The Half-Physler: An oscillating real-time interface to a tube resonator model

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ABSTRACT

Physics-based sound synthesis allows to shape the sound by modifying parameters that reference to real world properties of acoustic instruments. This paper presents a hybrid physical modeling single reed instrument, where a virtual tube is coupled to a real mouthpiece with a sensor-equipped clarinet reed. The tube model is provided as an opcode for Csound which is running on the low-latency embedded audio-platform *Bela*. An actuator is connected to the audio output and the sensor-reed signal is fed back into the input of *Bela*. The performer can control the coupling between reed and actuator, and is also provided with a 3D-printed slider/knob interface to change parameters of the tube model in real-time.

Author Keywords

Physical modeling, Clarinet, Haptic feedback, Bela, Csound, 3D printing

CCS Concepts

•**Applied computing** → **Sound and music computing;**
•**Hardware** → **Haptic devices;** *Sensors and actuators;*

1. INTRODUCTION

In the early 1990's Julius Smith proposed that "abstract-algorithm synthesis seems destined to diminish in importance due to the lack of analysis support". Furthermore he stated that it "is difficult to find a wide variety of musically pleasing sounds by exploring the parameters", concluding that "this boils all synthesis techniques down to those which model either the source or the receiver of the sound" [12]. The methods to model sound sources are also often called physical modeling synthesis, a field that evolved significantly since then [1, 2, 14]. Within the same time period, developments in computer science improved the machines so that the models of acoustic instruments can run in real-time as virtual instruments, even on consumer PCs. As a consequence research on ways to play and control these virtual instruments gained larger attention within the NIME community [6, 8].

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2. MOTIVATION

Multiple designs that combine physics-based sound synthesis with haptic control over the excitation meachnism do exist. For example the BladeAxe [9] is an electronic instrument in the shape of a guitar that uses piezzo-based sensors to convert plucking gestures into signals that drive a Karplus-Strong string model. A technically comparable piezzo interface has been presented in [8] that is driving a complex model of a string coupled to a 2-D plate resonator. However, in both designs the interface is one directional, only sending the captured impulse to the model.

The instrument design presented in this paper builds upon such hybrid physical-virtual instruments, but extends the earlier presented approaches by coupling the physical-virtual instrument parts in a bi-directional way so that the resonator acts back to the excitation mechanism similar to the case of acoustic instruments.

Recently, a team at Queen Mary University London presented an embedded processing platform called *Bela* which supports ultra-low latency (<1 ms) audio processing [7]. Although the processing speed of such a small embedded system is slower than that of regular desktop computers, the precise control over the latency on *Bela* opens up new possibilities to interact with physical model-based sound synthesis.

This paper presents a prototype for an open-source construction kit to build a hybrid single-reed instrument. The excitation mechanism of the instrument is based on actual instrument parts (mouthpiece, clarinet reed) but the tube is simulated on the *Bela* board. Hence, the player can interact with the reed, which allows to shape the sound and to receive haptic feedback in real-time from the actual reed vibrations. The simulated tube can be modified via knobs and a slider that are mounted to a custom designed enclosure. The enclosure is inspired by the design of a real clarinet, as the embedded computational model is capable of resynthesizing the sounds of a real clarinet [11] and beyond. Thus, instead of tone holes, performers are presented with knobs to tune parameters during sound production beyond what would be possible in a real clarinet, such as changing the shape of the bore from being a cylinder to morphing into a cone. Due to this hybrid nature of the instrument it is named the *Half-Physler*.

3. REALISATION

The Half-Physler is comprised of two parts:
a) a clarinet reed mounted to a mouthpiece that is coupled to b) a physical model of a tube [11], which is running on the ultra-low latency embedded audio processing platform *Bela* (Version: Bela Mini).

The coupling between the reed and the tube is realised via a shaker (Vibration Generator 2185.0, by Frederiksen) and a bending sensor that is directly attached to the clarinet reed (Fiberreed Hemp Deutsche Klarinette, Medium Strength, by Hartmann) [3]. The sensor signal is given to the audio-input of *Bela* which runs the virtual tube model and the pressure value computed at one of the grid points is given back to the shaker. Figure 1 shows how the shaker (actuator) and the reed are mounted so that the performer can press the reed against the shaker to close the feedback loop.

