A Physical Model of a Single-Reed Wind Instrument, Including Actions of the Player

Eric Ducasse

To cite this version :

Eric DUCASSE - A Physical Model of a Single-Reed Wind Instrument, Including Actions of the
Player - Computer Music Journal - Vol. 27, n°1, p.59-70 - 2003

A Physical Model of a Single Reed Wind Instrument Including Actions of the Player

Éric Ducasse

École Nationale Supérieure d'Arts et Métiers, C.E.R. de Bordeaux-Talence, 33405 Talence Cedex, France.

eric.ducasse@ensam.eu

Introduction

Today, the musical interest and the stakes of Physical Modeling Synthesis are well identified (*cf.* particularly the discussion of Douglas Keefe in 1992 in the same journal; Smith 1996). In particular, time-domain simulation of the physical operation of musical instruments makes it possible to create transitory and perceptive phenomena which would have been difficult to obtain by other data processing. The design of the complete model (that is including the simplified modeling of the main actions of the player) of a single reed instrument presented here illustrates the fact that "*it may be that a simplified model of a wind instrument produces sound exceedingly similar to that of the actual system*" (Keefe 1992). Contrary to many approaches where the sound synthesis for musical interpretation is the principal objective, the objectives are here: firstly to "*test the accuracy of the implicit assumptions and structure of the underlying physical model*" with "*simulation*[s] *of* (…) *known instrument-player system*[s]" (Keefe 1992), secondly to allow the instrument maker to have an idea of the sound produced by an instrument in a playing situation before the construction of a prototype, and thirdly to be able to design physically unrealizable virtual instruments, as for example a transverse saxophone (cf. Bouasse 1929) while remaining in a "*timbre space*" and keeping the aspect of membership of a family of instruments. The emphasis is particularly laid on modeling even roughly the parts of the instrument as well as performance controls which have significant consequences on the generated sound.

The model of single reed instrument presented here is based on the principle of modularity: the instrument is built with interconnected elements. This is made possible by an adapted representation of tubes. Then the model of the single reed mouthpiece is detailed including the action of the player via his breath, tongue and lips. The tone hole model including the key or finger motion is also detailed. Each important element of the model is illustrated by results, in particular sound simulations.

A Modular Representation of the Instrument

The postulate of modularity is necessary for various reasons: firstly, it is perfectly adapted to the object-oriented programming of which one of the most noticeable characters is flexibility; secondly, it can be easily implemented on wind instruments because of the existence of elements called *anticipative* which connect the other elements known as *lumped*; and finally, it holds a strong potential for evolution and a progressive extension to the whole wind instrument family.

