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RECENT ADVANCES IN REAL-TIME BOWED STRING SYNTHESIS: EVALUATION OF THE MODELS.

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ABSTRACT

Physical models of bowed string instruments have achieved a level of complexity which allows the real-time simulation of most of the phenomena that appear in real instruments. One of the open issues is how to validate the model, that is how to compare its behavior to that of a real instrument. In the past, different evaluation techniques of the playability of a bowed string physical models have been proposed [10]. However, these techniques focus on the acoustical behavior of the models, without taking into account the end user (either the player or the listener).

In this paper, we propose an accurate yet efficient real-time bowed string physical model, and we describe different techniques to evaluate the model, from acoustical evaluation to usability in a performance context.

INTRODUCTION

Physical models of musical instruments have achieved a level of completeness that allows most of the phenomena that appear in real instruments to be simulated in realtime. In the multidisciplinary field of music technology, several approaches have been explored in the design and use of virtual musical instruments. For acousticians, it is of interest to validate the model by examining the waveforms produced when it is driven by different input parameters, and to compare such waveforms to those recorded from a real instrument. For engineers and computer scientists, one of the main interests is the development of models that work in realtime. This requires the design of efficient signal processing algorithms facilitated also by the fast developments in hardware technology.

Hardware engineers are interested in augmented instrument design that capture the subtle nuances of a bowed string's performer. Such augmented instruments appear in the form of traditional instruments enhanced with sensors. Psychoacousticians are interested in evaluating how models are perceived by players and/or listeners. Interaction designers build novel interfaces for musical expression. Finally, composers are interested in extending the models to create sonorities which cannot be achieved using acoustical instruments.

In this paper we address the issue of designing and validating virtual musical instruments from the different perspectives summarized in Table I, using a bowed string instrument as a case study. We propose a bowed string physical model that is accurate enough to reproduce most of the phenomena observed in real instruments, yet efficient to run in real-time. We describe how this model has been designed and validated using gesture data measured using state of the art technologies such as a Vicon motion capture system as well as a playable bow controller that functions also as a measurement system.

Person	Task	Methodology
Acoustician	Acoustical analysis Simulation Validation	Spectral analysis Physical models Waveform comparison
Computer scientists	Real-time simulation Validation	Physical models Performance tests
Engineers	Parameters' capture Validation	Sensors based interface Usability test
Psychoacousticians	Perceptual evaluation	Listening tests
Interaction designers	Physical interface design Validation	Design of controllers Human centered design
Composers	Musical performance	Extension of the models

Table I: Summary of the different perspectives in researching and using sound synthesis by physical models.

A BOWED STRING PHYSICAL MODEL

We built a bowed string physical model that combines waveguide synthesis [9] with the latest results in bowed string interaction modeling [12, 11]. In this model, the bow excites the string in a finite number of points, which represent the bow width. The frictional interaction between the bow and the string is modeled considering the thermodynamical properties of rosin, using the so-called plastic model proposed in [8], given by:

$$\mu = \frac{Ak_y(T)}{N}\text{sgn}(v) \qquad \text{(Eq. 1)}$$

where A is the contact area between the bow and the string, N is the normal load, and $k_y(T)$ is the shear yield stress as a function of temperature T. The temperature T of the shearing rosin layer can be estimated from the current sliding velocity v by passing it through an appropriate linear filter [8]. The bow width is modeled by discretizing the region of the string in contact with the bow using finite differences and calculating the coupling between the waves propagating along the string and the frictional interaction between the bow and the string at each point. Figure 1 shows how the Helmholtz motion varies according to the bow point. Note how, as expected, the bow sticks in one side closer to the nut (bottom plots) and slides in the side closer to the bridge (top plots).

Once the velocity of the string at the contact point has been calculated, the waves propagating along the string are modeled using digital waveguides. More precisely, transversal and torsional waves propagating toward the bridge and the fingerboard are modeled as pairs of one dimensional digital waveguides. The outgoing velocity at the bridge is filtered through the body's resonances and corresponds to the output waveforms perceived by the listener. A preliminary version of this model has been described in [7].

