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MODELING PRINCIPLES FOR TIME-DOMAIN SIMULATIONS OF WIND INSTRUMENTS IN PLAYING SITUATIONS

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ABSTRACT

The development of an evolutive free software which simulates the physical behavior of wind instruments in playing situations can be based on the following modular postulates. In an object-oriented context, the virtual instrument is designed as a set of "anticipative" and lumped elements. After connection rules are laid down, new elements are progressively added and each element is separately improved. One example illustrating this approach for single reed instruments includes modeling of air columns by usual waveguide or two-port, considerations about the reed, and a key-pad model. The current state-of-the-art research in acoustics has a great potential for future extensions.

INTRODUCTION

In sound synthesis by physical modeling, the physical behavior of wind instruments is simulated in the time domain to create musical sounds [1,2]. In this kind of simulation, priority is a real-time response of the simulator to the actions of the player through a suitable controller [3-6]. In this context where *real-time*, *playability*, *expressiveness* and *musicality* are the key-words, the models are often simplified. For more than two decades, many works have been published (*cf. e.g.* [6-24] on wind instruments) and commercial products are available (*e.g.* Modalys™ Software [25], Yamaha® VL70-m™ with WX11™ Wind MIDI controller, Korg® Prophecy™). Such a simulator can also be a useful tool for the wind instrument members of the acoustic community, but with different purposes. The comparison between measurements and simulation tests the validity of a given model by pointing out its qualities and deficiencies, helps the acoustician to ask himself suitable questions about his model, and permits him to balance several hypotheses or to evaluate the influence of one or several parameters. The sounds produced by such a virtual wind instrument give a qualitative criteria of evaluation but remain one part of multiple exploitable results. Thus, priorities are different in this case: the simulator has to follow as near as possible existing physical models. Because modeling techniques are improving, it has become more and more difficult for a researcher himself to develop a new simulator. A simulation software for acousticians, and perhaps for several manufacturers too, seems to be needed. A commercial product is not conceivable because of the market law: demand is too small for creating a supply. The work is still outstanding. A software could be made by a development team of motivated professional developers, mathematicians, and acousticians inside the community of wind instrument research. The key-words of such a software would be *physics*, *evolutivity*, *portability*, and *ergonomics*.

Before beginning any programming, a few modeling and programming principles need to be defined after they have been discussed. This paper is intended to launch a discussion. The first section proposes several principles which are applied in the second section to single-reed instruments.

A MODULAR ARCHITECTURE ASSURING BOTH HIGH-PERFORMANCE AND EVOLUTIVITY

A modular architecture for wind instruments modeling is postulated because it is natural for a physicist and corresponds to object-oriented development methods. This postulate implies three principles: firstly, a virtual wind instrument is built with elements seen as "black boxes"; then, connection rules have to be established with the aim of modifying or adding elements; and finally, discrete time modeling requires both a separation of "anticipative" elements from "lumped" ones and additional connection rules.

Modularity and Object-Oriented Conception

The wind instrument model is separated into elements such as mouthpiece, piece of tube,...etc. In the software conception, each element gives a discrete object that incorporates both data structure and behavior [26]. In this object-oriented context, existing elements can be modified and new elements can be added by anyone apart from the rest of the virtual instrument. Improvements and evolutions are facilitated by this process. Any new developer can add a brick to the wall provided that all source codes remain open. This is the philosophy of “free software” [27]. Moreover, parallel architecture is allowed in this scheme and a high-performance simulator is then hoped.

