The Birl Physical Model

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ABSTRACT

This paper outlines a project to couple a woodwind physical model that incorporates a continuously variable tonehole model [1, 2] with a new experimental electronic wind controller called the Birl, and to develop an algorithm to automatically adjust the parameters of the model based on the desired tuning of the final instrument.

1. INTRODUCTION

The Birl project [3, 4, 5] led by Jeff Snyder, attempts to create an expressive electronic wind instrument that allows continuously variable tonehole control and more complex embouchure detection than that available on existing commercial wind controllers. This particular contribution to the Birl project focuses on implementing a digital waveguide physical model [6] as a strategy for mapping the continuous tonehole control to sound.

Toneholes, especially in open-holed acoustic wind instruments such as the bansuri, shanai, or recorder, provide a wide range of sonic possibilities through the variety of ways that a performer can interact with them. Completely covering a tonehole effectively increases the length of the instrument bore, dropping the pitch to a lower frequency, while opening a tonehole does the opposite. Partially covering it results in interpolation between these two pitch boundaries. A combination of higher breath pressure and certain coverage values can produce unusual acoustic effects such as multiphonics, which create the perception of multiple pitches sounding at once. Different fingerings that produce the same pitch may nevertheless produce varying timbres, allowing for the use of an effect called a "timbral trill", in which the performer switches quickly between two fingerings to create an oscillation in tone color. These techniques are all possible due to the physical characteristics of the tube and the unique way that air pressure waves blown into it interact with the bore cavity, and how the toneholes dynamically alter these properties. However, much of this flexibility is lost in current commercially available electronic wind instruments such as the Akai EWI or the Yamaha WX series, which have only binary inputs for the toneholes (open or closed state). These instruments output a MIDI pitch value based on the combination of open or closed keys, which simplifies their communication with synthesis engines.

If one desires to take variations in continuous toneholes into account, then this mapping from the state of the toneholes to the synthesis becomes more complex. There have been some projects by other authors that involved the creation of electronic wind instruments with continously variable toneholes, most notably the PIPE, by Scavone [7], and the Epipe, by Hughes, Cannon and Modhrin [8]. In the case of the Birl, several mapping strategies have been attempted, including rule-based methods, and using trained neural networks to create interpolated states between particular finger positions and a desired pitch output [4]. This paper details our experiment in using physical modelling synthesis to achieve useful mapping of continuous tonehole parameters to sound. Compared to the neural net or rule-based approaches, this solution comes with many limitations in the possibilities of pitch mappings, as it is limited to creating a model that is similar to a physical instrument with a limited number of toneholes in particular locations. Despite these limitations, a physical modelling approach allows for very interesting and acoustically-inspired sonic results, and very intuitive performance possibilities, as mentioned in an early paper describing the addition of tonehole models to digital waveguides [9]. For instance, we were particularly interested in allowing the execution on a digital woodwind instrument of extended acoustic wind instrument techniques such as half-holing, cross-fingering, overblowing, and multiphonics.

One downside inherent in a physical modelling approach that uses a more complex model with multiple toneholes, when compared to a simpler model that simply adjusts the length of a single tube, is the difficulty of setting the parameters of the model to achieve the desired tuning results for the pitches produced when the toneholes are closed and opened. Therefore, another goal of this project was the development of an algorithm to simplify the procedure of setting these parameters so that a musician could define any arbitrary musical scale and a model would be calculated to achieve that result. The goal is an electronic instrument that retains many interesting performance capabilities of acoustic instruments, but is not subject to the same physical constraints.

2. IMPLEMENTATION

2.1. Physical Model

The implementation of the Birl physical model is based on the BlowHole STK (Synthesis Toolkit) class [10], which is a single tonehole implementation of a digital waveguide algorithm with woodwind-like components. The reed table, tonehole filter, and termination reflection filter are drawn directly from BlowHole. The tonehole model was set up as a pole-zero filter, and the equations relating the filter coefficients and the tonehole radius were implemented as part of the tonehole initialization according to [1, 2]. Furthermore, a three-port scattering junction as in [2] was also in place.

For the body, BlowHole uses an optimized single delay line (SDL) implementation, but we found it easier to conceive the model as a bidirectional waveguide so we converted it. Information on converting between SDL and bidirectional waveguide models can be found in [11]. Then, we removed the register vent for simplicity and extended the model to include 11 toneholes, to match the number of tonehole sensors on the Birl controller.

A design decision was made to use only integer-length delay lines and to correct for the resulting rounding error by adjusting the diameter of the next tonehole. This was done both to avoid signal distortion and for performance benefits. Fractional delays involve interpolation functions to yield an approximation of a continuous input signal. Even with complex interpolation functions, a small amount of signal distortion is inevitable. Interpolation also invariably incurs more computational overhead. These two factors are insignificant for a small number of delays, but in a model that comprises a series of delays feeding into each other like the Birl, distortion and computational work accumulate rapidly.

