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3D Modelling and Printing of Microtonal Flutes

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Keywords
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ABSTRACT

This project explores the potential for 3D modelling and printing to create customised flutes that can play music in a variety of microtonal scales. One of the challenges in the field of microtonality is that conventional musical instruments are inadequate for realising the abundance of theoretical tunings that musicians wish to investigate. This paper focuses on the development of two types of flutes, the recorder and transverse flute, with interchangeable mouthpieces. These flutes are designed to play subharmonic microtonal scales. The discussion provides an overview of the design and implementation process, including calculation methods for acoustic modelling and 3D printing technologies, as well as an evaluation of some of the difficulties encountered. Results from our 3D printed flutes suggest that whilst further refinements are necessary in our designs, 3D modelling and printing techniques offer new and valuable methods for the design and production of customised musical instruments. The long term goal of this project is to create a system in which users can specify the tuning of their instrument to generate a 3D model and have it printed on demand.

Author Keywords

3D printing, acoustic modelling, design, flute, microtonal tuning, recorder

1. INTRODUCTION

1.1 Background

In recent years, there have been several examples of musical instruments made with 3D printing. Many of these projects tend to replicate existing instruments for comparison with the sounds of the original model, such as a 3D printed copy of a Stradivarius violin [20] or a 3D printed flute [25]. Others have used 3D printing to create new instrument bodies or shells for electric guitars, drums and keyboards, but these instruments rely on non-3D printed hardware (such as pickups, bridges, necks and machine heads) for their sound production [7].

In contrast, our project takes advantage of 3D printing's unique ability to customise designs for the purpose of creating flutes that can play microtonal tunings not possible on standard instruments. 3D CAD software is used to generate 3D models of the flutes and these are then printed using high resolution inkjet based 3D printing technology (Objet Connex 350). Comparisons between the theoretical models and actual 3D printed flutes allow for greater understanding of the acoustics of microtonal wind instruments. The long term goal of this new approach is to create a system in which, instead of the manufacturer dictating the tuning, musicians are able to customise the tuning of their instrument for their own unique needs and have it printed on demand.

1.2 Microtonality

Microtonality is a label that refers to tuning systems that include intervals smaller than the regular semitone, but it can also refer more generally to any scale other than the conventional Western system of 12-tone equal temperament. It is often assumed that 12-tone equal temperament, best represented by the 12 black and white notes of the keyboard, is a universal standard, and most of the music we hear today in the West is built around this scale. In reality, however, many other systems of tuning are possible. For example, a rich variety of scales with many more notes than just 12 are found in music from different cultures of the world, and Western music itself has a long history of different tunings also. Microtonal tuning is a rapidly expanding area in which musicians from various genres are experimenting with a diverse range of tuning systems in their search for new resources for making music. In the future, instead of a single system, it is likely that musicians will adopt many different approaches to tuning.

1.2.1 Microtonal Instruments

One of the challenges in the field of microtonality is that conventional musical instruments are inadequate for realising the abundance of theoretical tunings that musicians wish to investigate. Already there is significant interest in instruments with microtonal capabilities, such as keyboards [16] and re-fretted guitars [22], but there seem to be very few microtonal wind instruments on the market.

Flutes are of particular interest because they are consid-

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ered to be amongst the oldest instruments in existence and they are also found in many cultures around the world [18]. There are different types of flutes, from side-blown to end-blown examples, as well as whistles, ocarinas, panpipes and so on. For our project we chose to focus on two types of flutes: the recorder, or fipple flute, because they are relatively easy to play and maintain a stable pitch, and a simple transverse flute, without movable parts such as keys for the time being, in order to begin with a minimal design.

Zoran demonstrated that a replica concert flute could be produced with 3D printing [25] but there were problems with water-tightness of walls and decomposition of material, which meant the flutes were not musically viable. More recently, Harrison has also developed software for 3D printing various flutes, whistles and shawms [10], but none of these are designed to play microtonal scales. Furthermore, there is no literature explaining or validating the mathematical methodology behind these designs.

