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Reed instruments modular representation and their interactive real time simulation

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Abstract

The CORDIS-ANIMA formalism allows musician or acoustician to describe and simulate physical objects in a modular approach. It has been especially designed to synthesize musical sounds from instrument or to simulate sounding objects. This paper presents a physical model of reed instruments based on this formalism, which guarantees the energetic consistency and provides real time instrumental playing.

1. Introduction

In the field of physical modeling for musical sound synthesis, the CORDIS-ANIMA [1] formalism is a way to design virtual musical instruments and sounding objects as an assembling of elementary mechanical components. By this means, we are able to build models of a wide variety of physical objects, which can be objects having linear behaviors or regular topology, as well as objects producing complex acoustical phenomena (matter heterogeneity, structural non linearities, large geometrical size, non regular topology ...). For this kind of phenomena, global analytic representations would be quite unwieldy, even impossible.

The CORDIS-ANIMA formalism is based on the assembling of two kinds of generic modules called <MAT> and <LIA>. Typically, the basic <MAT> module algorithm is a discrete implementation of the Newton's second law and it is called the *punctual mass algorithm*; The <LIA> module represents interactions between two punctual masses. More generally, the <MAT> module computes the extensive phenomena and the <LIA> module computes the intensive correlation between them. Then this formalism can be used for a wide kind of physical or non physical phenomena. It has been used for modelling multitude behaviours such as flowing of human crowd [2] and obstacle avoidance in traffic flowing [3].

This physical assembling principle insures at each time the mechanical energy flow conservation between each modules. It allows a good control of energetic properties of virtual instruments. Above all, it allows a clear identification of the active and passive parts of the physical instrument and then contributes highly to realism, richness and sensitivity of synthesized sounds.

Here is a fundamental difference between the CORDIS-ANIMA formalism and the "data-flow" formalism. Data-flow formalism, chaining explicit signal processing components, insures information flow conservation rather than energetic flow conservation.

The wind instruments modeling in the CORDIS-ANIMA formalism is founded on two complementary techniques:

1. The first is a particle-based representation of matter: fluid located in the cavity, surfaces of the cavity, injected fluid or mechanisms controlling the flowing. This approach provides a direct control of (a) the geometrical properties, (b) the oscillating phenomena, (c) the transport phenomena and (4) the interactions between the different objects (fluid/cavity interactions, fluid/fluid interactions ...). Because of its expansive computational cost, at this time, it has been used only to render fluid turbulences in image synthesis requiring a larger simulating rate (1 KHz) than acoustical phenomena.[4]

2. The second is the method presented in this paper. It is based on a functional physical model. It allows to perform real time simulation with a medium scale computer and then, to gesturally control the sound.

A modular acoustical model of an aerien cavity.

In the previous physical models, each <MAT> represents a matter element that moves in a physical space (Euclidian 2D or 3D). In the functionally based physical model presented here, dedicated to acoustical phenomena, our <MAT> component, called "acoustical <MAT>" is like a quantum of space containing a variable amount of matter. The state equation of this acoustical <Mat> is then a discretized form of the compression law (deduced from a mass conservation principle) :

$$P_{n+1} - P_n = T_e \cdot K_a \cdot U_n \quad \text{with} \quad K_a = \frac{\rho c^2}{V_0}$$

In this equation P and U are the pressure and the velocity of the total volume of the matter entering in a quantum of space. T_e is the time step and K_a is an acoustic stiffness (with c : sound celerity, ρ the volumic mass and V_0 the volume of the space quantum).

The complementary acoustical <LIA> component represents the interaction between the <MAT> space elements. These interactions are characterized by the possible relations between the flow velocity from one element to another and their pressure difference.

Two main linear <LIA> elements can then be defined as physically relevant :

- This first generic link describes the inertial behaviour of the gaz according to the following discrete equation :

$$U_n - U_{n-1} = \frac{T_e}{M_a} \cdot (P_n^i - P_n^{i-1}) \text{ with } M_a = \frac{\rho \cdot \Delta x_l}{S}$$

where M_a is an acoustical inertia which depends on the length Δx_l and the area S of this link element.

- The second generic link is a linear acoustic damper. The damping law has been introduced by using classical analogy with the mechanical models. Moreover, it characterizes some physical systems like capillary tubes [5]. The module is defined by the following equation:

$$U_n = \frac{1}{Z_a} \cdot (P_n^i - P_n^{i-1})$$

where Z_a is the acoustical viscosity.