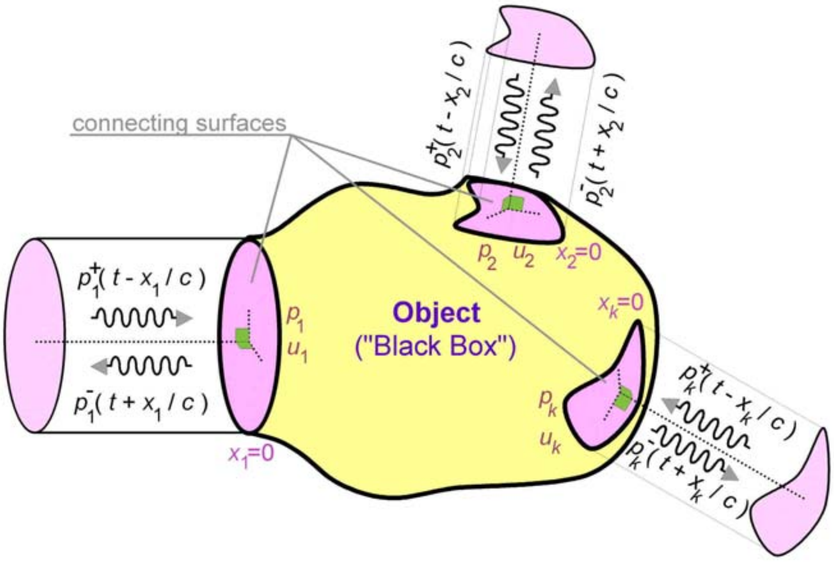

Figure 1 : An element and its connections to the rest of the virtual instrument

Connection Rules and Physical Hypotheses

Communication between objects necessitates connection rules. Each “Black Box” element is connected to the rest of the instrument by K surfaces (*cf.* Fig. 1). It may be noted that any interaction of an element with the outside like a player action or radiation is considered as internal. The following physical hypothesis is made: on the neighborhood of the k^{th} surface of area S_k, a unidimensional propagation is supposed so as to describe the acoustic state entirely by mean pressure p_k and ingoing volume velocity u_k. Generalizing the idea given by the definition of the reflection function in Shumacher [28], let us imagine that a cylindrical tube of cross-section S_k is connected to the k^{th} surface. Provided that S_k is neither too large nor too small [29], the acoustic pressure wave in this tube is the sum of an ingoing plane wave p_k^+ and an outcoming plane wave p_k^- (*cf.* Fig. 1). The element is a K-Port of which input and output vectors verify [30]:

$$\overrightarrow{p}^{+}(t)=\begin{pmatrix}p_1^+\\ \vdots\\ p_K^+\end{pmatrix};\ \overrightarrow{p}^{-}(t)=\begin{pmatrix}p_1^-\\ \vdots\\ p_K^-\end{pmatrix};\ \forall k\in \mathbb{N}, 1\le k\le K,\ \begin{cases} p_k^+ = (p_k+\rho c\, u_k/S_k)/2 \\ p_k^- = (p_k-\rho c\, u_k/S_k)/2 \end{cases} \tag{1}$$

where c is the sound speed, ρ the mean air density, and $\mathbb{N}$ the natural numbers set.

Additional Connecting Rules for Keeping Modular Structure of Discrete-Time Calculation

In discrete time, each element is supposed to be causal *i.e.* the output vector can be written:

$$\overrightarrow{p}^{-}(n)=\varphi\left[\overrightarrow{p}^{+}(n),\overrightarrow{p}^{+}(n-1),\cdots,\overrightarrow{p}^{+}(n-m_1),\overrightarrow{p}^{-}(n-1),\cdots,\overrightarrow{p}^{-}(n-m_2),\overrightarrow{a}(n),\cdots,\overrightarrow{a}(n-m_3)\right] \tag{2}$$

where the vector $\overrightarrow{a}$ represents both internal modifications and actions from the outside.

When two elements are connected, the input of one is the output of the other. A numerical coupling is ordinarily generated. This is the reason why a distinction has to be drawn between “anticipative” elements which verifies Eq. (3) below and the others called “lumped” elements [31].

$$\overrightarrow{p}^{-}(n)=\varphi\left[\overrightarrow{\boldsymbol{p}}^{+}(\boldsymbol{n}-\mathbf{1}),\cdots,\overrightarrow{p}^{+}(n-m_1),\overrightarrow{p}^{-}(n-1),\cdots,\overrightarrow{p}^{-}(n-m_2),\overrightarrow{\boldsymbol{a}}(\boldsymbol{n}-\mathbf{1}),\cdots,\overrightarrow{a}(n-m_3)\right] \tag{3}$$

An additional rule is then, so as to avoid undesired coupling: several lumped elements can not be directly connected to each other. If they are they merge into a new lumped element.