4. TUBE RESONATOR MODEL

The virtual acoustic tube is based on a mathematical time-domain wave propagation model. This model represents the particle velocity (v) and the air pressure (p) inside the tube of length L by a boundary value problem [11]. The problem is discretized using the finite difference method in order to approximate the values of v and p on M equispaced grid points $x_0 = 0, x_1, x_2, \ldots, x_M = L$. The model complexity and the computational cost depends on the number of physical effects that are taken into account. For this study, different levels of detail for a time-domain wave propagation model were implemented and tested on the embedded processing platform *Bela mini*. The most complex model given in [11], supports various geometries and takes visco-thermal and radiation losses into account. Due to the limitations in processing power, we simplify the tube model and its discretization described in [11] by neglecting the visco-thermal losses and taking into account only the radiation losses given by the boundary condition at $x_M = L$. For $x \in [0, L]$ and $t > 0$, the model we use is given by

$$\partial_x p(t,x) + \rho \partial_t v(t,x) = 0, \tag{1a}$$

$$\partial_x (S(x) v(t,x)) + \frac{S(x)}{\rho c^2} \partial_t p(t,x) = 0, \tag{1b}$$

where S is the cross-sectional area of the tube, ρ the density and c the speed of sound. The boundary conditions in the time domain are a given particle velocity at $x = 0$, $v(t,0) = v_{\text{in}}(t)$, and the radiation at $x = L$,

$$p(t,L) = S(L) z_r * v(t,L), \tag{2}$$

where z_r is a given radiation impedance [10].

5. EXCITATION MECHANISM

To activate the *Half-Physler* the player has to touch the reed and press it slightly against the shaker (actuator). This causes the reed sensor to create an initial impulse. Holding the sensor-reed against the shaker, couples the reed and the resonator in the form of a controlled feedback loop. The reed signal is given as a particle velocity (v_{in}) to the closed end ($x = 0$) of the tube model. In a real clarinet, the pressure changes at the same point would act back on the reed over time and cause it to vibrate in a frequency according to the standing wave inside the tube. In order to compensate for the small latency of the digital system, the pressure $p(x_{\text{lat}})$ at an interior point x_{lat} is read-out to drive the shaker. This latency is known in advance due to the properties of the audio processing *Bela* board. Sound output for the listener is read-out as the pressure at the end of the tube model $p(L)$.

Table 1: User parameters for the tube model.

Parameter	Range	Functionality
L	0.25-0.75 (m)	length of the tube
r_{in}	7.5–9.5 mm	radius at the tube entry
slope	$= 0$: cylinder, $\neq 0$: cone	slope of the tube
α	0.1–2.0	multiplier for end reflection coefficient (radiation resistance)
β	0.1–30.0	multiplier for air density

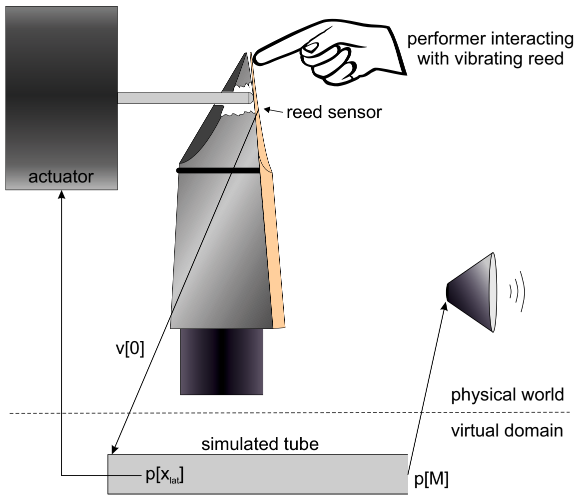

Figure 1: Schematic of the setup for a hybrid physical modeling clarinet. Mouthpiece, reed with bending sensor, shaker (actuator) and speaker are connected to an embedded audio processing platform that runs a tube simulation in real-time. The performer can interact with the reed and modify the coupling between the physical reed and the simulated tube resonator by pressing the reed against the actuator and by applying different forms of reed damping.

