Modeling and Control of Performance Expression in Digital Waveguide Models of Woodwind Instruments

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Abstract

Most digital waveguide models of woodwind instruments to date have provided only basic control parameters such as frequency, breath pressure, and vibrato. It is clear that if these models are to gain popularity as real-time performance synthesizers or as composition tools, more flexibility is necessary. This paper discusses the implementation of expressive controls for flutter tonguing, growling, tone-bending, multiphonics, and variation of attack style. These effects are implemented on existing clarinet and flute waveguide instruments using the application SynthBuilder on a NeXTStep computer platform. Finally, control of these expressive effects using MIDI controllers is discussed.

1 Introduction

Research in physical modeling of woodwind instruments has largely focused on methods to accurately represent the instrument bore (Välimäki and Karjalainen, 1994), toneholes (Välimäki *et al.*, 1993), and nonlinear excitation mechanism (Scavone, 1995). The understanding of these issues is far from complete and work should continue to improve the existing models. However, there is a growing demand by composers and musicians to use physical models in new compositions and performance settings. In these cases, the models need more flexibility so as to produce a wide variety of sounds, both similar to real instruments and sounds which would be physically impossible in the real world. This paper first presents methods for achieving such flexibility within the context of digital waveguide modeling. The control of these extensions using MIDI controllers is discussed in the second part of this paper. The implementation of performance expression within the context of stringed instruments was previously discussed by Jaffe and Smith (1995), but issues of real-time MIDI control were not considered.

2 Modeling Performance Expression

The expressive controls discussed here fall into three principal categories – attack variation, breath pressure modification, and bore manipulation. The attack or onset of sound generation in musical instruments is a particularly important aspect of instrument performance and offers enormous expressive flexibility to both the composer and performer. Further, this attack information is a critical element in distinguishing different instruments from one another. Breath pressure modifications, such as flutter tonguing, growling, and singing into the instrument, are possible in all wind instruments, though they are a more common element of woodwind instrument performance. The production of multiphonics, achieved by non-traditional fingerings, is particular to woodwind bores with tonehole lattices.

2.1 Attack Variation

A variety of attack styles are possible in woodwind instruments, ranging from breath attacks to extremely percussive, "slap tongue" effects. Most models typically implement only breath-like styles of attack. Hard tonguing effects are achieved by using the tongue to briefly push the reed against the mouthpiece facing, stopping the reed vibrations and air flow into the mouthpiece. The rapid increase in pressure and air flow into the mouthpiece upon removal of the tongue from the reed, together with noise produced by this highly turbulent initial air flow, produces the resulting attack sound. Lighter tonguing effects are created by briefly interrupting the reed vibrations with the tongue and lesser degrees of flow interruption. The upper half of Figure 1 represents a common method for implementing a breath attack. The breath noise scaler controls the level of noise present in the steady-state sound. A tongued attack is implemented with an additional burst of DC pressure and noise, as shown in the lower half of Figure 1. The tonguing envelope controls the magnitude and duration of the attack and should have a shape of the form $x\,e^{-x}$. Scaling of the tonguing envelope corresponds to "hardness" of attack and provides an important performance expression control parameter. The relative degree of air flow stoppage is controlled with the tonguing noise scaler.

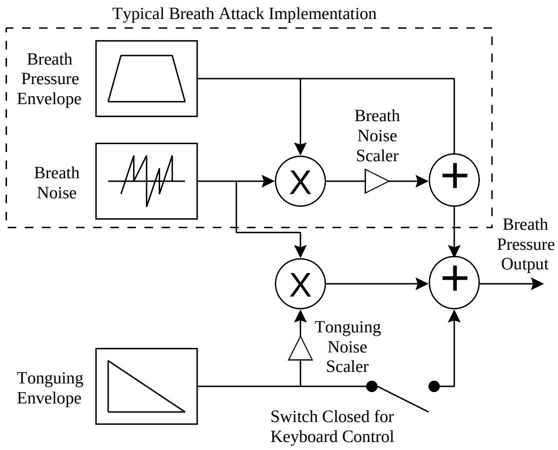

Figure 1: Tonguing System

Slap tonguing is an effect whereby the reed is pulled away from the mouthpiece lay using a suction force between the reed and tongue. When the elastic restoring force of the reed becomes greater than the suction force between the tongue and reed, the reed separates from the tongue and "slaps" against the mouthpiece lay. Varying amounts of breath pressure are then added to produce a range of effects from dry to fully sounding. Implementation of this effect can be accomplished in several ways. One method involves the recording of a dry slap with the mouthpiece removed from the instrument. This signal is then added to the normal breath pressure signal and input to the instrument's nonlinear excitation. This effect can also be achieved by approximating the slap with a predetermined filter impulse response, which is added to the breath pressure signal.