This viscosity element can be explicitly combined the acoustical <MAT> to introduce damping in the resonators. The serial composition with the other <LIA> element (the acoustical inertia) often used in acoustical models [6] is also possible by integration in a specific <LIA>.

Then arian cavities may be represented as a <MAT> / <LIA> network built with the three above elements. Such nets are similar to the standard CORDIS nets that represent mechanical vibrating structures (figure 1). The analysing tools developed in the context of these mechanical nets studies [7a, 7b] can directly be applied. They allow especially to control with accuracy the modal properties of the net taking in account the temporal and spatial discretisation.

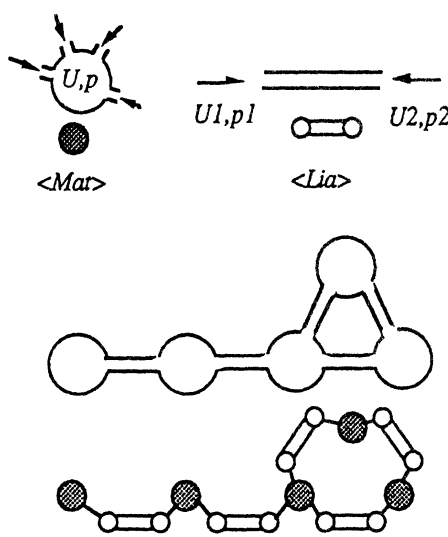


Figure 1. The two basic acoustical components <MAT> and <LIA> and an acoustical network

The low frequency reed representation.

In many physical models of reed instrument used in musical synthesis, a functional representation of the reed is used, given by a flow / pressure relation deduced from the flowing law of a fluid across a restriction (Bernoulli's law) and of the deformation of the reed whose inertia is neglected. This gives a memory-less system that can be integrated in a specific <LIA> component characterized by a U(P) function that get a negative slope zone.

This component allows to build in the CORDIS-ANIMA modular context a first family of reed instruments. The modularity provides means to investigate many ways of experimentations and studies on the resonator especially concerning the effects of damping, the introduction of lateral holes and non homogeneous sections or non-lineic topology to represent non tubular resonators.

Similar investigations on the exciter parts are not possible since all its parts or functions are integrated in only one component. Then, this monolithic form eliminates the ability of coupling any mechanical element to the reed (for example to simulate the lip control).

An hybrid acoustic/mechanic reed model.

In order to overcome this limitation we have developed an hybrid reed model in which the acoustical and the mechanical properties are both explicitly represented in two separate [<MAT> <LIA>] systems, one modeling an acoustic domain, and the other a mechanical domain.

The coupling between these two systems is necessarily founded on the use of quadripolar elements in order to preserve the action-reaction principle in the mechanical domain and the air flow conservation principle in the acoustic domain. Each of these quadripoles is made of two internally linked <LIA> elements, one which is connected in the acoustical domain and the other in the mechanical domain.

The reed model is made of two such quadripoles.

1) The first looks like an ideal piston that represents the air action on the reed sides (figure 2). This component is non-energetic, (neither accumulative nor dissipative) and then transforms in a reversible way the mechanical <LIA> in acoustical energy. This mechanical <LIA> represents the rod / body dipole and the acoustical <LIA>, the two chambers dipole.

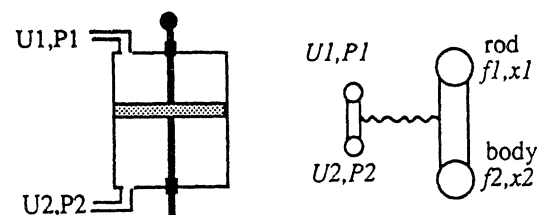


Figure 2. Transducer quadripole. A non-energetic piston.

2) A “relay” quadripole that can be represented as a valve whose aperture is controlled by a mechanical lever displacement (figure 3). This module describes the variable flow restriction effect of the reed. It is a pure dissipative element that needs no control energy. To define it, instead of the Bernoulli law, we have used the acoustic viscosity model that is linear and in which the $C_a = 1/Z_a$ coefficient is controlled by mechanical displacement y . As this coefficient must always be positive we have chosen to define it as a quadratic function of y according to the following expression :

$$C_a(y) = \alpha(y - y_0)^2 + C_{a0} \text{ if } \alpha(y - y_0)^2 + C_{a0} > 0$$

$$C_a(y) = 0 \text{ if } \alpha(y - y_0)^2 + C_{a0} \leq 0$$

The parameter y_0 will be used to determine the reed aperture at rest position. The other parameter C_{a0} if positive defines the minimum of C_a . In this case the valve model will be used to make free reeds. If C_{a0} is negative, the valve is closed ($C_a(y) = 0$) as long as $\alpha(y - y_0)^2 + C_{a0} < 0$ and in this case, a non null elastic force feedback is supplied at the mechanical command dipole. In this C_{a0} negative case the valve will be used to make striking reeds. The C_{a0} absolute value will determine the sharpness of the closing point on the $U(\Delta P)$ function.