5.1 User Parameters

Users are provided with the following parameters to control the tube model: a) length of the tube, b) radius at the tube entry, c) slope of the tube, d) end reflection and e) air density. Table 1 gives an overview of the model parameters with respect to their physical units. For efficiency reasons to run the model on the *Bela Mini* the length (L) of the resonator is only computed for lengths between 0.25 m and 0.75 m, the approximate length of a B♭ clarinet.

5.2 Real-Time Sound synthesis with Csound and Bela

The tube model was implemented in C++ within the *Csound Plugin Opcode Framework* [5]. This allows to run the tube model as an opcode in the Csound sound-synthesis environment. In Csound it is easy to map controllers (MIDI, OSC, or *Bela* Inputs), to scale input signals and it even al-

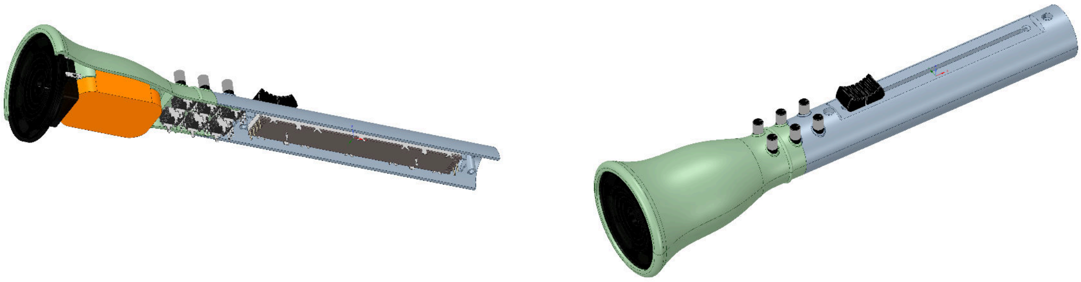

Figure 2: 3D design for the enclosure of the Half-Physler controller with space for a 10 cm slider and 6 control knobs. The *Bela Mini* (orange) and a small speaker can be mounted inside the bell-formed part of the controller.

lows other experiments, such as combining the model with traditional sound processing algorithms[1].

To run the model on the *Bela Mini* with (audioFrames = 32), the number of computations for each sample had to be optimised. The *Bela Mini* hardware is currently running with a fixed sampling rate of 44.1 kHz. In order to reduce calculations the following simplifications were made to the model, compared to the full model given in [11]:
a) All computations for visco-thermal losses were omitted. In this case energy in the tube is only lost due to sound radiation at the end of the tube.
b) In the original model, the optimal number of grid points is calculated for each given geometry, based on the length of the tube (L), the sampling rate and the stability conditions of the model. As for each sample, the complete grid has to be recalculated, tubes > 0.5 m were too costly for the processor of the *Bela Mini*. Furthermore, changing the length of the tube requires to re-calculate all settings and to re-initialize the grid. Thus the number of grid points (M) has been set to 32. This simplification results in decreased model accuracy for tubes > 0.5 m and restricts to set L = 0.25 m for the shortest tube length for stability reasons.

Two Csound opcode implementations of the tube-model are provided in an open-source library[2]. One version is optimized for *Bela*, whereas the other version is for usage on a consumer PC and requires more CPU power. The latter uses an algorithm that re-calculates the optimal number of grid points (M) for each new geometry setting.

5.3 Interface

As the *Half-Physler* is made of both, a physical instrument part that is coupled to a simulated instrument part, this allows the player to directly interact at the cross section of both domains. Players can dampen parts of the reed which forces it to vibrate in different modes, use other objects on the reed to create collisions, that result in high-frequency spectral components in the signal or develop their own manipulation techniques.

On the modeling side of the system, we provide controlled access to 5 parameters given in Table 1. To control the length of the virtual tube, a 10 cm slider has been mapped to L. Potentiometers, connected to the analog inputs of the *Bela Mini*, are provided to change the entry radius, the slope of the tube, the radiation losses and the air density of the model.