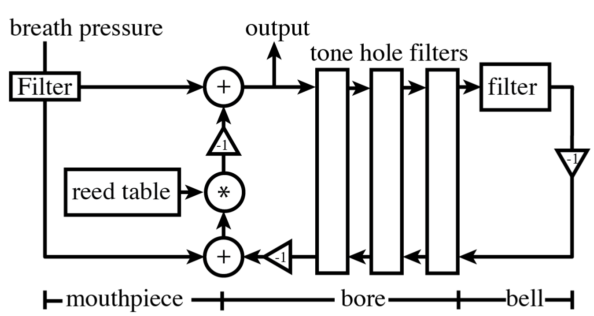

Figure 1. A basic schematic for the digital waveguide synthesis used in the Birl physical model [12].

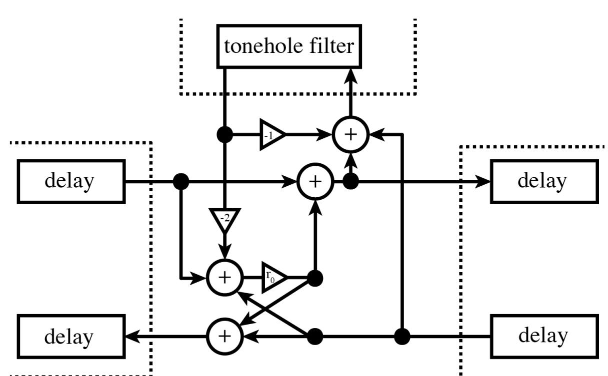

Figure 2. Three-port scattering junction. [2]

2.2. Tuning Algorithm

In order to allow the user to specify arbitrary tunings for the instrument, an algorithm was implemented that relates the desired tuning or scale to the delay line lengths and tonehole radii. A system of equations is given in [13] that determine the parameters of a delay line tube section and tonehole filter that must be appended to the model in order to produce each desired pitch.

The Birl model is a closed-open tube, so its output frequency is related to the tube length according to

$$F_1 = \frac{c}{4L} \tag{1}$$

where L is the effective tube length, F_1 is the fundamental frequency, and c is the speed of sound. Since air pressure waves actually travel a small distance beyond the open end of a tube, the discrepancy between the effective length and the cut (actual) length of the tube must be calculated. This difference is the end correction of the tube (Δl_T).

In a closed-closed tube $\Delta l_T = 0$, since the pressure waves reflect exactly at the ends of the tube. A closed-open tube of cut length l_T will produce a fundamental frequency equal to that produced by a closed-closed tube of the corresponding effective length L_S, so $L_S = l_T + \Delta l_T$. The following equation is used as an estimate of Δl_T:

$$\Delta l_T = 0.3 d_1 \tag{2}$$

where d_1 is the bore diameter.

The same principles apply to toneholes as well. The length from the mouthpiece end of the tube to the center of any given tonehole i is equal to the effective length of the tube when all toneholes before tonehole i are closed. This per tonehole cut length is labeled l_H, and the corresponding effective length $L_{S(h)}$. Their relationship is

$$\Delta l_H = z L_{S(h)} \tag{3}$$

$$z = 0.5g\sqrt{1 + 4\frac{L_{B(h)}}{gL_S}} - 0.5g \tag{4}$$

$$L_{B(h)} = (l_H + d_H)(\frac{d_1}{d_H})^2 - 0.45 d_1 \tag{5}$$

d_H refers to the tonehole diameter, and $L_{B(h)}$ is a variable that does not have a physical manifestation, but refers to "the length of a fictitious duct that has the same diameter as the main tube, and the same conductivity as the tonehole" [13]. g is the interval ratio between the current tonehole and the previous one (closer to the mouthpiece).

To solve for the position and radius of a tonehole, (3), (4), and (5) must be combined with (1) to find suitable values for l_H and d_H. $L_{S(h)}$ can be determined from the desired pitch using (1). Then, a reasonable starting value must be chosen for either d_H or l_H which can be used to solve (3).

Algebraic manipulation of (3), (4), and (5) yields:

$$L_{B(h)} = \frac{(L_{(h)} + 0.5gL_{S(h)} - l_L)^2}{gL_S} - \frac{gL_S}{4} \quad (6)$$

$$d_H = \frac{d_1^2}{L_{B(h)} + 0.45d_1} \quad (7)$$

The general algorithm for tuning the model at a tonehole position given a desired frequency for that tonehole is outlined here. Note that this algorithm must be run iteratively for each tonehole in the model.

1. Calculate the effective length $L_{S(h)}$ for this tonehole.
2. Calculate the interval ratio g by dividing two ratios. The numerator is the ratio of the current tonehole pitch to the fundamental, and the denominator is the ratio of the previous tonehole pitch to the fundamental.
3. Start with a reasonable diameter value d_H that is above a minimum threshold. Compute $L_{B(h)}$ using equation (6).
4. Solve for z using equation (4).
5. Compute l_H using $l_H = L_{S(h)} - zL_{S(h)}$. Round down to the nearest integer.
6. If l_H is the same length as a previous delay line, then increase oversampling rate and restart algorithm for entire model.
7. Compute d_H using equation (7). If d_H is too small, decrement l_H by 1 and repeat steps 4-5.

Tuning the fundamental is simpler as $L_{B(h)}$ is not involved. The integer tube length can be calculated directly from $L_S = l_T + \Delta l_T$ and (2).