2.2 Breath Pressure Modulation

Several extended performance techniques involve the superposition of higher frequency components with the DC breath pressure applied to the instrument. This type of modification is referred to here as modulation, though not in the strict sense of amplitude or frequency modulation. Flutter tonguing, accomplished using either the tongue or ventricular folds (false vocal folds), simply amounts to the addition of a 15 – 30 Hz signal to the breath pressure. Growling and singing are audio rate modulations of breath pressure. One interesting non-physical extension possible in the digital domain is modulation with speech signals, particularly fricative sounds.

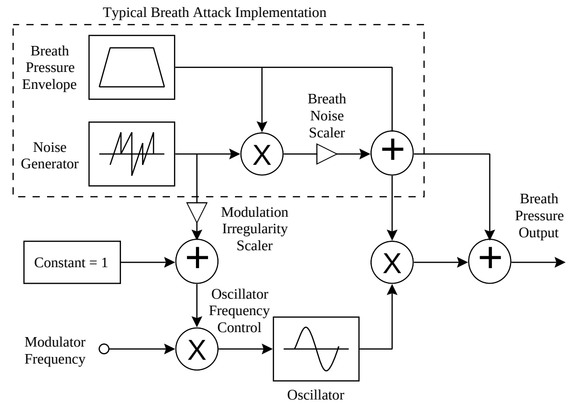

Figure 2: Breath Pressure Modulation System

The implementation of these effects can be achieved using the system depicted in Figure 2. A sinusoidal signal of some desired modulation frequency is added to the original breath pressure and the modulation frequency is randomly varied around its mean to attain a more realistic modulation signal. Modulation of breath pressure with speech can be achieved using recorded signals, though memory considerations in real-time DSP implementations often make this prohibitively expensive. A more desirable implementation provides real-time digital input via a microphone, which can be scaled and added directly to the breath pressure signal. As discussed later in conjunction with wind controllers, a breath pressure sensor sampled in the range of 2 kHz would be ideal for breath pressure control and eliminate the need for most of the system in Figure 2.

2.3 Multiphonics and Pitch Bending

Multiphonics are a common contemporary performance technique produced on musical instruments which have a tonehole lattice. Acoustically speaking, non-traditional fingerings produce air column resonances which are not harmonically related, but which are strong enough to entrain simultaneous inharmonic reed oscillations. The resulting tone is heard as comprised of two or more synchronous and distinct pitches, or as a tone with a rough and beating quality.

The most accurate method of modeling this phenomenon is to implement a full series of toneholes which exactly reconstruct the real instrument behavior. The present understanding of tonehole behavior and interaction does not allow realization of this goal and designs using current tonehole models would prove extremely difficult to properly tune. Further, the complexity of such a model would make real-time performance difficult to achieve in most situations. An efficient, though non-physical, technique for generating multiphonics is to add more bores to the model, each of different length. In terms of digital waveguide modeling, this corresponds to the addition of more delay lines and a summing operation for feedback to the excitation mechanism, as shown in Figure 3. Each delay line represents a particular resonance and set of overtones, while the input scalers roughly control their relative strengths.

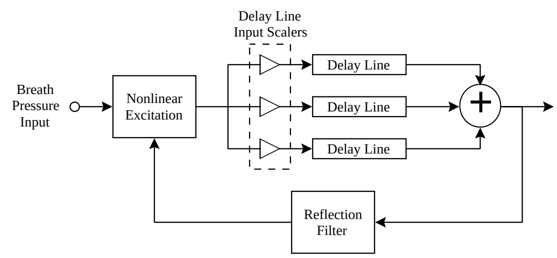

Figure 3: Multiphonic Generation System

Another performance technique is pitch bending. On single reed instruments, equilibrium reed position can be manipulated by the performer's lower jaw, allowing the sounding pitch to be lowered by as much as a quartertone. Some increase in pitch is possible by tightening the embouchure but this effect is much less significant. Oral cavity manipulations allow a further lowering of pitch, the magnitude of which varies over the range of the instrument and can be greater than a fifth. This effect is most easily implemented in a digital waveguide context using a smooth delay line interpolation method. Linear and lagrangian interpolation techniques produce no transients due to filter coefficient changes, but care must be taken to avoid signal discontinuities when changing delay lengths. For the small incremental delay length changes necessary for pitch bend, these techniques generally work well without producing audible discontinuities. Allpass interpolation can prove troublesome because of the transients associated with coefficient modifications in a recursive filter structure. Two methods exist for minimizing these transients in waveguide models (Välimäki *et al.*, 1995; Van Duyne *et al.*, 1996).

