WAVEGUIDE SIMULATION OF NEOLITHIC CHINESE FLUTES

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Abstract

As an exploration in "musical archeology," our team is attempting to create computerized simulations of instruments up to 9,000 years old excavated at the Jiahu site, Henan Province, of Central China. These vertical flutes are from the hollow ulnae (wing bones) of the red-crowned crane. Some were discovered in playable, albeit extremely fragile, condition. A small number of recordings were made before conservation dictated protection from further handling. The recordings have permitted us to develop a waveguide digital simulation of the instruments matching the sound as closely as possible by ear. Examples from two of the twenty-five existing instruments are guiding the synthesis project which will soon "extrapolate" the sound of other flutes in the collection.

The present paper addresses two questions in this quest. Is the model accurate enough so that new instances can be made directly from physical measurements? And, which among the several model parameters are the most sensitive for an accurate timbre match?

WAVEGUIDE MODEL

A companion paper [1] describes some of the musicological considerations in extending the present work to create an ensemble of ancient flutes. Here we present the synthesis method and some considerations when evaluating its quality.

Our synthesis method continues development of the "classic" one-dimensional model for flute synthesis. Originally proposed as a variant of the lumped-circuit waveguide instrument, it has been applied in several implementations. Two representative versions include, the Hanninen, Valimaki flute [2] and the Synthesis Tool Kit (STK) flute [3]. Simplfication to a one-dimensional (longitudinal) waveguide assumes negligible contributions to the overall regime of oscillation from modes in other dimensions.

General approach.

Our synthesis method has its theoretical roots in established explanations of musical oscillators from the early 80's [4] and their representation as digital waveguides [5]. A musical oscillator, whether air column or stretched string, is separated into linear components (all-pass delay and filter sections) and non-linear components (active and passive) which are coupled in a recirculating loop. For example, a clarinet consists of the bore (round trip delay, loop filters, radiation filter, etc.) coupled to the reed (represented by a non-linear, reed-like, gating of incoming breath pressure, entrained by wave motion in the bore). Extensions to the general form have been explored for specific instrument families.

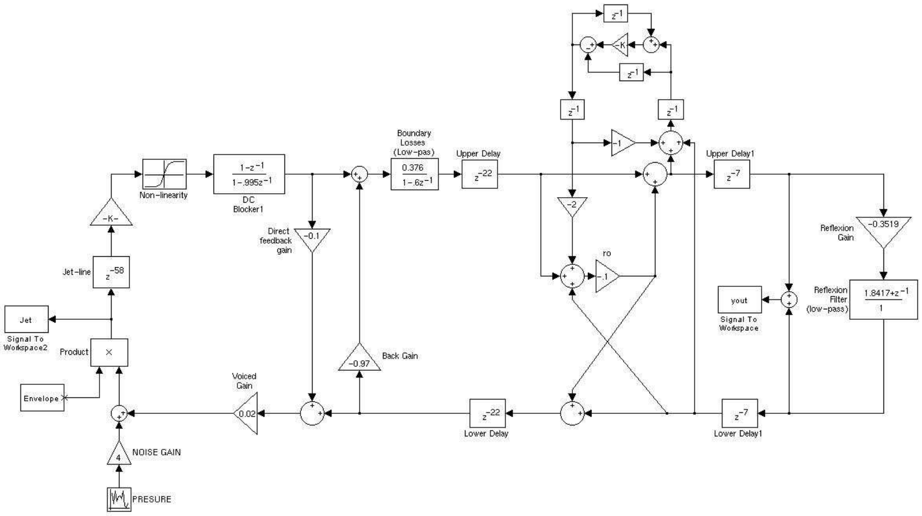

Figure 1: One-dimensional flute model.

Flute specifics.

The flute has two principle delay sections. Like the other winds, pitch is governed by air column length. Flute excitation is an edge-tone type which produces a switching air jet. At the edge, a region of interaction of finite width confronts the incoming air flow with the oscillating acoustic pressure wave. This causes period-synchronous switching of the air flow into and out of the bore. A "side branch" comprising a second delay is added to the circuit and represents the distance traveled by the flow before reaching the edge. Figure 1 shows a block diagram of the flute circuit.

Excitation and noise.