It is possible for wind players to achieve microtonal pitches on their instruments using normal performance techniques such as adjusting their embouchure, or varying the speed and direction of the air stream. It is also common for cross-fingerings to be used [4] and much research has been done in this area for flutes [6] as well as recorders [3]. Alternate fingerings, however, can sometimes be awkward or difficult to achieve, especially in fast passages of music, and are not always practical. The resulting pitches for cross-fingered notes may also vary between different models of instruments. Furthermore, they can also result in changes in timbre, which may or may not be desirable.

How can 3D printing help solve these problems? The aim of this project is to explore the potential for 3D printing to create a set of custom-designed flutes that can play music in a variety of microtonal scales without the need for elaborate alternate fingerings.

A group at Glasgow University is reportedly developing a 3D printed clarinet focusing on 19-tone equal temperament [1]. In contrast, our project aims to develop a 3D modelling and printing work-flow that allows customised designs for a range of different microtonal tunings, not just one particular scale. To achieve this, our project to date has involved designing and printing flutes based on pre-existing models, then extending this work to explore the effects of modifying several variables, such as the position and size of tone holes, as well as the shape and dimensions of the bore of the instruments. These are parameters that normally cannot be varied using standard mass production manufacturing methods. We have also developed two different types of mouthpieces for a recorder and transverse flute, with the goal of producing a set of microtonal flute bodies with interchangeable mouthpieces.

2. DESIGN AND IMPLEMENTATION

Wind instruments typically consist of a tube in which a standing wave is generated by an excitation mechanism, such as a player blowing into a mouthpiece. Pitch is controlled by changing the effective acoustic length of the instrument [2]. This is usually done by opening or closing tone holes resulting in a shorter or longer standing wave being established. It should be noted that the effective acoustic length differs from the physical length of the instrument. In instrument design, notes can be tuned up by enlarging the holes, or shortening the length of the tube. Alternatively, notes can be tuned down by making the holes smaller, or extending the effective acoustic length by making the tube longer. The problem with extending the acoustic length is that it can be difficult to add material to make the tube longer. This is why instrument building is often an iterative subtractive process in which the instrument maker begins with a longer tube and then gradually reduces the length until a desired tuning is achieved. Another reason for this manual tuning requirement is due to traditional manufacturing processes resulting in variations between one produced instrument and another. Contrary to this, 3D printing is an additive technique that allows for very exact manufacture of physical components and parts based on 3D design models. Hence, manufacturing variations between different produced instruments are significantly reduced and the key task is to design an accurate 3D model.

2.1 Calculation and Methodology

Producing a complete mathematical model of a wind instrument is a challenge. While a model may very accurately match a particular style and tuning system, when certain characteristics of the instrument are changed the model may diverge greatly from what is expected. To calculate the design parameters of wind instruments a number of techniques have previously been explored. The two main methods are direct numerical simulation and approximation of acoustic impedances by bore segmentation.

Direct numerical simulation methods such as the Finite Element Method (FEM) can characterise the nature of excitation mechanisms and wind instrument acoustics [14]. The drawbacks of direct numerical simulations include computational requirements, software licensing, time and expertise needed. It would usually take a number of hours [14] for a highly powerful computer to simulate the complete geometry of a simple wind instrument. Furthermore, real data is often needed to verify simulation results or to optimise parameters of the model. The FEM will be used in future work to characterise the performance of our 3D printed microtonal flutes that are designed using our modeling approach described below.

The Transmission Matrix Method (TMM) is an approximation method which calculates the effective impedances by segmentation of the bore. Lefebvre explored the use of FEM to characterise the inaccuracies of the TMM method to estimate boundary conditions more accurately [14]. TMM has also been used to model the characteristics of the Chinese xiao (flute) [13]. Adapting the TMM method to the design of 3D printed microtonal flutes and validation with measured data is the subject of future work.

Simplified theoretical models have been developed based on research into characterising wind instrument acoustics by Benade [2] and Nederveen [17]. For our project, a version of the mathematical model by Hoekje was rewritten in MATLAB and modified to estimate the effective model parameters used in our designs for our desired microtonal scales. The model is based on the work of Benade and described by Hoekje in [12].

