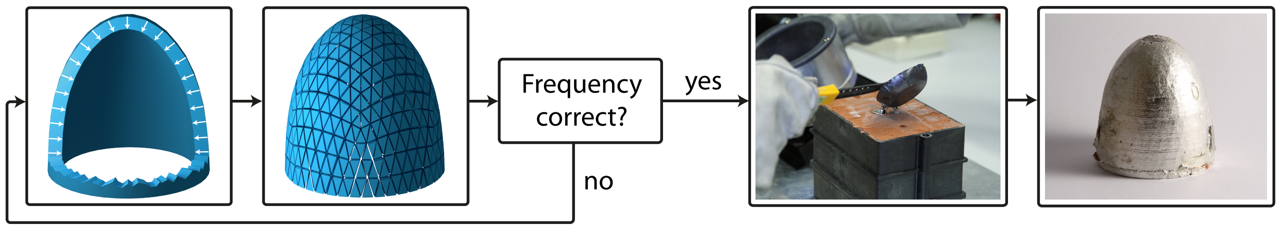

Figure 1: *The optimization loop works on offset surfaces and evaluates the incumbent solution using a finite element mesh. Once the optimal wall thickness for a given pitch is found, we cast the result using sand molds and tin.*

1 Introduction

Keyboard percussion instruments such as xylophones and glockenspiels are composed of an arrangement of bars. These are varied in some of their geometrical properties—typically the length—in order to influence their acoustic behavior. Most instruments in this family do not deviate from simple geometrical shapes, since designing the natural frequency spectrum of complex shapes usually involves a pain-staking trial-and-error process and has been reserved to gifted artisans or professional manufacturers.

In our work, we propose an automatic approach for creating novel instrument designs in a general setting far beyond 2d plates. Our goal is to develop a framework that takes a target shape, a target pitch, and material properties as inputs. With the help of an optimization routine, a 3d solid is then synthesized that matches both the target shape and pitch as closely as possible when fabricated out of the specified material.

2 Approach

Realistic sound synthesis of virtual objects has a long tradition in computer graphics [O'Brien et al. 2001]. In this paper, we approach the inverse problem: given a desired sound and a base shape, find a similar shape that exhibits the sound. A first attempt in providing an intuitive design tool to allow the creation of complex planar shapes was presented by Umetani et al. [2010]. During the editing process of a 2d shape, a user is informed about its acoustic properties (i.e., the pitch) interactively. However, deviations of up to 6% between the simulated frequencies and the frequencies of fabricated results necessitate manual adjustments after production.

In this paper, we build upon the theory of the finite element method, however, we developed a modal analysis tool that can predict the natural frequencies of 3d solids to an accuracy of at least 2.5% without requiring any parameter tuning. This is made possible by the use of quadratic thin-shell elements. In contrast, linear elements, which are used by most shape optimization applications (e.g., Umetani et al. [2010]), cannot accurately predict bending phenomena and are unsuitable for accurate vibration analysis and further synthesis.

*e-mail:chafner@cg.tuwien.ac.at

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Figure 1 illustrates the pipeline of our approach. Given a target shape and pitch, we parameterize the shape using an offset surface with a single offset value. We found that it suffices to optimize a single parameter to attain this pitch in the fabricated object. Currently, we input a triangular mesh and synthesize a thin-walled solid from it by computing a corresponding offset inner surface. Self-intersections of the offset surface are handled by suitable constraints. The wall thickness constitutes our optimization parameter and we seek to minimize the deviation of the lowest frequency of the solid's natural spectrum from the target pitch. Our framework is formulated in a general manner and any off-the-shelf solver can be used for the implementation of our system. We opted for Matlab's `fmincon`, which utilizes sequential quadratic programming.

3 Results

We validated the accuracy of our simulation by comparing the output frequencies to the natural frequencies of real-world objects in the form of aluminum plates. We recorded the sound of the plates when struck with a mallet with a conventional microphone and extracted the frequency peaks using Fourier analysis. Using reference material properties for aluminum, we observed agreement between the calculated and the recorded frequencies within 1.5%.

We tested our framework by optimizing a 6cm tall bell-shaped surface to yield the frequency of the tone "A6" (i.e., 1760Hz) if cast out of pure tin. After 40s of computation time, the optimal wall thickness was found to be 3.2mm. In our production pipeline, a plastic copy of the solid was generated with an FDM printer, which was used to create a negative out of molding sand, which, in turn, was filled with molten tin. After rasping off small fabrication errors, we found a deviation of only 2.5% between the simulation result and the pitch of the bell sound. This was achieved using reference material parameters and without any parameter tuning. This gives us confidence that the final framework will allow the intuitive design of a wide range of shapes with accurate acoustic behavior.

References

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