Working with Banded Waveguides and Friction in Musical Contexts

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***Abstract*— Physical Modeling of audio signals is a method for achieving musical textures in a class of sounds related to a timbre class associated with an instrument family or perhaps acoustical phenomena which can be applied to a musical context. Many of these models are based on the concept of a waveguide algorithm defined simply as a model of a traveling wave, its reflections and its discontinuities. Banded Waveguides proposed by Essl and Cook circa 1999 are an efficient method for physical models of friction based sound sources such as bowed bars, glass, bowls and the like. How to control these models is often a challenge for performers and composers using these algorithms and therefore some experimentation is needed in order to stimulate creativity in performance or compositional situations.**

I. Introduction

Physical models are mathematical abstractions in the form of an algorithm and can be used for analyzing and synthesizing the behavior of physical phenomena. In science this method has been used for some years and in particular inside the field of acoustics physical models are used for the study of how sound behaves and how it needs to be manipulated to obtain optimal timbres in musical instrument situations. For synthesis of audio signals with Physical Modeling users have been focusing more on the mechanics of how sound is generated instead of the sound itself. Being the case sound generation in this way deals more with the excitation of an elastic medium and how the waves travel across a resonant body [Smith, 1987].

For composition purposes most of these algorithms have been evolving for the past 25 years and now are in a state of readiness so that they can be used in real-time situations because they resemble real instruments and can be manipulated in a realistic and traditional fashion [Chafe, 2004] Many of these models can also be used on a sample-by-sample basis and thus used for rendering a sound-file with not only acoustical data but also with expressive and gestural data.

Physical models are attractive to composers mainly because a class of timbres generated by the model can be taken to the extremes and further achieving musical textures which are hard to produce with actual instruments. Additionally they can be perceived as an extension of the real instrument by toggling with the interface and different ways of performing and controlling the timbre with additional parameters. In general it can be stated that while working with physical models, the composer or performer is more concerned on how to generate control signals which affect the sound produced by the model and its expressive qualities [Roads, 1997]. Consequently this makes music performance an intrinsic part of Physical Modeling.

The model of an instrument or acoustical phenomena for musical contexts consists of a set of various parameters that control not only the frequency and the dynamics of the sound but also parameters which handle the excitation process and how sound is sustained all along a resonant body. Most of the control parameters are generally perceived as expressive parameters for performing and manipulating an instrument. One type transforms the spectral domain while the other the dynamics of the sound. This sort of musical signals which run at a haptic rate $(< 30Hz.,)$ are categorized as vibratos, thrills, grace notes, appogiaturas, etc. Others which are more performance oriented are tempo changes, rubato, staccato, etc.

II. Gestures and Controlling a Model

Manipulating parameters in a sound synthesis algorithm can be a fairly easy task if they are global but by the same token being global and general don't give them much flexibility. Controlling options in a physical model can be a complex task if they are specific and if combinations are desired. Human-computer interfaces or machine interfaces need to resemble the instrument or the process they are modeling in order to have usability qualities [Verplank and Mathews, 2000]. The interface designer most take into account that controls in traditional instrument interfaces are mastered by instrument performers and by having a familiar interface for the model the user can master its control parameters with more ease. In acoustic instruments, controllers tend to be global leaving tuning as a not-so global parameter.

Since new features might appear in models of instruments (i.e. like changing the size of the resonator), new parameters which are inherent might appear in the model. Also combinations of controllers which are not possible in the real situation might add some complexity to the interface, not so familiar to a musician trying to achieve performance level with the model.

Some points should be kept on mind while controlling a physical model: the composer should generate a sound space with several renditions of different sounds that belong to a timbre class. A timbre class consists of different sounds characterized by the sound synthesis algorithm in use. Different sounds can be achieved by changing parameter values. This approach has one caveat which is the psychoacoustic effect of characterization after several samples have been listened for a long period of time. Other important issue in Physical Modeling is that the rate of change for controlling a sound is somewhere across a haptic interval and always ($< 30Hz.$). Timbral expression parameters changes can and should be treated as signals in order to get more expressive results because control is often applied while listening to the sound that is being performed. Last but not least, control parameters for musical expression are best described by streams of asynchronous events. Figure 1 shows a bow interaction physical model diagram. Notice the analysis of the excitation part.