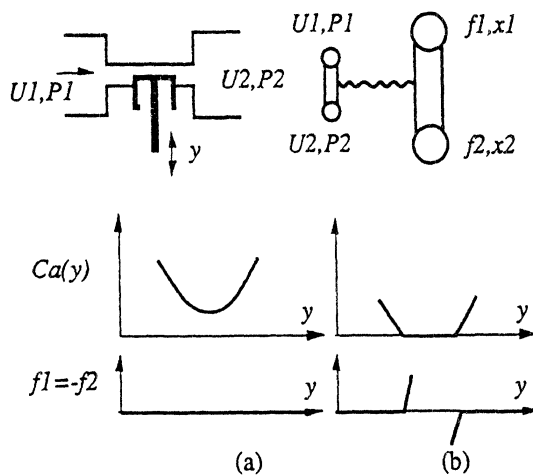


Figure 3 . The relay quadripole.
 $C_a(y)$ and $f(y)$ force at the control dipole
 for the free reed (a) and for the striking reed (b)

The complete reed system is then built from these two components. The reed mechanical properties are represented by a Mass Spring Damper cell that is connected to the piston rod (figure 4).

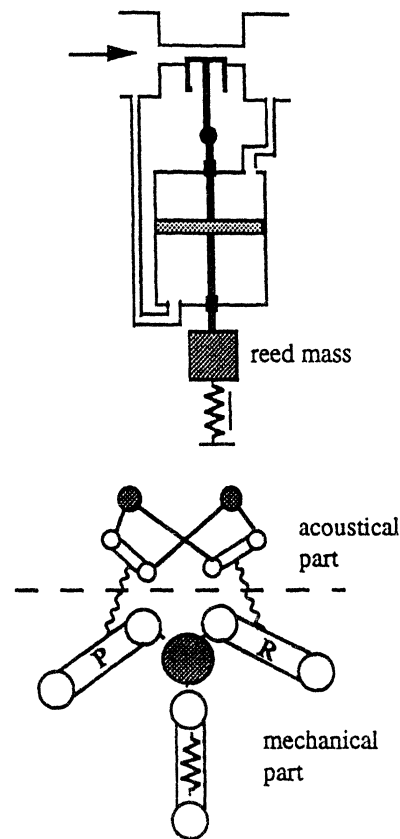


Figure 4 The modular reed model.

This reed model then provides independant access to the mechanical and acoustical parts of the reeds and therefore it provides new ways for experimental investigations on the model:

- the ability to evaluate the effect of the inertia and damping coefficient of the reed; these two parameters can be adjusted in a wide area, including the low frequency configuration.
- the study of the effect of the pumping flow that could not be taken into account in the low frequency model, and that is naturally provided by the piston in the modular model.
- the improvement of the reed model as a set of several masses providing a more realistic bar model.
- the improvement of the valve quadripole; indeed, in the case of striking reed with $C_{a0} < 0$, the valve quadripole works like a buffer on its mechanical side. This buffer function can be improved by introducing a multi-level buffer elements. This configuration can be used to introduce a realistic and energetically coherent gestural control of the reed stiffness.
- the design of double reeds; an elementary double reed model can easily be built from the defined components. It is composed of two pistons transducers and of one relay valve that is driven in a differential way by the two reed masses.

Real time instrumental playing with gestural interactions.

Our goal is not to reproduce exactly the same conditions than in the case of real wind instruments playing, that would need a special breath interface, but to find relevant means to interact with the model. In order to save the energetical passive behaviour of the virtual instrument and use efficiently its dynamic qualities, we use an FFGT (Force Feedback Gestural Transducer) designed for a hand manipulation [8] that controls the "mouth" acoustical dipole through an ideal blower modeled as a piston quadripole. Another FFGT channel can be used to gesturally control the reed according to the multi level buffer control.

CONCLUSION

The goal of this modeling work was to investigate the domain of reed instruments in a modular approach taking into account the ability of these models to be simulated in real-time for instrumental interactive control. This constraint led us to define new efficient modules for acoustical model representation and means to design acoustical /mechanical hybrids.

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