The inclusion of minimum threshold values for d_1 and d_H is the result of observing detuning effects that occur when tonehole diameter values are too small. Intuitively, small radii may reflect an air pressure wave entirely. In the digital domain, this translates to the filter's coefficient values reflecting the signal completely, eliminating the effect of the filter. The exact minimum threshold at which unwanted detuning begins to occur is unknown, but values of 1.0 (in sample lengths) for both variables were deemed adequately effective in the Birl model.

Step 6 uses oversampling to work around the problem of delay line length clashes. If the user specifies two frequencies that are close enough together such that their corresponding wavelengths are within 1 sample length of each other, the tuning algorithm will return the same delay line length for both. Oversampling increases the granularity of the model so that the difference threshold at which this problem occurs is divided by the oversampling rate.

3. EVALUATION

3.1. Physical Model Evaluation

A formal user study of this research has not been conducted. However, as part of the evaluation process, a professional saxophonist was invited to informally explore the Birl while it was connected to the physical model. He noted that half-holing and cross-fingering felt natural, and multiphonics generally felt similar to the way that they are achieved in a saxophone, by using a "somewhat unpredictable embouchure/air stream" in conjunction with certain cross-fingerings. He was also able to achieve overblowing, but this was not realistic enough to perform on-demand. In acoustic wind instruments, overblowing occurs when the player blows firmly into the mouthpiece, but in the Birl a particular fingering configuration was also needed. Overall, the acoustics felt "very authentic." However, he also mentioned that the instrument felt " a little too sensitive" and that it was hard to know when the model would start squeaking. The biggest area of improvement he suggested was in providing the user with more control over the sound output by the model. Recordings of the model producing these effects can be found on this project's online git repository [14].

3.2. Tuning Algorithm Evaluation

While the tuning algorithm produced scales that sounded close to the intended results, there remain several problems. The most obvious defect of the current Birl model is an absolute pitch offset that is unsolved at the time of writing. When tuning the fundamental, the result is invariably sharp of the expected pitch. One possible explanation is equation (2). Forster acknowledges that this is not exact, but rather a "good estimation" for the relationship between d_1 and Δl_T, and "an exact equation for the end correction of open and closed tubes does not exist because the end correction depends slightly on wavelength" [13].

Relative tuning is also inaccurate, although less so: toneholes closer to the open end of the bore (lower-pitched) tend to be sharper. We have discovered that two bores with equivalent length, one with a closed tonehole and one simply contiguous, will not produce the same pitch. The addition of the tonehole filter slightly increases the output pitch. The compounding of this error may be the cause of the relative tuning error for toneholes further down the bore.

Another flaw in the current model is that oversampling rates above 2X result in high-frequency artifacts. Therefore step 6 in the tuning algorithm in Section 2.2 will only work once. The exact cause of this issue is unknown at time of writing, but we are exploring the possibility that the tonehole model needs to be adjusted for higher sampling rates beyond simply using the higher sample rate in coefficient calculation.

4. CONCLUSION AND FURTHER WORK

The Birl physical model is a proof-of-concept that certain unique acoustic properties of woodwinds can be achieved by using a digital waveguide with continuously variable toneholes coupled with a controller that allows for continuous tonehole control. However, its current drawbacks prevent it from being ready for a performance setting. The source of the global and relative tuning errors in the tuning algorithm, as well as the oversampling issues, need to be determined and resolved before the instrument is ready for performance. We also need

Specified Pitch (Hz)	Output Pitch (Hz)	Absolute Error (cents)	Relative Error (cents)
440.00	462.20	85.22	21.95
493.88	513.90	68.79	5.52
554.37	578.10	72.56	9.29
587.33	612.90	73.78	10.51
659.25	687.05	71.51	8.24
739.99	765.70	59.13	-4.14
830.61	858.50	57.18	-6.09
880.00	916.50	70.36	7.09
987.77	1019.20	54.23	-9.04
1108.73	1150.00	63.27	0.00

Table 1. Absolute and relative tuning error between one set of desired input frequencies and the actual frequencies produced by a model with parameters calculated by the tuning algorithm. The relative error is calculated in reference to the highest pitch, as that tonehole has the least amount of toneholes in front of it, and so should have the least error.

to build into the model an effective way for the performer to control overblowing.

One approach we are currently exploring as a solution to the tuning error is the use of pitch-detection within the tuning algorithm. During initialization, the error between the actual and desired pitch output can be used to inform a searching mechanism that would adjust the tonehole radius until the desired pitch is reached. We are currently working on incorporating the YIN pitch detection algorithm [15] as an additional step in the tuning algorithm to adjust for the discrepancies.

We also have plans to further extend the Birl physical model. For example, a register vent could be added to allow for octave jumps (one already exists in the STK BlowHole). This would follow the specification of a two-port scattering junction as outlined in [1]. Other extensions such as tonehole chimneys and non-constant bore diameter or curvature could be added to implement models of more complex instruments.

Work on the Birl is ongoing, and the results so far of this physical model implementation are encouraging. We also hope that others will find our repository of code useful for their own explorations.

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