3 Controlling Performance Expression

The enormous flexibility originally proclaimed on behalf of physical modeling is finally coming to fruition and in many ways, we are unprepared to control it. Implementation of the expressive techniques discussed above is straight forward and intuitive within the physical modeling context. Finding ways to control these behaviors in real time is far from simple given current MIDI standards and controller technology. It is obvious that MIDI was not designed to handle extended techniques. Is it possible to adequately control these parameters without inventing a new protocol? The clear choice for controlling woodwind synthesis models is a MIDI wind controller. However, the few wind controllers commercially available offer only basic features and prove inadequate for the control of most of the extended techniques discussed in this paper. The MIDI keyboard is also far from ideal in this context, but it must be supported for historical and pragmatic reasons. The limitations of the keyboard are sometimes circumvented by providing wind-like controllers, such as the breath pressure controller supplied with Yahaha's VL1 synthesizer. In order to accommodate the advantages and disadvantages of these two controller types, different control schemes are necessary for each.

3.1 Wind Controller Issues

Flexible attack control requires two degrees of freedom and can be achieved using both breath pressure and velocity MIDI messages. The breath pressure messages control the breath pressure envelope while velocity controls the tonguing noise level, or tonguing noise scaler in Figure 1. In this way, a wide range of combinations of breath attack and tonguing level are possible. The Yamaha WX series of wind controllers generate both breath pressure and velocity MIDI messages via the pressure sensor in its mouthpiece. It is unclear how the velocity messages are determined in the WX controllers, though playing experiments show precise control of this parameter to be difficult. Of all the wind controllers commercially available at present, those of Yamaha are the only ones which generate breath dependent velocity messages. Physically relevant breath velocity messages can be obtained, however, by differentiating the breath pressure signal, so that velocity control using controllers without MIDI velocity output can still be possible if implemented onboard the synthesizer or computer.

The performance techniques based on modulation of the breath pressure signal present significant challenges in developing a realistic means of control. The most physically accurate solution would incorporate a breath pressure sensor that is sensitive enough to detect the modulations in the performer's breath input. Audio rate modulations, however, would require pressure sensor sampling rates on the order of 2 kHz. Under current MIDI standards, message rates can theoretically run as high as 1.5 kHz using running status and 2-byte messages, but such a strategy would be inefficient and hinder control of other aspects of the model. A more ideal solution would be to output breath sensor readings on a separate data line for real-time digital breath pressure input to the instrument model. Under the limitations of current wind controller technology, one possible scheme for the control of flutter tonguing and growling provides the performer with a foot switch mechanism that allows control of the modulation rate.

Multiphonics present an even greater control problem when using a wind controller. Potentially, non-traditional fingerings could be detected and output with special MIDI parameter values. The Synthophone wind controller provides this flexibility, allowing non-standard fingerings to be programmed with particular parameter values. However, the Yamaha WX and Akai EWI wind controllers output a standard MIDI key number for all fingerings without allowing the key combinations to be reprogrammed. This limitation might potentially be circumvented by using a particular MIDI program change message to control a "multiphonic" mode of operation, but any control scheme developed under this scenario would only function as a poor substitute to the desired behavior. Clearly, the programmable environment offered by the Synthophone should serve as a model for future wind controller development.

3.2 Keyboard Controller Issues

The mapping of MIDI keyboard control mechanisms to wind instrument expressive parameters is less obvious than when using a wind controller. However, the keyboard provides more flexibility than current wind controllers when used in conjunction with a breath pressure sensor. This is largely due to the fact that only one hand is needed to play the keys of the keyboard, leaving the other hand free to modify additional parameters. Without a breath pressure sensor, attack control via the keyboard is completely dependent on key velocity messages, resulting in significant loss of flexibility. In this context, low velocity values might be made to correspond to soft breath attacks and high velocity values to loud, hard tongued attacks. Lost in this scheme would be such effects as strong breath and lightly tongued attacks. The addition of a breath controller gives the keyboard musician much of the same attack flexibility enjoyed by users of wind controllers equipped with breath sensitive velocity detection.

As previously mentioned, natural control of breath pressure modulation requires a high breath pressure sampling rate. Until new controller technologies make this possible, the system of Figure 2 can be implemented and the various modulation parameters can be assigned to such keyboard controllers as modulation wheels or foot pedals. In this instance, the keyboard's wide array of controllers give it more flexibility than the wind controller.

Control of the multiphonic implementation of Figure 3 using a keyboard can be achieved by depressing multiple keys at the same time and assigning the various delay line lengths by the corresponding key numbers.

4 Conclusions

Physical models of woodwind instruments provide flexible control over a wide range of performance expression techniques. The implementation of these effects is reasonably straight forward because of the one-to-one correspondence between the model elements and physical elements. Unfortunately, control of these techniques is less straight forward, even when using a MIDI wind controller. With current technology, schemes can be developed which allow control of performance expression using both wind controllers and keyboards, though such control is not always intuitive or natural. The flexibility of physical modeling should result in the future development of new controller technologies that make such control more natural.

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