The block diagram structure of the complete bowed string physical model is shown in Figure 2. In it delay lines correspond to traveling waves propagating from the bow point to the bridge and the nut; LP and AP represent respectively the lowpass filters that simulate losses and the allpass filters that simulate dispersion. For a description of how the allpass filters' coefficients were estimated see [6]. The input parameters of the model corresponding to the right hand of the player are bow position relative to the bridge (normalized between 0 and 1, where 0 corresponds to the bridge, 1 corresponds to the nut, 0.5 corresponds to the middle of the string), bow pressure, bow velocity, and amount of bow hair in contact with the string. The model has been implemented as an external object in the Max/MSP[1] environment.

ACOUSTICAL PLAYABILITY OF THE MODEL

Acousticians define playability as the region of the multidimensional space given by the parameters of the model where good tone is obtained. In the case of a bowed string, "good tone"

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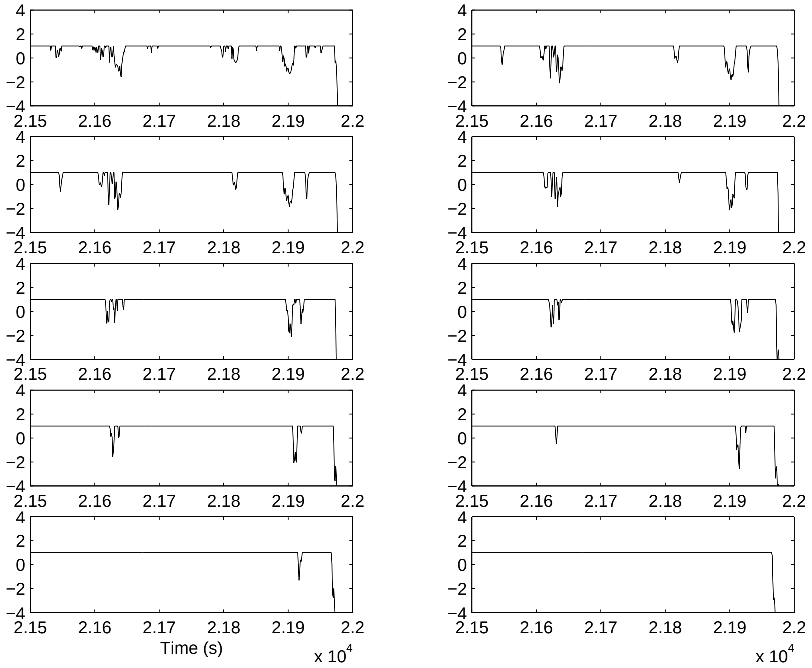

Figure 1: *Motion of the string captured at different samples under the bow. From top to bottom, from closer to the bridge to closer to the fingerboard.*

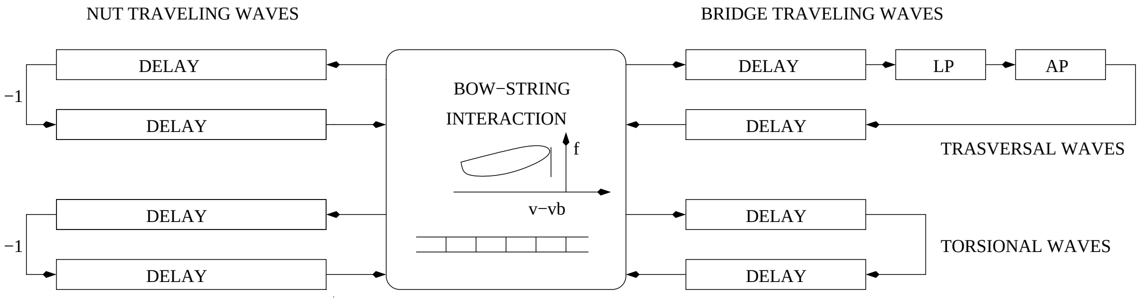

Figure 2: *Refined block diagram structure of the bowed string physical model used in the simulations.*

is generally referred as the Helmholtz motion, i.e., that motion of the string which every player tries to achieve as fast and accurate as possible [10]. Experiments show that accurately simulated bowed strings have the same playability as real bowed strings as calculated by Schelleng [5, 11]. Further experiments also show that the playability of virtual bowed strings increases when accurate friction models that account for the thermodynamical properties of rosin are taken into account [7].

