REAL-TIME BOWED STRING SYNTHESIS WITH FORCE FEEDBACK GESTURE INTERACTION

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ABSTRACT

The CORDIS ANIMA formalism has been designed to model and simulate physical objects in a modular methodology, which guaranties at each step of modelling the energetic consistency of the model motions and internal behaviour.
Maintaining this energetic consistency is a crucial point in the use of interactive synthesis by the means of Physical Modelling and Force feedback gesture device.
It can be used to synthesise musical sounds and design virtual instruments, which can be played thanks to the real-time simulation and force-feedback gesture interfaces. Bowed string model of such virtual instruments can be designed and built with this tool. Like real bow instrument they may present a great sensitivity to the gesture dynamic. The simulation and tuning possibilities of the modular approach provide in addition new means for understanding these properties.

INTRODUCTION

The context of this work is the research program that aims generally at creating an ‘instrumental relation’ between musicians and computers. The main research axes are the followings:
1) The physical model formalism definition and conceptualization: Based on the mass/interaction physics, it provides a very general mean of designing instrument models.
2) Experimental and theoretical works on physical models among which bowed string, reed instrument plucked string and percussion instruments.
3) Computer architecture and software for interactive real-time synthesis.
4) Force feedback gesture interface devices for the gesture interaction.
5) User graphical interfaces that include modeling, compositional and analysis tools.

In this context it is possible to make interactive physical model synthesis that present interesting gesture sensitivity in a similar way than real instruments.
In the sustained oscillation instrument the sound evolution is closely linked to gesture and even in its short time determination, it depends on the action or behaving of the instrumentalist. It is well known that the player can widely induce the timbre properties of a sustained instrument sound.
In the following we present a bowed string interactive Physical Model synthesis that present such properties. Our goal is not to reproduce the exact playability of violins but to extract from the knowledge on these instruments some minimal significant properties to make new computer instruments. In a first part we present some similar works in the field of real-time synthesis. In the second and third part we present the bowed string model and its implementation on a real-time workstation.

RELATED WORKS

Several real-time implementations of sustained sound instruments have been made since 1982 (Smith, 1982, Smith 1986, Cook 1992). They are based on wave-guide techniques, which provides an interesting efficiency for real-time implementation. To our knowledge, they have anyway never been used with a real-time gesture force feedback interaction.

On the contrary, interesting works on hybrid wind instrument and hybrid bowed string instrument provide a real interactive gesture control (Boutillon1995, Guérard 1998). Technically, these works improved the knowledge on hard real-time interaction between real world and a simulation. In 1985, we introduced a first real-time bowed string simulation based on the particle-interaction system we had designed. It was not retroactive but allowed a gesture control of pressure and sliding by an especially designed device. (Florens &al. 1986) The force-feedback gesture interaction was introduced in the same mass-interaction context in 1990 with a force feedback keyboard (Cadoz & al., 1990). This interactive simulation demonstrated that it is possible to obtain a very sensitive virtual instrument even with an elementary model (Florens, 1990).

PHYSICAL MODELING CONTEXT

In our physical modeling context objects are designed as physical system whose internal evolution law can be computed in an explicit and deterministic way. The ability of these objects to be composed with each other's is obtained by providing them with the connection points that are dual physical signal input-output pairs. The main difference with other physical model approaches and musical synthesis tools is that, at the modeling level, the user is never concerned by the data flow manipulation but only by structural operations as defined.

The minimal elementary components from which a general physical model can be built are 1) the <MAT> element (typically the punctual inertia). 2) The <LIA> element, or interaction element, that generates the axial interaction force between the two <MAT> it is connected with. All these components are provided with sizing constants (physical parameters) that belong to the 4 categories : Inertia for the MAT, stiffness, viscosity and length for the LIA.

In addition to these basic components special modules may be necessary to model specific properties in a non-expensive way. One of these is the parameter control function that we will use in the bow/string friction model. The gesture interface may be seen as a set of specific <MAT> elements, and so linked to the simulated objects by using the normal object composition rules.

The displacement space is usually limited to one dimension in the context of sound synthesis, which implies that neither shape nor other geometrical properties are represented, but allows high efficiency in modeling the significant and essential dynamic properties of the instruments.

THE BOWED STRING MODEL

Using this modeling language our bowed string is made of 3 main elements: The bow module, the bow/string interaction and the string module (figure 1). In addition and apart to the computed parts of the model we must firstly consider the gesture interface whose configuration determines the gesture morphology of the instrument.

