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3D printing for custom design and manufacture of microtonal flutes

Christian Ritz, Matthew Dabin, Terumi Narushima, Kraig Grady, and Stephen Beirne

Mathematical modeling of wind instrument acoustics facilitates the manufacture of flutes with customized tunings.

Conventional Western instruments are designed and manufactured to play music in the standard tuning system of 12-tone equal temperament. As a result, they are inadequate for realizing the abundance of alternative tunings that musicians may wish to explore. Experimenting with other tuning systems requires a customized microtonal instrument, or for the musician to develop a specialized playing technique. With growing interest among musicians in alternative tuning systems, customers—rather than manufacturers—may wish to dictate the tuning for fabrication of their own bespoke instruments.

Although keyboards[1] and re-fretted guitars[2] demonstrate microtonal capabilities, there are very few microtonal wind instruments commercially available. The flute is the simplest example of a wind instrument, and there are currently design techniques and software tools that flute makers can use to determine where finger holes should be placed for a desired tuning.[3] Typically, an instrument maker begins with a hollow tube, places finger holes according to the guidelines, and then goes through an iterative process of testing and modifying the instrument until reaching the desired tuning. This physical refinement stage is time-consuming, does not allow for accurate replication of instruments, and relies on a trial-and-error approach informed by a designer's experience.

To address these limitations, developers have used 3D printing. This offers repeatability, control, and a level of precision not possible with manual techniques.[4] In addition, this approach enables rapid manufacture, with more predictability in terms of the expected performance of the final instrument. In one example, 3D printing enabled the production of a traditional transverse flute.[5] That work, however, relied on replication of the exact measurements. For flutes in alternative tunings, pre-existing examples are unavailable to be replicated. In our approach, therefore, we use mathematical models to create 3D designs for printing. In the past, researchers have used physical acoustics—describing how sound interacts with physical objects—to describe the characteristics of wind instruments, including the flute.[6–9] One key factor that governs the sound produced by the instrument is the acoustic length. This differs from the physical length of the tube and is a function of its diameter, as well as the diameters and locations of the finger and mouth holes. In our work, we explore the use of more accurate mathematical models of acoustic length. We can thus achieve a better estimation of the physical length and finger hole locations prior to 3D printing.

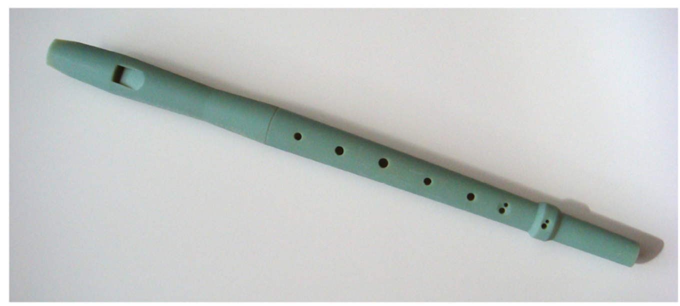

Figure 1. *3D-printed replica of an alto recorder.*

In our research we focus on two types of flute. The first is the recorder, because it is relatively easy to play. It is also easy to maintain a stable pitch and hence test our designs. We have also focused on a simple transverse flute. Our initial musical evaluation and analysis of recordings showed that printing resolution plays a significant role in the ability to sustain a note and achieve a desired tone quality. As expected, the use of a fused deposition modeling low-resolution printer resulted in a rough surface.

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The acoustic impedance (how air flows through the instrument) was thus increased. This has a direct impact on the ability to play stable notes at desired frequencies using this flute. In contrast, the use of a high-resolution Polyjet printer resulted in replication of an alto recorder with near-identical acoustic properties (see Figure 1), as judged by our experienced musicians. These flutes have proven to be robust and viable instruments that musicians successfully played at the 2014 Darwin and OzAsia Festivals in Australia.[10,11]

Although we can judge the performance of the flute through its use by experienced musicians, or by analyzing recordings,[5] in this project we used mathematical models to predict the acoustics before manufacture of the instrument. To develop these models, we considered that a physical flute—designed to produce certain sounds—will have a corresponding acoustic impedance, which can be measured or calculated. Our specific models are based on a theoretical approach,[9] which focuses on using a model of acoustic admittance (the inverse of acoustic impedance).[8] This is affected by the number, size, and placement of the finger holes, and the intended frequency of sound produced. Using an electrical circuit analogy for the design,[9] we can account for the combined effects of bore variation and frequency-dependent admittance sections. We are using this model for the first time to obtain more accurate estimations of components for our 3D-printed flutes (recorder and flute heads).