PERCEPTUAL EVALUATION

The relationship between physical components of a bowed string instrument and they way they affect human perception can be understood only performing formal listening tests. Perceptual evaluation of bowed string physical models has not been investigated extensively as, for example, plucked string models [4]. Recently, an investigation of the impact of different body models while driven by the same input signal was performed [2].

Perceptual evaluation techniques are also important for perceptual pruning: the elements of a bowed string physical model which are not audible by listeners can be removed from the simulation, to increase computational efficiency. In our investigations, we discovered that accounting for the bow width improves the sound quality of the model, even if the playability region in the sense described above is not improved by this addiction. Simulating string stiffness is important for D and G violin's strings (294 Hz and 196 Hz) , but the effect of stiffness is not perceivable when playing A or E string (440 Hz and 660 Hz). As expected, the quality of the model increases when its parameters vary over time in natural way.

COMPARISON TO A REAL INSTRUMENT

In evaluating acoustical playability of bowed string physical models, the input parameters that drive the model corresponding to the right hand of the player are kept constant for each simulation. This situation is clearly not equivalent to what occurs in real life, where it is the continuous evolution of the input parameters that constitute the nuance of an expressive performance.

In order to address this issue, Askenfelt [1] studied the contribution of bowing parameters in different bow strokes, trying to determine the physical limits of the input parameters in order to achieve a specific stroke. He determined the maximal duration of the pre-Helmholtz attack allowed in order to judge a particular stroke as acceptable. The previous definition of playability is the one we are interested on examining in this paper. Similar work with a stronger focus on performance issues rather than acoustical validation was proposed in [3]. In this research the combination of the input parameters of a bowed string physical model was used to reproduce different bow strokes such as detaché, legato and spiccato.

When focusing on musical control, the word playability assumes therefore a different meaning [14]. We have been exploring the possibility of reproducing traditional bowing techniques using a bow controller that behaves in a manner as closely related to that of a traditional violin bow as possible. This allows us to validate both the model and the controller by comparing it to the behavior of the traditional instrument.

We therefore used the real-time bowed string physical model together with a wireless bow controller and Vicon motion capture system to examine the response of the model to real player gesture data captured in previous recordings as well as its response to gesture data generated in realtime by a player.

EXPERIMENTAL SETUP

Figure 3 shows data from a typical experiment, conducted in a Vicon motion capture studio. The violinist played a bow controller composed of a CodaBowⓇ Conservatory^{TM} violin bow enhanced with gesture sensors, and a Yamaha SV-200 Silent/Electric Violin (which was also augmented with electronics to faciliate gesture measurements utilized in related experiments). The violin audio produced by the player was recorded using the internal pickup in the test violin, and using a calibrated force sensor comprised of strain gauges mounted on the bow stick (a subset of the bow sensing system), the downward force produced by the player was captured. For a detailed description of the bow controller, see [13]. Both the bow and the violin were fitted with infrared markers to facilitate the motion capture of the bowing movement and therefore determine the bowing parameters of bow velocity and bow position.

Using a Apple Macbook with a 2 GHz Intel Core Duo processor (OS X) running a PureData (Pd) implementation of the bowed string physical model, the recorded real player gesture data were input to the model, and the resulting synthesized violin audio was recorded for comparison to that of the "real" violin.