Calculations are made to find the locations of each hole to produce a desired playing frequency. This is based on an acoustical model that relates the sound frequency to the length, diameter and thickness of a pipe or tube. A tube of a given length that is open at both ends and has no finger holes can produce sound of a desired frequency based on physical acoustics relating the speed of sound to the length of the tube. A finger hole results in an increase in the effective length of the tube and so this needs to be accounted for so that the flute still produces the same desired frequency as a tube without finger holes.

The model firstly approximates the effective length of an acoustic tube for a single finger hole and derives an end correction factor. This gives the actual tube length required when a single finger hole is open, as well as the corresponding location for the hole. This step is repeated to find end corrections for additional open holes as well as corrections resulting from closed holes. Initially the mouthpiece end correction was approximated following the work of Hoekje [11] to produce Recorder 1 which is discussed in the evaluation (Section 3) below. In the next iteration, the end correction was interpolated from a small data set of experimentally measured end corrections to produce Recorder 2. The application of this model to our design is discussed in the section below.

2.2 Design and 3D Printing

2.2.1 *Mouthpiece Design*

The acoustic excitation source is a fundamental component of all wind instruments. To begin the design process we started by printing existing 3D models of recorders. We found that most of these designs were not playable or produced undesirable higher harmonics due to problems with the mouthpiece.

Next, we replicated the design of a commercially available Aulos alto recorder mouthpiece. The design is shown in Figure 1 with some basic dimensions included. Initially the recorder mouthpiece was printed using a fused deposition modelling (FDM) based 3D printer (Dimension uPrint-Plus). This system can be considered a low resolution 3D printer with a layer height of 0.254mm. The general operation of the system sees a thin filament of ABS polymer being extruded through a heated nozzle while being positioned by a 3 axis robot. While this results in robust models for demonstration purposes, there is a distinct roughened surface finish that affects airflow in comparison to the smooth surface that would result from a typical injection moulded component.

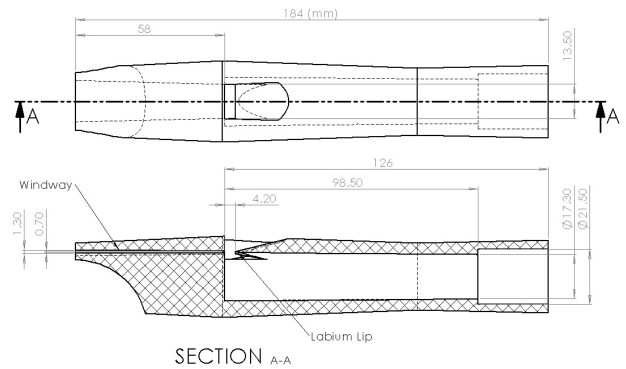

Figure 1: Recorder mouthpiece design.

Another limitation of FDM technology for this application is the minimum wall thickness that can be achieved. In particular it was found that the desired sharpness of the labium, the hard-edged blade of the mouthpiece, could not be achieved through this approach. A common feature of 3D printing technologies is the use of a sacrificial support material to allow the production of complex geometries. Again, for this application it was found that the support material used in the FDM process would negatively affect the quality of the surface finish. Through physical flute models produced using the FDM approach it was observed that the internal surface roughness of the bore caused the player to have to produce higher blowing pressures and that a longer time was needed to produce and establish a stable note in comparison to a typical commercial flute.

Ultimately, while FDM technology does allow the production of a physical model, the layer resolution and surface finish that are achievable do not enable the reliable production of the fine features that are necessary. Another more sophisticated form of 3D printing, Polyjet Technology, was chosen as a more reliable alternative. The main benefits of this technology are: a dramatically increased layer height resolution of 0.016mm as opposed to the 0.254mm of FDM, a significantly improved surface finish, gas-tight walls, and the ability for the printed material to be hand finished to further improve surface roughness. This technology relies on UV cured acrylate base materials. In this case a proprietary material called Objet MED610 was selected, so that a robust, rigid component with excellent feature definition could be produced using an Objet Connex 350 printing system.