We have also explored new designs for flutes with customized microtonal tunings (see Figure 2). In music, the difference between two frequencies is often measured using a logarithmic unit known as *cents*. We found that existing mathematical models[3] gave approximate solutions to finger hole locations, usually with an accuracy of 30 cents compared with the desired frequency. To achieve greater accuracy, we have experimented with flutes printed at different lengths. We can thus gain

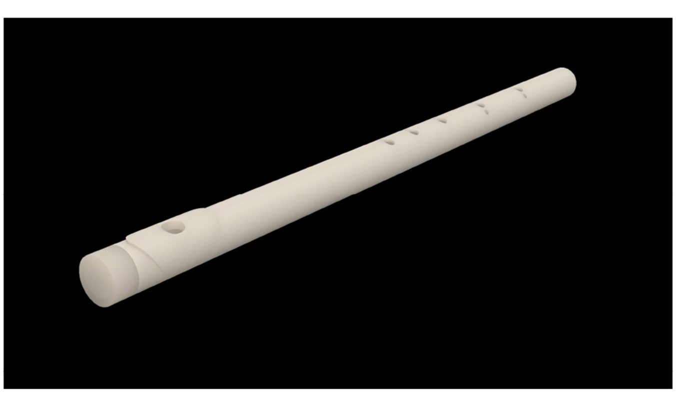

Figure 2. *3D model of a microtonal transverse flute.*

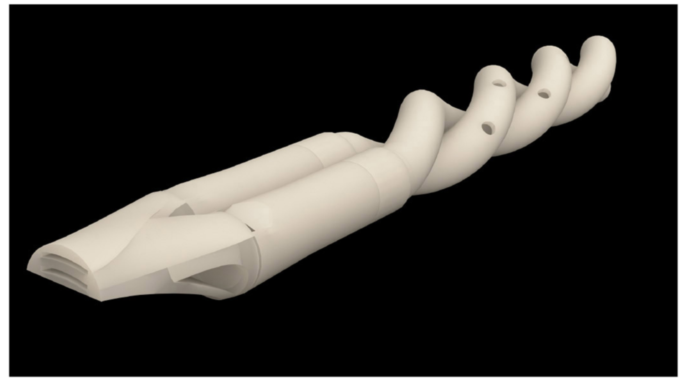

Figure 3. *3D model of a double helix flute.*

a more precise approximation of the acoustic length for the desired tuning system. This allows implementation of microtonal scales with much more accurate tuning in the final print. Our goal is to achieve no more than a five-cent error, which we consider to be an acceptable deviation for wind instruments such as the flute.

We have successfully designed and manufactured pre-existing flutes using 3D printing. From our initial experiments, we obtained promising results for creating custom microtonal tunings. Our current objective is to use more accurate mathematical models and more rigorous testing techniques. We also plan to create more radical designs, such as a double helix flute (see Figure 3).[12]

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Author Information

Christian Ritz, Terumi Narushima, Kraig Grady, and Stephen Beirne
University of Wollongong
Wollongong, Australia

Christian Ritz is an associate professor, with significant research expertise in digital signal processing for speech, audio, and acoustics. His current research interests include 3D audio recording, analysis, and synthesis, as well as customized manufacturing of musical instruments and microphone arrays using 3D printing technology.

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Terumi Narushima is a music lecturer, composer, performer, and sound designer specializing in microtonal tuning systems. Her works include *Hidden Sidetracks*, a creative work for custom-made instruments premiered at the Sydney Opera House, and music for a theater production *(Yasukichi Murakami: Through a Distant Lens*).

Kraig Grady is a composer and performer with 35 years' experience in designing and building acoustic microtonal instruments. He has taught music at the University of Wollongong, where he also completed a Masters in visual arts. His interest is in developing ensembles of instruments capable of expressive flexibility.

Stephen Beirne, under the banner of the Australian National Fabrication Facility, has been directly responsible for the implementation of a suite of commercial and custom additive fabrication tools. His primary research focus is in the development of new hardware, methods, and materials targeted towards additive bio-fabrication.

Matthew Dabin
Royal Melbourne Institute of Technology University
Melbourne, Australia

Matthew Dabin is a PhD candidate whose research area includes microphone array signal processing, spatial and temporal signal processing, 3D modeling, and acoustics.

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