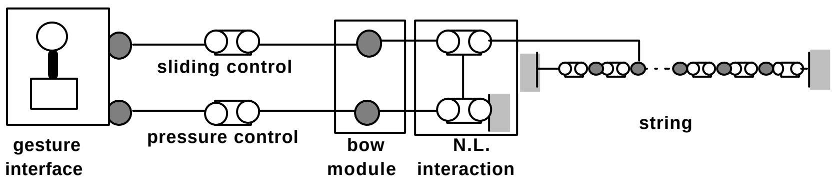

Figure 1. The bowed string model.

Gesture interface.

The gesture interface provides the force feedback coupling with the virtual bow. In the simplest model this coupling only concerns the two main minimal motions of a bow that are the sliding motion and the pressure control that can be obtained by a joy-stick configuration.

Compared to real bowing we have neglected many other motion axes, like ability to vary the hair width, or the distance of the bowing point fom the bridge. In addition, the stick bowing

differs from the usual bowing by the lower amplitude of the sliding motion and the direct and simpler action of pressure control instead of a variable torque that is needed in the case of the real bow.
The gesture interface is made of two parts:

- A special Electro-dynamic multi-axis actuator that has been specially designed for the force feedback coupling with high rigidity that may be required in the case of musical instrument excitation gesture. This device is made of a set of parallel flat coils that move in a magnetic field and whose currents are driven from the force signals produced by the real-time simulation. The iron-less structure allows intensive transient forces with a good linearity and high bandwidth. These actuator axis are also equipped with high precision inductive position sensors from which the position and velocity signals are fed back to the simulation.
- An adaptable passive mechanism that determines the manipulation morphology. It is shaped as a three-axis joystick whose extremity can be moved in a volume of about 20x100x100 mm.

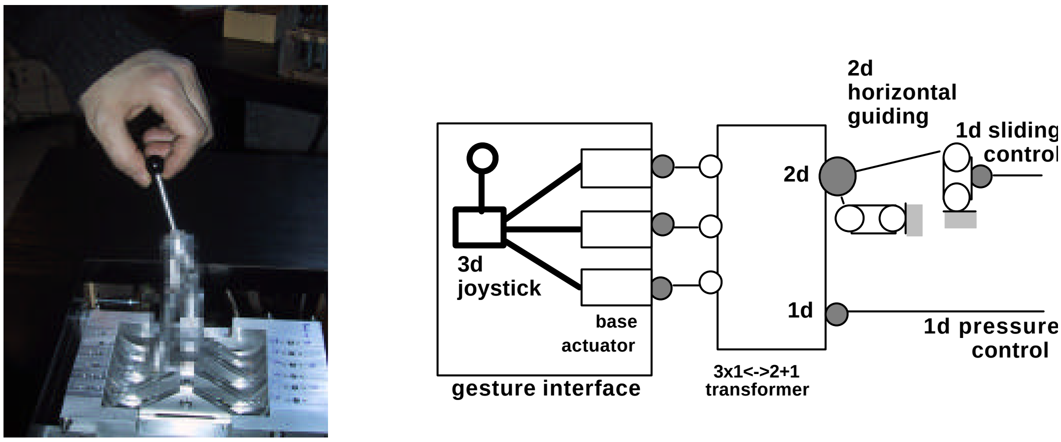

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Figure 2. The 3d bowing force feedback joystick and its coupling to the bow simulation.

In this system the mechanical frictions at low charge are minimized by the vertical orientation of the actuators axis, the moving parts weight being directly balanced by the active electromagnetic forces.
The 3d gesture interface is linked to the bowed string simulation through a bi-directional operator box. Its two distinct functions are: 1- establishing an adequate coordinate transformation between the actuator axis space and the model displacement space 2- constraining the 3rd degree of freedom of the joystick in order to obtain an equivalent 2d joystick coupling.
This operator is made of two stages (figure 2). The first stage splits the motion space into a 2d space and in a 1d space that respectively represent the horizontal and vertical displacement space of the joystick manipulation point. It behaves as a pure cinematic transformer without any energy accumulation or dissipation. It is based on cinematic model of the joystick.
The second stage contains a 2d physical model that constraints the 3rd D.O.F. as a horizontal virtual guiding. It is linked on one side to the 2d port of the 1rst stage and on the other side to the sliding part of the bow. The guiding is made of usual 2d CORDIS ANIMA elements
The vertical 1d port of the 1rst stage is directly linked to the pressure control of the bow. These different elements are equivalent to a passive mechanical coupling system. Thanks to this modular approach the orthogonal rigidity and damping of the horizontal guiding can be easily tuned.

<u>The Bow</u>

The part so called “bow” is an intermediate mass between the gesture interface and the string. It is linked on one side by a visco-elastic link to the interface and on the other side to the link by the non-linear friction module. Because of the 1D representation, the two axis of this part that correspond to each of the two dimensions of the gesture, are made of two distinct <MAT> / <LIA> links (figure 1). The tunable parameters of this element are:
The stiffness and damping of the link between this inertia and the gesture interface.
The scaling parameters of the link with the force feedback gesture interface. These concern independently the two axis forces and the two axis displacements.