In the step by step calculation, each step is divided into two sub-steps as shown in Fig. 2.

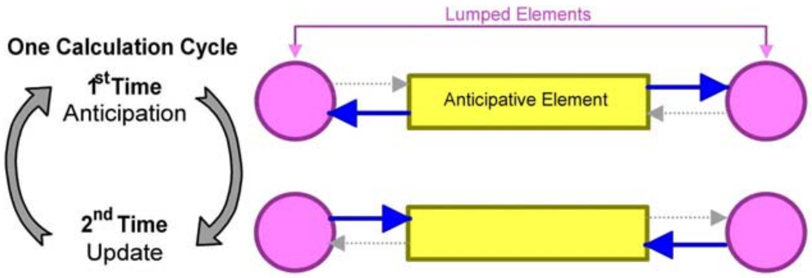

Figure 2: Each calculation step is divided into sub-steps: "anticipation", and calculation of lumped elements

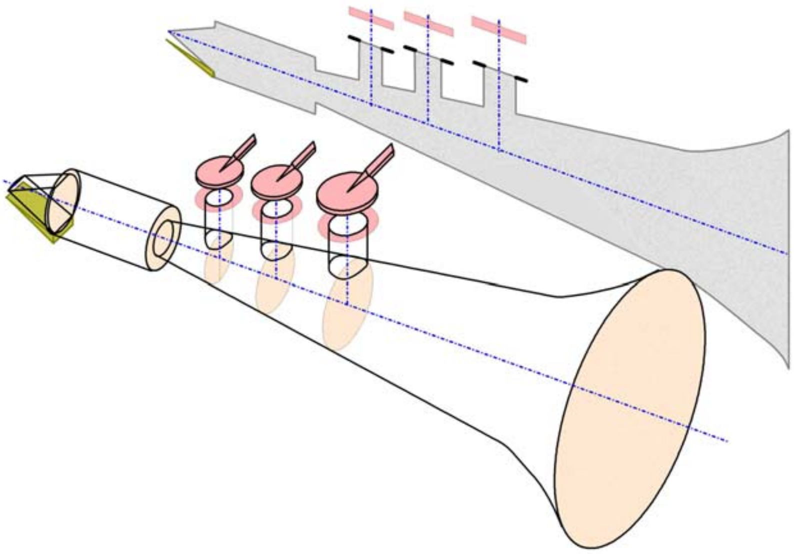

Figure 3 : A three-tone-hole simplified saxophone with key-pad systems

THIS MODELING SCHEME APPLIED TO SINGLE-REED INSTRUMENTS

The following example of a single-reed instrument (Fig. 3) illustrates on one hand that most of the usual simplified time-domain models can be included in this proposed modeling scheme and on the other hand that existing physical models can enrich and enhance wind instrument simulations and reciprocally.

Usual Simplified Models Compatible with this Structure

Except in the case where the whole resonator is characterized by either a reflection function or an input impedance (*e.g.* [7,8,10,16,28]), a virtual single-reed instrument is generally cut into elements as done in Fig. 4. The "anticipative" category contains a single element: an air column the length of which is greater than the sound speed divided by the sampling frequency. "Digital Waveguide" modeling [9,13 and also *e.g.* 1,2,6,11,17,18,20,24] is generally used for cylindrical and conical bores. With the connection rules above, an adaptation has to be made for conical bores [30] contrary to cylinders. For more complex shapes, a anticipative two-port can be designed [30,31]. Discontinuities (two-port junctions) and three-port junctions are characterized by both the continuity of pressure and conservation of volume velocity. Several kinds of models can be used for the single-reed mouthpiece: either a non-linear characteristic [8], or a dynamic model including both mechanics of the reed (either one-dimensional oscillator [32-35, 16] or beam [7,10]) and the air flow through the slit [36]. A radiation impedance [37,38] is a simplified representation of the end of the bell. Radiation at the exit of a tone-hole depends on the position of the key [33,39,31,24].