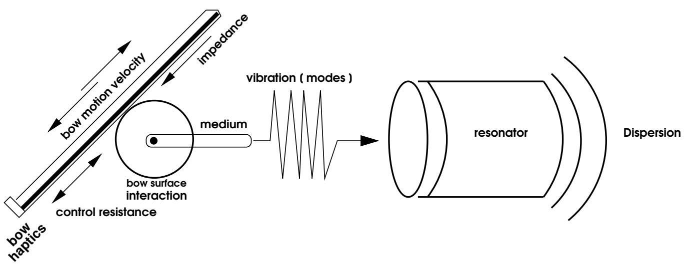

Fig. 1. Paradigm of a Bowed Friction Scheme for Physical Modeling

III. Physical Models of Bowed Instruments

Physical Models of bowed instruments other than strings have been developed by Cook and Essl [Essl and Cook, 1999] and further in the past few years by [G. Essl and Smith, 2004]. Examples of modeled bow timbre classes include the bowed string [Smith, 1982], bowed bars such as those found in marimbas and vibraphones [Essl and Cook, 2000], cymbals, glasses [S. Serafin P. Huang S. Ystad, 2002], and the singing bowl [Essl and Cook, 2002]. Special cases include the steel saw and corrugated surfaces [S. Serafin, 2003]. Most of these examples require a scheme for bow-surface interaction and parameter values describing bow motion such as bow velocity and instantaneous pressure differentials between both surfaces. These values can then be mapped to a bow-table [Smith, 1982].

The process of bow interaction can be seen as rub/friction excitation. In bowed strings and other systems that oscillate with periodic motion, this frictional interaction is called $stick/slip$ interaction because when bowing the bow sticks to the medium for a time, dragging it with velocity equal to the bow velocity. When the tension in the vibrating medium exceeds a certain point, the tension force pulling back towards equilibrium exceeds the static friction force and the medium snaps back towards rest position [Cook, 2002]. Depending on the material this kind of motion might go from some sort of sawtooth motion to triangular motion if the bowed material is stiff, and can be characterized as a variation of Helmholtz motion.

The actual parameters affecting the $stick/slip$ action include the normal force between the bow and the string (pressure differential), the bow velocity, and the ratio of two friction coefficients. To compute the system, the transverse string velocity and bow velocity are compared. The output of a friction function is then multiplied by the bow force to compute a frictional force [Smith, 1982]. If the frictional force is greater than the tension force then the medium sticks to the bow and is carried along with bow velocity. The resulting values of this system are then stored in a table and become scattering coefficients for the filters in the waveguide model[Smith, 1982].

IV. Waveguide Modeling

The building blocks while designing physical models with waveguides is a good interpretation based on discrete signals that belong to an oscillating system composed of pressure waves and velocity. A waveguide can be defined as any medium in which wave motion can be characterized by the one-dimensional wave equation [Smith, 2004]. In a lossless case, all solutions to the wave differential equation can be seen in terms of left-going and right-going traveling waves in the medium. The waves propagate unchanged as long as the density of the medium is constant [Smith, 1987]. When the medium changes, motion scattering occurs and therefore part of the traveling wave is reflected and part keeps its original path in such a way that energy is conserved. A good candidate for waveguide modeling might be the lossless string or a clarinet bore by itself. Signal scattering and discontinuities in the traveling wave path are generally modeled with filters. In the case of a string, signal scattering occurs at the edges since there is a path change. See figure-2 for a diagram of a waveguide.