The string

The basic model of the string is a chaplet composed of 25 to 60 masses linked by visco-elastic elements. Its ends are attached to high inertia damped oscillators that behave as bridges. These bridges can serve as sound output points or can be linked to other parts of the instrument. Because of its non-harmonic natural spectrum the discrete homogeneous chaplet produces slower attacks than a harmonic string (figure 3).
It may be useful to compensate this non-harmonicity by introducing a non-homogeneous repartition of the stiffness and inertia.

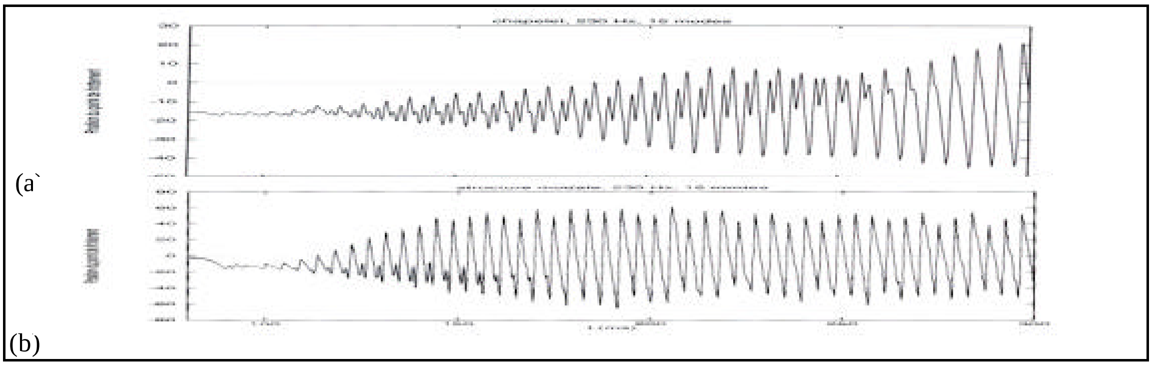


Figure 3. An attack transition of a homogeneous non-harmonic chaplet (a) and of a harmonic (b) one.

These re-tuning techniques are based on modal analysis and it has been shown in (Incerti 1996) that it is possible to obtain for a chaplet, any natural spectrum by an adequate repartition of stiffness and inertia.
We can also use in place of the chaplet, its equivalent modal model. The modeling formalism CORDIS-ANIMA allows building a standard modal structure (Cadoz 1993, Djoharian 1993) as made of a set of mass-spring cells and special coupling modules that provide the strictly equivalent <MAT> points of the chaplet. The re-tuning in this case consists in directly adjusting the modal cells parameter while saving the same modal deforms.

Bow-string interaction

The specificity of the bowed string instruments is mainly due to the particular properties of the bow-string interaction: sharpness of a specific dry friction and wide sensitivity of friction effect to bow pressure.
Recent related works on bowed string synthesis take into account some hysteretic properties of dry friction (Serafin &al 1999), in the aim of getting a more accurate representation of the rosin effect. In the past we have also used such a memory module (Florens 1990) in order to increase the sticking effect but in our case it was necessary because of the low computing power of the system whose computing rate was limited to 20 kHz.

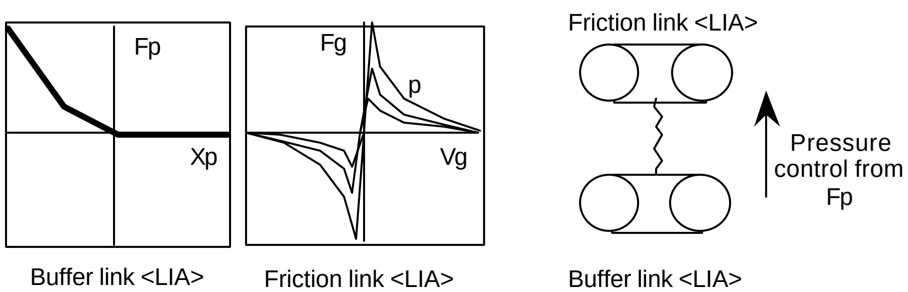


Figure 4. The friction physical module is a double non linear <LIA> : NL friction & buffer.

In the present simulation we use only the simplest memory-less model of rosin friction: This model is sufficient to provide the stick-slip effect and the usual behaviors of bowed string (like Helmholtz motions, sub-harmonic oscillation, and flattening).