[1]The model runs with Csound (Version 6.1+) on most regular operating systems and has been tested on Mac (OSX 10.13.6) and Ubuntu Linux (18.04).
[2]`https://github.com/ketchupok/half-physler.git`

6. INSTRUMENT MAKING

A 3D-printable cylindric enclosure with a horn-shaped ending has been designed with reference to the shape of traditional single-reed instruments, specifically the B♭ clarinet. Figure 2 shows the 3D-model of the enclosure that hosts the slider, the potentiometers, the *Bela Mini*, and allows to mount a 6.4 cm speaker (e.g. K 64 WP, by Visaton). The 3D-model was designed using the free version of the DS Mechanical Software (Ver 2.0, by Design Spark). A first prototype of the enclosure has been printed using the Formlabs Two (by Formlabs) 3D-printer with the according black resin. The approximate printing time was about 30 hours for the above shown top part of the enclosure.

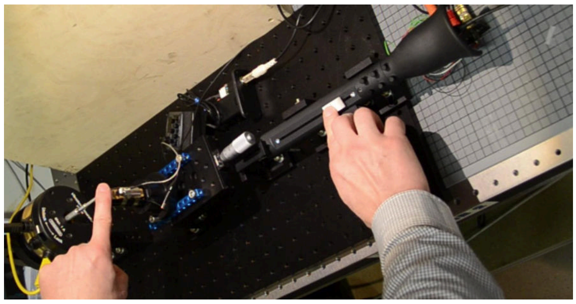

Figure 3: Setup with mouthpiece, shaker and 3D-printed controller of the half-physler.

6.1 Mapping

In the current version of the physler, all parameters presented in Table 1 are directly mapped to the controls presented on the enclosure in a one-to-one fashion. The length of the resonator (L) is mapped to the position of the 10 cm slider with incresing values towards the bell of the enclosure. Tube radius, slope, end reflection and air density are available as parameters directly controlled by the knobs at the bell end. One of the remaining knobs was assigned to control the amplitude of the feedback signal sent to the shaker.

Taking into account that research has shown for complex parameter mappings (one-to-many) to be able to extend the level of expression for digital instrument performances [4], a thorough investigation of mapping strategies for this instrument remains a future task. However, at this point this is left open to the performers/composers as it may require different mappings depending on the musical material that is forseen to be performed.

7. DISSEMINATION

A first prototype of the instrument has been presented to composers and instrumentalists in a workshop on *Digital Instrument Making* at the Hochschule für Musik, Theater und Medien Hannover (HMTMH). Based on the project material, students started to sketch ideas on how to play the instrument, manipulate the design and further push the limits of the instrument. Suggestions from the participants for changes on the design concerned the limitations of the sound quality of the small built-in speaker which they would prefer to be replaced by a bigger full-range speaker or would even make use of a professional P.A. during concert performances.

Participants saw limitations concerning the playing that are implied by the use of the long slider (see Figure 2). The slider was mapped to the length of the tube, and fast changes of pitch were consequently restricted to glissandi. Replacing the slider with a ribbon controller interface (e.g. foil potentiomenter) was discussed as an option. A further suggestion of the participants was to play the two parts of the instrument (excitation mechanism vs. tube model controller) by multiple players, so that each player can fully focus on the capabilities of their respective part.

8. LIMITATIONS & FUTURE WORK

The *Half-phylser* project presents an open-source construction kit around the *Bela Mini*, that allows to explore how to connect a virtual tube to the real world. This intersection of a simulated and a real wind instrument part allows to touch a physical process that is usually hidden inside the instrument and can only be controlled by the player's blowing. By taking the clarinet out of the mouth, disclosing the reed-resonator coupling and liquefying the shape of the resonator, the *Half-phylser* may also be a valuable asset in music acoustics education. However, future designs may also include other sensors to control the feedback loop (e.g. a blowing pressure sensor in the mouthpiece). In combination with smaller actuators and by merging it with wind-controller designs for fingerings (e.g. the birl [13]) the presented technology may be used to build a silent single-reed instrument with control over a vibrating reed that can either act like a clarinet, a saxophone or create other synthetic sounds.

9. ACKNOWLEDGMENTS

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