Expecting Improvements in Woodwind Simulations

More elaborated models can be used in the same modeling scheme. An alternative cut of the simplified saxophone (Fig. 3) is done in Fig. 5. Higher modes can be introduced to model either a change of cross-section [40-43] or the pressure field inside a bell [44-46]. Improvements in tone-hole modeling [47-49] should be taken into account, possibly including non-linearities [50,51]. Non-linearities could also be added to usual models either at discontinuities of cross-section or for the bell. Furthermore, there are other purposes such as to simulate either the effect of the player's vocal tract [52-54,10] or the radiated sound field.

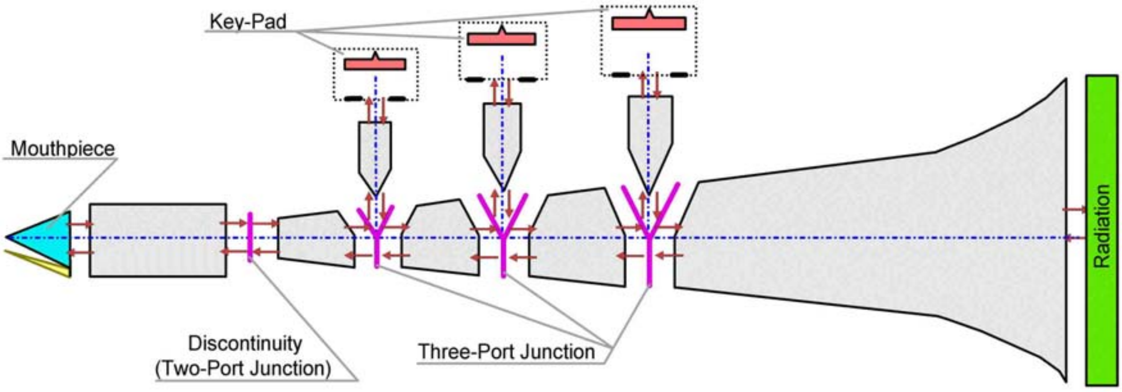

Figure 4 : Usual cut into elements of five types: mouthpiece, air column, junction, radiation, and system “exit of the tone-hole/key-pad”

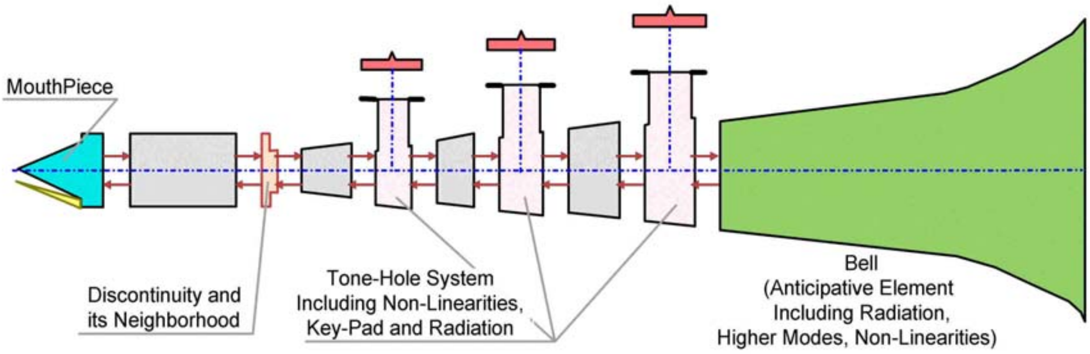

Figure 5: An alternative cut of the simplified saxophone of Fig. 3.

CONCLUSION AND PROSPECTS

These modeling and programming principles seem suitable for time-domain simulations of wind instruments. The example of single-reed instruments could be extended to the whole wind family by adding other types of mouthpieces, pistons, and slides. Non-linear propagation should also be added for brass instruments [55,22]. The work is still outstanding to permit future acoustic researchers to avoid spending their time programming for often disappointing results. A development team whose philosophy could be both close to the “free software” one and based on principles as shown in this paper, still has to be formed.

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