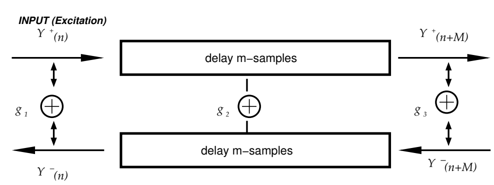

Fig. 2. Signal path in a waveguide implementation

V. Banded Waveguides

By constraining the input of a waveguide with bandpass filters some of the frequencies in the vibrating medium are isolated. This gives a better approximation to the vibrating modes of materials such as wood or metal found in marimbas and xylophones [Essl and Cook, 1999]. In a normal situation the left side is the input of the waveguide which is also the modeled excitation. Since banded waveguides are good to model bowed surfaces, the left side or input to the waveguide is the rub/friction interaction between the bow and the medium. Therefore the oscillations given in the bow-table are the coefficients for the leftmost waveguide scattering junction filter. Waveguides are also modeled with delays. Each scattering junction follows the input or a delay-line until the output of the waveguide. At scattering junctions wave direction is diverted and some energy might be fed back to the system while the other keeps on its output path. In a banded waveguide after the bow-medium interaction, the modeled signal of the traveling wave is distributed among a number of waveguides that are given by the number of the modes of vibration of the medium. Tables for modes of vibration for several materials can be found in many acoustic books [Neville H. Fletcher, 1991]. The length of each delay line depends on the number and position of the vibration mode. After the interaction and on the input of each waveguide there is the bandpass filter tuned to the frequency according to the position of each mode. As proposed by Essl and Cook, the structure of a banded waveguide can be seen in figure-3.

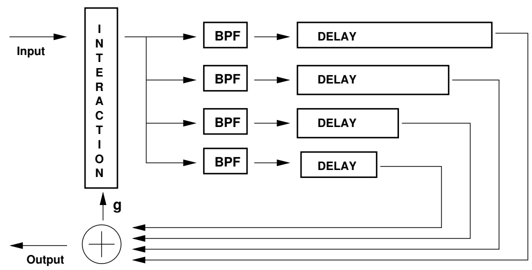

Fig. 3. Structure of a Banded Waveguide

VI. Control Parameters for a Banded Waveguide Model

In a parameter space for controlling a banded waveguide model, several factors are taken into account:

- Number of bandpass filters corresponding to the modes of vibration of the vibrational medium.
- Proportional length for each delay line.
- Center frequencies for the bandpass filter (frequency of vibration mode).
- Bow velocity along the duration of a given note.
- Scheme for attack, sustain and decay.

The first parameters correspond to the spectral domain while the last ones to the time domain. Bow velocity is related to the excitation of the model and thus plugs-in to the input of the next block which is a filter-bank block. With this waveguide model the spectral parameters, namely the center frequencies for each bandpass filter are constants built into the algorithm. Usually these frequencies are obtained by finding the impulse response of the vibrating surface or in previously referenced acoustics books. The length of the delay lines depend on the pitch and the fundamental frequency of the oscillation. Impulse responses for a tuned bar, uniform bar and glass harmonica have been obtained by Essl and Cook and are available in the STK (Synthesis Toolkit) distribution [Scavone and Cook,].

VII. A CLM Instrument

The original algorithm can also be found in STK [Scavone and Cook,], Percolate [Trueman,], and Pd [Puckette M.,]. $BandedWG.ins$ is a CLM (Common Lisp Music)[Schottstaedt,] implementation based on the Essl-Cook algorithm with applications for physical modeling synthesis of sounds of bar percussion instruments such as bowed bars of wood or metal, bowed glasses and bowed bowls. Impulse responses for saws and corrugated surfaces need to be obtained in order to be tested in this model for synthesis of such timbres. $BandedWG.ins$ has been designed with the bow table method plus an array of bandpass filters in parallel which are seen as the basis for a banded waveguide. Since audio signals in CLM are not usually intended for real-time situations, sound in BandedWG.ins is rendered on a sample-by-sample basis. Control of the physical model is exerted either at the sampling rate (for spectral changes) or at much lower rates $[sampling - rate/1000]$, for sound shaping and musical gestures. At present this instrument provides the following control parameters:

- Frequency (Pitch).
- Bow pressure parameter for computing the slope of the curve in the bow-table.
- A bow velocity envelope for bow velocity changes at a haptic rate.
- A dynamics envelope (ADSR) for controlling the energy of the system or time domain envelope.
- Reverb and spatial motion controls.
- Duration variable which is used to calculate the number samples for the sound (iterations of the algorithm).