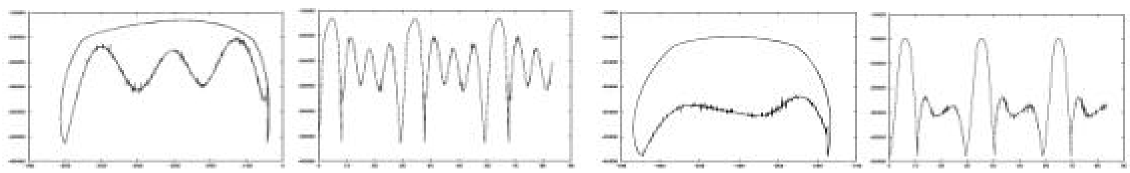
Within it, sliding forces are linked 1) to the sliding velocity by a non-linear function and 2) to the pressure by a proportional law. This model has been implemented in a special double <LIA> module, which also takes into account the “vertical” component of the interaction. In this module this vertical interaction model is an elastic buffer whose force is used as the pressure control parameter of the friction part.
The use of such a “quadripole” element avoids explicit signal flow manipulation and is thus compatible with the physical basic formalism. One can check that this module is strictly dissipative and can then be used as an independent physical component.

IMPLEMENTATION

The bowed string model has been implemented on a SGI workstation specially adapted for physical model interactive simulation. It is equipped with specific hardware mainly the gesture interface system, an audio interface system, and hardware concerning clock generation and synchronization.
The software environment is a simulation engine that consists in an open library of physical modules and a kernel that assumes all real-time synchronization and communication functions. This software takes advantage of the multi-processor architecture by dedicating one processor to system management whereas all of the others perform the real time computations in a special reserved mode (Florens 1998)
The specificity of the model that are the sharpness of the non linear part and the need to provide an efficient gesture coupling have led us to use various computing rates for the different parts of the model.
The critical parts that are 1) the bow-string non-linear interaction module 2) the last mass element of the bow module, are computed at the higher frequency (typically 48kHz). The link to the force feedback gesture interface is computed at the maximum rate of 3kHz that is compatible with the reactivity of the system.
This multi-rate mode is supported by the simulation engine in which several rate level are pre-defined, each elementary component being affected to one of these levels.
We must also precise that all the synchronization constraints are driven trough the data-flow conservation rules, from the unique master clock.

EXPERIMENTATION / RESULTS

Generally, this bowing model reinforces the idea that one can obtain musical timber variation and phrasing even on simple model, provided the use of a gesture interaction.
Compared to our previous works on the same topics, the main results are:
The ability to use a 'sharper' bow-string interaction model, while preserving the stability of the computation. This allows higher bow pressures, higher pitches and string damping.
Some general rules that concern the gesture interface coupling and the use of multi rate simulation have been obtained and will be useful in the future developments.
The model presents other interests that could not be found in real instruments. For example, by tuning the displacement and force scaling factors of the device, we provide a way to enhance some sensitive and effective gesture effects without changing the virtual model. This means that we can focus our research on the perception of the musician gesture and then explore furthermore the gesture/sound relation.



(a) (b)

Figure 5. The bowing force observed (coil current) for two different values of the damping coefficient in the string: low damping (a) and high damping (b). The left diagrams (force versus string displacement) area is the energy supplied to the string at each cycle.

A more precise restitution of this bowing force has been obtained. We can observe in particular that its pulsed component amplitude directly depends on the vibration energy that is dissipated in the string (figure 5). We can also observe some oscillations during the sticking phase. These are produced by the reflections of the Helmholtz corner against the bow as explained in (McIntyre &al. 1981). We have observed that they were playing an important role in triggering some secondary Hemholtz motions.

In the simulation, thanks to the bandwidth improvement of the force feedback interface these main pulsed components of the bowing force are also driven to the instrumentalist's hand, as it does in the case of a real bow (Askenfelt &al. 1992). By this mean the hand is closely linked to the vibrating system.

CONCLUSION

This model and its implementation allow investigations concerning bowed string sound synthesis or other sustained oscillation models that use a sharp non-linearity.

Its high efficiency enlarges the field of possible complexity and higher pitch frequencies for the real time interactive simulations.

The high bandwidth of the gesture interface channels has provided in the case of force feedback coupling a more precise and sensitive interaction between the instrumentalist's hand and the vibrating string. This is interesting in the case of live synthesis but also for the musical studio creation in which one may use either sequences of real playing or artificial gesture composition.

It also provides a powerful experimentation tool on the instrumental gesture that concerns especially the high bandwidth coupling. Indeed, thanks to ability to tune the gesture coupling scale factors, some interesting tenuous effects can be revealed and enhanced.

All these results open a new way in for the musical creation and technical research in the context of virtual instruments.

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