A Representation Adapted to Object-Oriented Programming

In an object-oriented programming system, each object (*class*) has associated attributes characterizing its structure as well as methods defining its behavior. This object communicates with the others by its parameters and *public* properties, that is properties seen by the other objects, which must be defined once and for all according to a communication standard. On the other hand, the working procedure of the object, characterized by its parameters and *private* properties, can be modified without disturbing the total model. This allows a great flexibility since the modeling of such or such element of the instrument is not fixed once and for all.
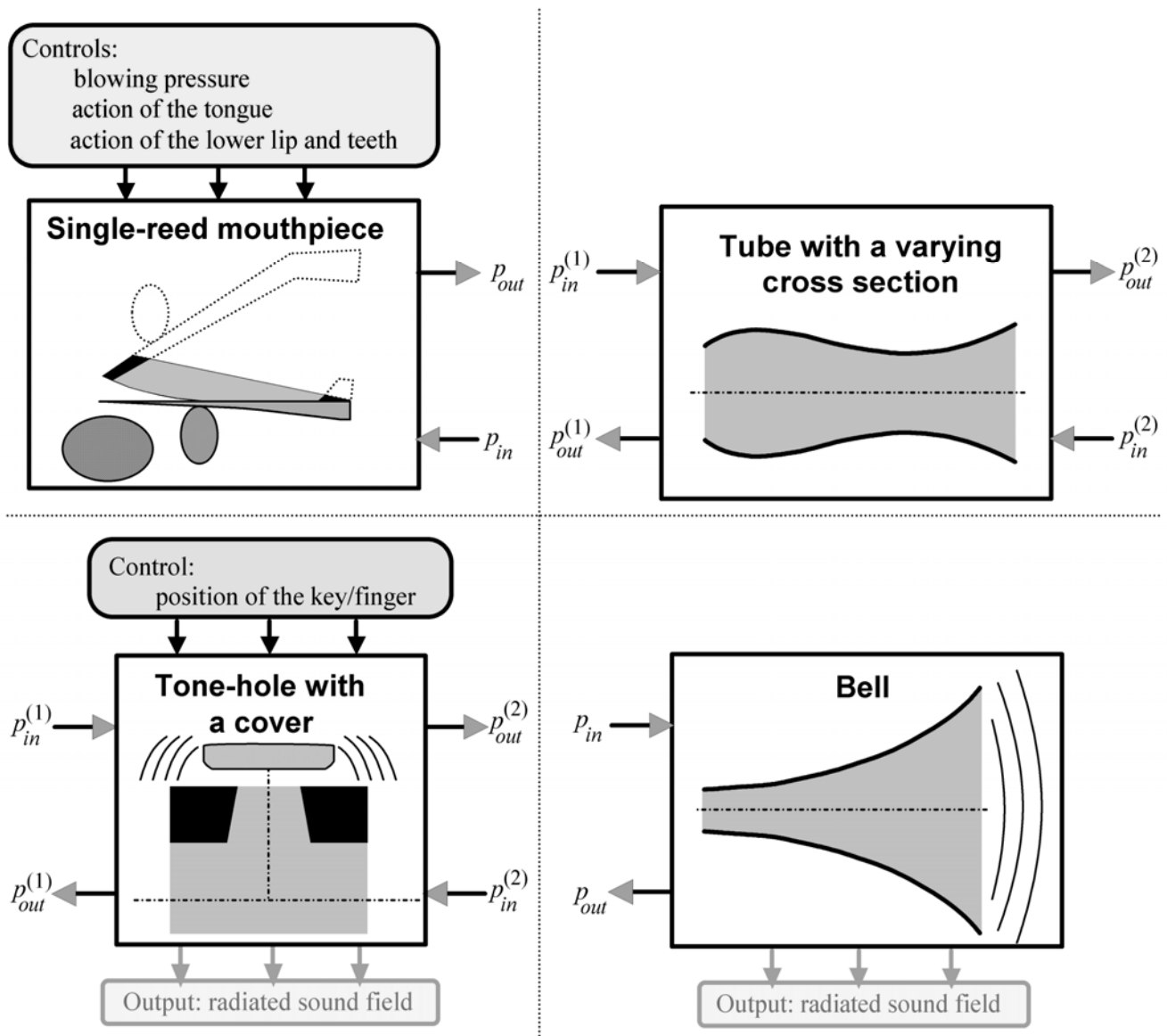

Figure 1: *Four basic modules for building a single reed wind instrument.*

For the modeling of single reed wind instruments four objects are distinguished: the mouthpiece with reed, the tube, the tone hole with possible closing by a finger or a key, and the bell (*cf.* Fig. 1). Each element has one or two ports, each one being characterized by an input p_{in} and an output p_{out}. According to the plane wave approximation at any port, the average pressure p on the cross section S and the volume velocity u entering through this section are written:

$$\begin{cases} p(t) = p_{in}(t) + p_{out}(t) \\ u(t) = \dfrac{S}{\rho_0 \, c}\left[p_{in}(t) - p_{out}(t)\right] \end{cases}$$

(1)

where ρ_0 is the density of the air and c the speed of sound.

Each connection of two or more elements is realized by writing the continuity of pressure and conservation of volume velocity. Thus, this constitutes the communication standard between the various elements.

Lumped Elements De-coupled due to the Anticipative Property of Tubes

A causal discrete-time system is called "anticipative" if the outputs can be calculated at least one time step in advance, i.e. any output at n^{th} sampling instant is calculated according to the various variables at sample (*n-1*) and previous samples. Among the whole of the elements constituting the wind instrument, the tube presents this anticipative property provided its length is sufficient, that is larger than $c \times T_s$ where T_s is the sampling period chosen for the whole simulation.