Using the Polyjet printer to print the recorder mouthpiece, a much sharper labium was achieved. Initial comparisons between the commercial Aulos mouthpiece and our 3D printed one showed little distinguishable difference in pitch and blowing pressure required. To further improve the design, the wind-way or narrow duct through which the breath passes, was increased to allow a higher volumetric airflow rate to account for any wall smoothness issues and to aid in the cleaning process. This resulted in very loud and stable notes to be established.

In addition to the recorder mouthpiece, a head joint for a transverse flute was also printed on the higher resolution Objet Connex 350 printer. This was based on the design of a Western concert flute with a simple taper towards the embouchure hole. The head joint connection was designed so it is interchangeable with the recorder mouthpiece. Due to the high resolution of the printer, a relatively sharp edge was produced and notes were easy to sustain. Figure 2 shows the prototype head sections for the recorder and transverse flute.

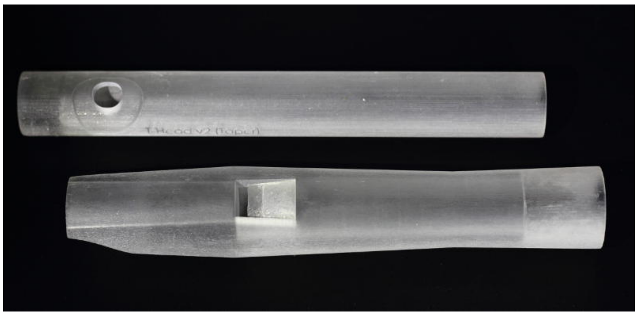

Figure 2: Interchangeable flute and recorder head joints.

2.2.2 *Acoustic Body Design*

In addition to the mouthpiece, the body of an Aulos alto recorder with standard tuning was also replicated. For simplicity, we started with a straight bore with a diameter of 17.3mm to make it compatible with commercially made mouthpieces. Wall thickness was 3.2mm and size of finger holes ranged from 4mm to 6.5mm in diameter. The size and location of tone holes were calculated from the acoustic model described by Hoekje and the frequencies required for our microtonal scale pitches (Figure 3) were implemented using the method described in Section 2.1.

2.3 Microtonal Scales

The first microtonal tunings to be implemented for the project was a set of subharmonic scales. These are scales built from notes of the subharmonic series, which is the inversion or mirror of the more familiar harmonic series.

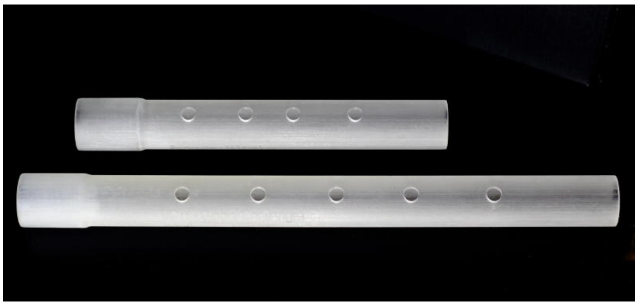

Figure 3: 3D printed microtonal flute bodies.

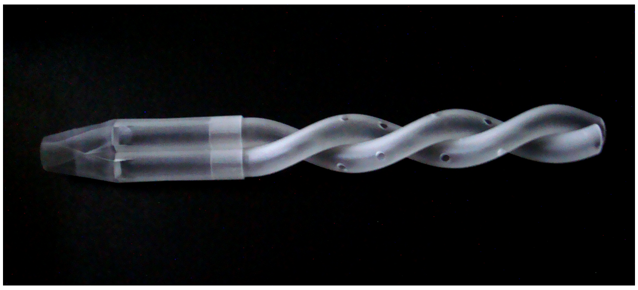

Figure 4: 3D printed double helix flute.

Subharmonic scales were chosen as a starting point for our flutes because of their potential to be realised using simple designs consisting of equally-spaced finger holes, as suggested somewhat controversially by musicologist Kathleen Schlesinger [21]. Such scales would fit comfortably under the hand without the need for cross-fingerings or special keys to cover tone holes.

Subharmonic scales also provide a useful test case for implementing microtonal tunings because unlike equal temperaments, they consist of intervals that are not equidistant but vary in size between successive notes of the scale. Furthermore, tuning theorist Erv Wilson has proposed various methods for extending subharmonic flute scales through simple modifications, thus enabling a diverse range of tuning options to be generated [24]. Details for one of the subharmonic scales used in the project are given in Table 1 below.