A variety of approaches which model the switching air jet have been described in the literature including Verge's aero-acoustical model of the recorder [6]. Ours uses the "classic" sigmoid non-linearity [4], certainly an over-simplification of the physics, but still a mechanism that mimics the dynamics of the instrument and its tonal characteristics. The Verge model accounts for complex fluid dynamics at the air jet and is a more complete representation of phenomena including vortex shedding. We approximate the same qualities of aperiodicity and period-synchronous noise shaping with a one-dimensional method for "vortex noise" which is analogous to chaotic time-series [7]. The type of noise created in this way exhibits a range of aperiodicities with similar features to actual edge-tone oscillators.

Toneholes.

The simplest waveguide wind instrument has no toneholes and adjusts pitch by lengthening the bore. For toneholes, a new output is created by tapping the pressure wave at an intermediate point in the bore waveguide, while still allowing some amount of signal to travel to the open end and back. Scavone's clarinet tonehole circuitry [8] has been adapted for the model. Its formulation permits continuous control of tonehole width, effectively representing a smooth transition from fully-open to fully-closed. In the collection of Jiahu flutes, the number varies between 5 and 8 toneholes.

In contrast to modern instruments, no register hole exists. To obtain overblown notes, we have explored possibilities of embouchure adjustment.

Mouth cavitiy implementation.

performance parameters	fixed parameters
breath pressure	corner-rounding (aka, loop) filter
embouchure delay	radiation filter
non-linearity slope	mouth resonance
tonehole settings	vortex noise

Table 1: Parameters affecting timbre.

We have included resonance of the mouth cavity which has been demonstrated to be significant for timbre adjustment. Typically, a player is able to enhance the sounding pitch by reinforcing it with an appropriate mouth shape, much as singers do. A Helmholtz resonator has been used to model the mouth cavity, as described in [9], using the resonator formulation described in [10]. Its addition to the model is physically plausible: using the resonance cavity in the path of the pressure waves and adding the resonance of the mouth cavity to the output signal.

Sources of overblowing without register hole.

Vertical flutes can be overblown by speeding the incoming air and adjusting the angle of blowing relative to the edge. A sensitive adjustment of breath pressure accompanies the tilting. In terms of the model, speed of the air equates to length of the jet delay and tilt equates to variations on the shape and position of the non-linear function.

TIMBRE

Table 1 lists parameters in the model that affect timbre.

Performance parameters.

Much as a bowed string has 3-dimensional timbral interaction between *bow force, velocity and contact position*, the flute model has timbral interaciton between breath pressure, speed and embouchure tilt. A given pitch can be played with a variety of timbral qualities. Additionally, mouth cavity resonance and cross-fingerings (alternate tonehole arrangements for a given pitch) contribute to the resulting timbre.

To maintain a given timbre from one pitch to the next, slight embouchure adjustments are also required. Within the model, it is a function of compensating the ratio between the effective bore length and the embouchure delay. The non-linear excitation function has an adjustable slope parameter which affects brightness.

Fixed model parameters.

In designing the waveguide, it is necessary to choose a method for fractional delay interpolation because toneholes (and their pitches) do not correspond to integer spatial sample positions in the waveguide. The choice of interpolation scheme for obtaining fractional delay can affect spectral quality of the instrument. The Lagrange interpolators we have applied can be adjusted to have a less severe effect on the frequency response by increasing the order of the filters. In general, they contribute a lowpass effect. Since they are applied at several locations along the air column, there is a cumulative effect which we are presently working to determine. This effect is in addition to the low-pass filter already included to model the losses in the bore.

SUMMARY

Flute number M341:2 with six holes is being modeled as our first target. It is from the earliest period (7000-6600 B.C.). A recording of it is available for comparison (playing the Chinese melody *Hua Hama*). In [1], we describe two software environments currently being developed for playing the model, in real time and from score. All parameters mentioned above are optimized by ear for a best match. Synthesized performances obtained in this way will be evaluated by expert listeners in China to gain further suggestions about timbre adjustments.

If a sufficient timbre match is made through adjustment of the parameters above, and if it plays in tune, then we will proceed to re-create a second flute directly from tonehole and length measurements. Our second target is the other flute with existing recordings, M280:20 (seven holes, middle period, 6600-6200 B.C.). This is intended to qualitatively verify the approach before attempting the first extrapolation to a broken flute, M341:1 (five-hole from the earliest period).

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