There is anticipation, on the side No.1 of the tube for example (*cf.* Fig. 2), if an equation such as the following can be written:

$$p_{1,out}^*(n) = \left| \begin{array}{l} \varphi_{11}\left[n, \ p_{1,in}^*(n-1), p_{1,in}^*(n-2), \cdots, p_{1,in}^*(n-k_{11})\right] \\ + \varphi_{21}\left[n, \ p_{2,in}^*(n-1), p_{2,in}^*(n-2), \cdots, p_{2,in}^*(n-k_{21})\right] \\ + \phi_1\left[n, \ p_{1,out}^*(n-1), p_{1,out}^*(n-2), \cdots, p_{1,out}^*(n-n_1)\right] \end{array} \right.$$

(2)

where the following notation is used: the sampling of any continuous-time signal s complying with the assumptions of the theorem of Shannon gives a discrete-time signal s^* defined for all n by $s^*(n) = s(n\,T_s)$.

This leads both for a *Digital Waveguide* model (Smith 1986, 1992) of a cylindrical portion of tube and for a two-port model of a tube of varying cross section (*cf.* Fig. 2 & Ducasse 2002) to the linear invariant following system:

$$\begin{cases} p_{1,out}^*(n) = \displaystyle\sum_{j=0}^{k_{11}} h_{11}^*(j)\, p_{1,in}^*(n-j) + \sum_{j=1}^{k_{21}} h_{21}^*(j)\, p_{2,in}^*(n-j) \\ p_{2,out}^*(n) = \displaystyle\sum_{j=0}^{k_{22}} h_{22}^*(j)\, p_{2,in}^*(n-j) + \sum_{j=1}^{k_{12}} h_{12}^*(j)\, p_{1,in}^*(n-j) \end{cases}$$
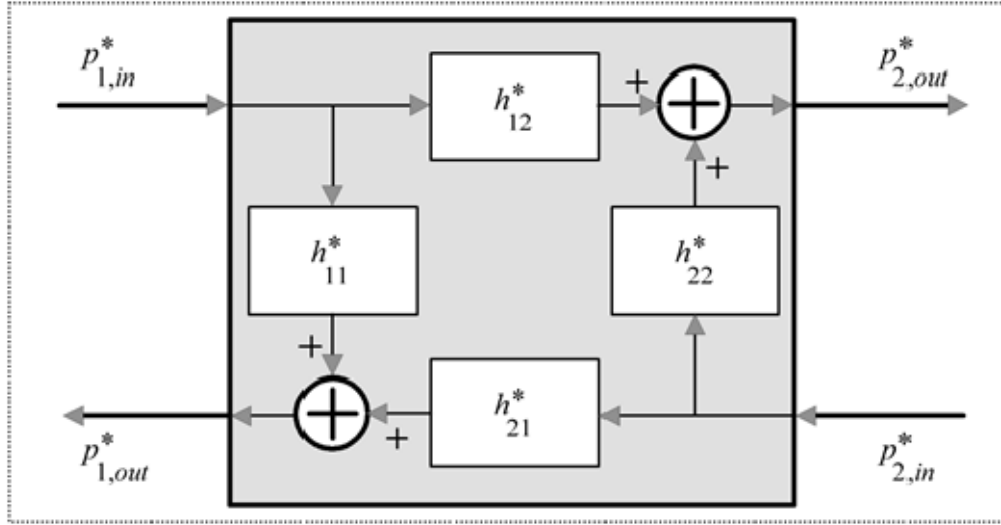
(3)

Figure 2: *The two-port representing a portion of tube of variable section.* h_{11}^*, h_{12}^*, h_{21}^* *et* h_{22}^* *are the four discrete-time impulse responses of this two-port.*

This system does not directly check the condition (2) because of terms $p_{1,in}^*(n)$ and $p_{2,in}^*(n)$. But because it is legitimate to suppose that $\left| h_{11}^*(0) \right| \ll 1$ and $\left| h_{22}^*(0) \right| \ll 1$ (owing to the assumption of slow variation of the section, *cf.* Ducasse 2002), the following change of variables can be done, for example, side No.1:

$$\begin{cases} p_{1,in}^{**} = [1 + h_{11}^*(0)]\ p_{1,in}^* \\ p_{1,out}^{**} = -h_{11}^*(0)\ p_{1,in}^* + p_{1,out}^* \end{cases} \tag{4}$$