3. EVALUATION

The project so far has prioritised the development of a microtonal recorder over the transverse flute, mainly because it is easier to produce and maintain a stable pitch on the recorder. To test our instruments, recordings were made in an anechoic environment with a Behringer ECM8000 measurement microphone and Behringer ADA8000 pre-amplifier. Recordings were then analysed using Melodyne software [15] to obtain pitch information.

Table 1 compares notes of different recorders that were produced for a particular subharmonic scale. This scale spans a section of the subharmonic series from the 7th to 12th subharmonics, with target frequencies for each note of the scale shown in the second column of the table. Results for our first attempt at producing a subharmonic instrument (Recorder 1) are shown in the third column. Differences from the target frequencies are shown in cents in the fourth column. Subsequently, another instrument was produced (Recorder 2), resulting in improved pitch accuracy for some but not all notes of the scale. Minor adjustments were made manually to Recorder 2 by filing two of the tone holes. The results from these modifications are shown in the rightmost columns of the table. Although the accuracy of particular pitches fluctuated, the average difference in cents was improved overall with each new version of the recorder. Whilst the intonation of wind instruments will always be influenced by the performer, our goal is to continue to improve the pitch accuracy of our 3D-printed designs to no more than a five cent error so that manual adjustments are not needed.

One of the advantages of 3D printing is that it allows identical components of an instrument design to be reproduced with the same acoustic qualities. This was verified by printing identical pairs of subharmonic recorders with matching pitches. These instruments have been used successfully in numerous live musical performances in conjunction with other microtonal instruments [23] [5].

3.1 Conclusions and Future Work

Our research shows that 3D modelling and printing techniques offer new approaches to instrument design and production. The infinite flexibility of 3D printing technology provides an excellent opportunity to experiment with new designs, particularly designs that are impractical to produce through conventional means. For example, to demonstrate the possibilities of what can be achieved through 3D printing we created an experimental flute with a double mouthpiece connected to two tubes that are twisted together into a double helix shape (Figure 4). This instrument, along with two other 3D-printed examples of a microtonal transverse flute and recorder, was showcased in a recent exhibition that featured designs using cutting-edge technologies [8].

3D printing also allows for greater understanding of acoustic instrument design through its capacity to reproduce identical components whilst also enabling specific modifications. Although we have found prior research into the mechanics of wind instruments using parametric equations to be suitable for approximating notes, further refinements are needed in order to achieve the level of accuracy we seek for microtonal flutes.

One of the limitations experienced so far is that we have not been able to fully characterise the frequency dependency of the mouthpiece by simply calculating the end correction. In the next stage of our project, mouthpiece characterisation will be addressed by collecting a large data set of pitches from the recorder and transverse head joints. We also hope to improve the accuracy of our designs by exploring methods from [19] and [14], such as the TMM optimisation using FEM simulations.

With improved acoustic models, we plan to extend our research to implement other microtonal tunings beyond subharmonic scales. Complementary 3D scanning techniques could also be used to replicate rare or inaccessible instruments, such as flutes from different cultures as well as historical examples. Another direction we would like to explore is the use of different types of materials in additive fabrication. Flutes serve as the initial stage in an investigation that could be extended to other woodwind and brass instruments in the future.

Our long term goal is to provide a design tool that allows a user to request a specific set of pitches for their instrument and have it printed on demand. We believe that 3D printing has the potential to challenge traditional methods for manufacturing musical instruments: instead of the manufacturer determining the construction of an instrument, in the future customers will be able to specify the design of their instrument for their own unique needs for creating new music.