The sample-by-sample generating loop implementation in Lisp with a Bandpass filter procedure and delay-line procedure in BandedWG.ins is as follows:

```
;;
;; Run loop in CLM
;;
(run
  (loop for i from st to nd do
   ;;
   (let ((input 0.00)
         (wguide 0.00)
         (velinput  0.00)
         (bowvelocity 0.00))
   ;;
   (dotimes (k nrmodes)
      (incf velinput
        (*(aref basegains k) (aref delays k))))
    ;;
    ;; Excitation and bow interaction
    ;;
    (setf bowvelocity (* (env vel-env) maxvelocity))
    (setf input  (- bowvelocity velinput))
    (setf input (* input (bowtable bowtab input)))
    (setf input (/ input nrmodes ))
    ;;
    ;; Banded-Waveguide block implementation
    ;;
    (dotimes (j nrmodes)
    (set-resonance filt (*  freq (aref modes j)) t)
    (set-del-par delayline (aref delays j))
    (let* ((filsig
               (bandpass filt (+ (* input 0.08)
               (* (aref gains j)
               (dll-output delayline)) )))
               (delsig
                 (delayl delayline (bpq-out0 filt))))
             (incf wguide   (bpq-out0 filt))))
    ;;
    ;; Output  Y(n)
    ;;
    (outa i (* 4.0 (env amp-env)  wguide))
    (if *reverb*
      (progn
        (outa i (*
                (* 4.0 (env amp-env) wguide) rev-amount)
                      *reverb*)))  )))
    ;;
    ;;  End
    ;;
```

VIII. CONTROLLING THE MODEL

Several features can be added for controlling the model with a score-file on a sample-by-sample rendered sound application. As in real-time situations, the most important parameters are pitch frequencies and durations and how the sound is manipulated along its duration. In this case the dynamics envelope and the bow velocity envelope control how sound changes with duration. But spectral variations also occur and are function of the frequency response of the banded waveguide filter and delay-line block. Depending on the vibration modes of the medium , the system only responds to a limited range of frequencies which are function of the sampling rate. Bandwidths can go from $100Hz.$ in the case of the glass harmonica, $240Hz.$ for the uniform bar and $340Hz.$ for the tuned bar. The fundamental frequencies are around $\approx 900Hz.$. Changing bow-velocity is perhaps the most dramatic and realistic effect since this parameter controls the bow-surface-medium interaction, and gives a rubbing surface effect and subtle vibrato at the decay of the sound.

Depending on the physics of friction and rubbing, $stick/slip$ interaction and other gestures can be achieved. This model has been tested producing spiccato or striking notes with short durations and staccatos but the model is more useful with long notes some with legato. Glissandi effects are very hard to obtain in physical models because of a given constant change in boundary conditions in the system. Nevertheless by adding a global variable for changing dynamically the overall length of the delay-lines might produce the glissando effect. This remains an option for testing and implementing in the future in this model. Note that this glissando effect is not possible in real bar percussion instruments. Other useful effects include reverberation and sound source localization. An advantage from its real-time counterpart is that this physical model can be used in a polyphonic context and note durations extended well beyond the length of an actual bow. Most of the control variables can be passed at haptic rates to the model by means of a score-file also written in Common Lisp. CLM provides tools for generating and manipulating envelopes over time at haptic rates.

IX. CONCLUSIONS

The problem with Physical Models is that these systems generally respond to an initial set of boundary conditions and seldom can be used in a broad range of pitches. Nevertheless the model can be taken to extreme conditions (like an infinite length bow), within its response range and furthermore building a timbre space with several renditions of a sound class. This is very useful for compositional situations on which the composer is experimenting novel ideas.

In designing and composing with physical models, the composer should pay close attention to the mechanics and haptics of instruments because it is indeed that control signals shape the behavior of the sound and the traveling wave simulation. Not all control signals respond the same way in all frequency ranges and not all excitations produce signals that will resonate.

$BandedWG.ins$ is a Lisp implementation of the Banded Waveguide model to render sounds of bowed percussion instruments and open for more options provided more impulse responses are added to the algorithm. Its control and expressive parameters can also be modeled by Lisp functions and pass-through with the option of a score-file. The playability of the model is constrained to the resonances obtained by vibration modes of different materials.

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