Mapping

Since both the physical model and the methods of measurement of the bowing gesture from real players were developed to reflect calibrated bowing parameters, the mapping between the two was straightforward. The three primary bowing parameters, downward bow force, bow velocity and bow position, were mapped directly to the corresponding input parameters of the physical model.

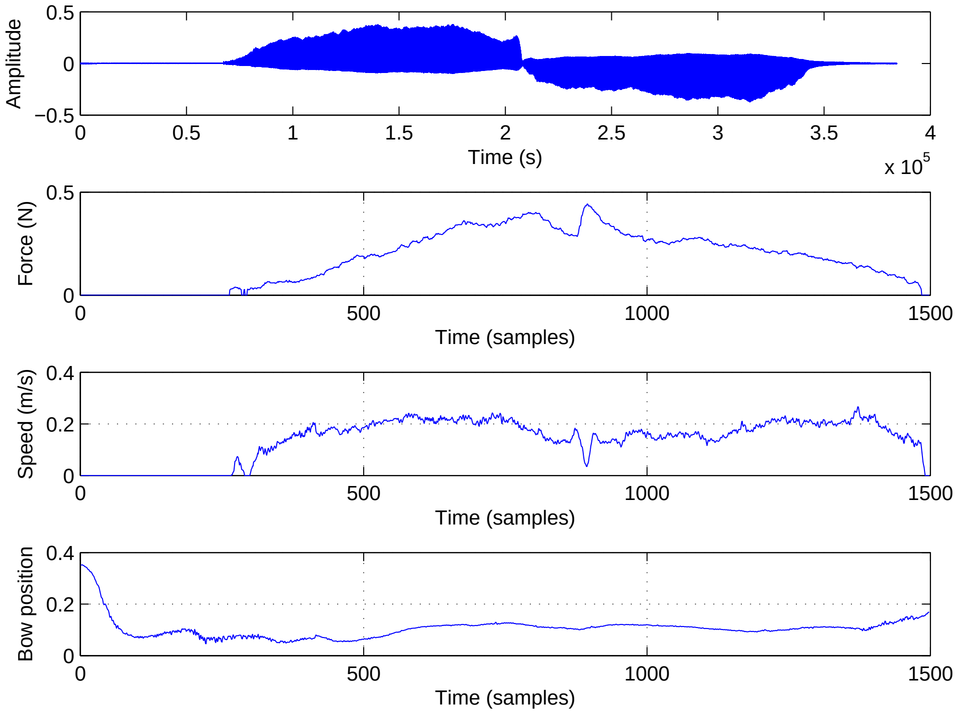

Figure 3: *An example of measured gesture data from a real player. From top to bottom: waveform captured at the bridge of the electric test violin, bow force (N), bow speed (m/s), and bow position (normalized between 0 and 1, where 0 represents the nut and 1 represents the bridge).*

Validation

Evaluation of the bow strokes using the experimental setup was done by comparing the output of the violin to the output of the physical model, using the same input parameters. This evaluation was first performed both acoustically and perceptually. The acoustical evaluation was obtained by comparing the shape of the time domain and frequency domain waveforms produced by the two instruments. This evaluation, however, did not seem very effective in the case of complex bow strokes. The main problem encountered was the way the waveform was recorded at the bridge of the acoustical instrument, which did not provide clean Helmholtz motion like in the case of the simulated model. Perceptual evaluation provided us with better insights.

CONCLUSIONS

In this paper, we propose an overview of evaluation techniques for virtual bowed string instruments. We focused on the different elements which produce a virtual musical instrument, i.e., its acoustical validation, real-time simulation, perceptual validation and control using a gestural controller.

We firmly believe that all these aspects need to be taken into account in order to create a playable virtual musical instrument. In this paper, we did not address compositional issues, which are usually mostly related to extending the models to create sonorities which cannot be achieved by real instruments. This choice was made since while acoustical, perceptual and playability properties of the model can be evaluated using either signal processing techniques, perceptual evaluation techniques or usability testing, artistic properties are in our opinion harder to scientifically assess.

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