Table 1: Comparison of results for 3D printed subharmonic recorders

		Recorder 1		Recorder 2		Recorder 2 Modified	
Subharmonic scale pitch	Target frequency (Hz)	Resulting frequency (Hz)	Difference (cents)	Resulting frequency (Hz)	Difference (cents)	Resulting frequency (Hz)	Difference (cents)
/12	616	628	+34	617	1	612	-10
/11	672	681	+23	664	-21	673	5
/10	739	749	+24	738	-3	745	14
/9	821	828	+14	810	-24	815	-13
/8	924	932	+16	908	-30	923.5	-1
/7	1056	1060	+6	1031	-40	1049	-12
/12 (overblowing)	1232	1246	+19	1228	-5	1236	5
/11 (overblowing)	1344	1359	+20	1335	-11	1351	9

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5. REFERENCES

[1] N. J. Bailey, T. Cremel, and A. South. Using acoustic modelling to design and print a microtonal clarinet. In *Proceedings of the 9th Conference on Interdisciplinary Musicology - CIM14*, pages 272–275. Berlin, Germany, December 2014.

[2] A. H. Benade. *Fundamentals of Musical Acoustics.* Oxford University Press, New York, 1976.

[3] K. Bennetts, D. Bousted, and P. Bowman. *The Quarter-Tone Recorder Manual.* Edition Moeck, Celle, 1998.

[4] A. Botros, J. Smith, and J. Wolfe. The virtual flute: an advanced fingering guide generated via machine intelligence. *Journal of New Music Research*, 35(3):183–196, 2006.

[5] Clocks and Clouds. http://www.anaphoria.com/clocksclouds.html, 2016.

[6] R. Dick. *The Other Flute: A Performance Manual of Contemporary Techniques.* Oxford University Press, London, 1975.

[7] O. Diegel. ODD guitars. http://www.odd.org.nz, 2011.

[8] Embracing Innovation Volume 5. http://www.arts.act.gov.au/functions/news_and_events/items/embracing-innovation-volume-5, 2015.

[9] Global Challenges. Manufacturing innovation. http://globalchallenges.uow.edu.au/manufacturing-innovation/UOW165117.html, 2015.

[10] P. Harrison. Demakein: design and make instruments. http://www.logarithmic.net/pfh/design, 2014.

[11] P. Hoekje. A brief summary of A.H. Benade's wind instrument adjustment principles. *J. Catgut Soc*, 2(7):16–24, https://purl.stanford.edu/zk714gv4615 1995.

[12] P. Hoekje. Musical acoustics. http://homepages.bw.edu/~phoekje/acoustics/mahome.html, 2014.

[13] Y. Lan. *Acoustics of the Xiao: A Case Study of Modern Methods for the Design of Woodwind Instruments.* PhD thesis, University of British Columbia, 2015.

[14] A. Lefebvre and G. Scavone. Finite element modeling of woodwind instruments. In *Proceedings of 20th International Symposium on Music Acoustics*, pages 215–222. Sydney, Australia, August 2010.

[15] Melodyne editor (Version 3) [Computer software]. Retrieved from www.celemony.com.

[16] T. Narushima. *Mapping the Microtonal Spectrum Using Erv Wilson's Generalized Keyboard.* PhD thesis, University of Wollongong, 2013.

[17] C. J. Nederveen. *Acoustical Aspects of Woodwind Instruments.* Revised. Northern Illinois University Press, DeKalb, IL, 1998.

[18] B. Nettl. *Excursions in World Music.* 4th ed. Pearson/Prentice Hall, Upper Saddle River, NJ, 2004.

[19] M. Prairie. Understanding the acoustics of the native american-style flute. http://www.flutopedia.com/refs/Prairie_2006_UnderstandingAcousticsOfTheNAF.pdf, 2006.

[20] Print me a Stradivarius: how a new manufacturing technology will change the world. *The Economist*, http://www.economist.com/node/18114327, February, 2011.

[21] K. Schlesinger. *The Greek Aulos.* Methuen, London, 1939.

[22] J. Schneider. Just guitar. *Guitar International*, 6:42–50, 2004.

[23] The Music Show. Yasukichi Murakami - Through A Distant Lens. ABC Radio National. http://www.abc.net.au/radionational/programs/musicshow/terumi-narushima-through-a-distant-lens/5716334, 2014.

[24] E. Wilson. Flute scales and notes. www.anaphoria.com/FluteNotes.pdf, 1984-2007.

[25] A. Zoran. The 3D printed flute: digital fabrication and design of musical instruments. *Journal of New Music Research*, 40(4):379–387, 2011.