This makes it possible to obtain the anticipative equation of propagation:

$$p_{1,out}^{**}(n) = \sum_{j=1}^{k_{11}} \frac{h_{11}^*(j)}{1 + h_{11}^*(0)} p_{1,in}^{**}(n-j) + \sum_{j=1}^{k_{21}} \frac{h_{21}^*(j)}{1 + h_{22}^*(0)} p_{2,in}^{**}(n-j) \tag{5}$$

As well as the two connecting equations:

$$\begin{cases} p_1^*(n) = p_{1,in}^{**}(n) + p_{1,out}^{**}(n) \\ u_1^*(n) = \dfrac{S}{\rho_0\, c}\left[\dfrac{1 - h_{11}^*(0)}{1 + h_{11}^*(0)} p_{1,in}^{**}(n) - p_{1,out}^{**}(n) \right] \end{cases} \tag{6}$$

In contrast to the tubes, the other causal elements are regarded as lumped because of the missing of anticipation. They are characterized by a system of algebraic or differential equations. Consequently, if lumped elements are directly connected one to the other they merge to form a single lumped element. This is why the following rule is adopted (*e.g.* Smith 1996): any connection can include only one lumped element. This rule implies the existence of only two types of connection. Firstly, the *junction* of a number *k* of tubes, which only

linearly redistributes *k* output signals on *k* inputs owing to the continuity of pressure and conservation of volume velocity. Secondly, the connection of *k* tubes to a lumped element: the system of equations representing the inner behavior of this element includes its exchanges with these tubes.

This approach makes it possible to carry out a time-domain simulation according to a calculation performed over two cycles: at every time *n*, first the outputs of all the pieces of tube are calculated owing to their anticipative property, then the second cycle is the calculation of the outputs of the junctions and lumped elements, some parameters of which are controlled by the player in the course of time. Each output thus calculated is either the input of a tube, or a radiated signal. The numerical decoupling of the lumped elements thus makes it possible to appreciably limit the complexity of the equations to be solved, reducing calculation time and numerical errors.

Potential of Evolution and Generalization to other Wind Instruments

Modularity and object-oriented programming enable the evolution of the modeling of existing elements as well as the generalization to other wind instruments by addition and modification of modules, without modifying either the total structure, or the other elements. In addition to the modeling of other types of mouthpiece (for example Verge & al. 1994; Verge 1995 for the flute; Barjau and Agulló 1989 for the double reed; Msallam & al. 2000; van Walstijn and Campbell 1999 for brass instruments), one can for example imagine a non-linear modeling of the portions of tube of brass instruments taking into account possible shock waves formation (Hirschberg & al. 1996; Msallam & al. 2000), taking into account of effects due to a curved bore (Nederveen 1998-1), a modeling of the bell with higher modes calculation and the directivity of the radiated field (Pagneux & al. 1996; Amir & al. 1997; Kemp & al. 2000).

The detail of the modeling of the two lumped elements in which the controls of the player are important, namely the mouthpiece with single reed and the tone hole coupled with the finger/key, is provided hereafter and is illustrated by sound generated by simulations. For these simulations a simplified model for the bell has been chosen: the bell is modeled as a tube of varying cross section, the open end of which is characterized by the radiation impedance of a cylinder of the same diameter (Levine and Schwinger 1948). From this radiation impedance, two linear causal invariant filters are calculated. Their common input is the output signal of the tube at the open end. One calculates the reflected signal returning in the tube, and the other delivers the transmitted radiated signal, assuming a monopolar radiation.

The Mouthpiece with Single Reed and the Mouth of the Player

The reed is modeled as a harmonic oscillator, usually used with fixed parameters (*cf. e.g.* Wilson & Beavers 1974; Gazengel & al. 1995). Here, these parameters are variable to take into account the action of the lower lip as well as the shape of the slit. The reed interacts with the tongue of the player. The flow from the mouth to the inside of the mouthpiece depends primarily on the pressure difference between the mouth and the mouthpiece, and of the reed slit opening. In the modeling, one of the difficulties is to separate the quasi-static phenomenon - the flow- from the acoustic phenomenon. The effect of the player's vocal tract is neglected (*cf. e.g.* Backus

1985). After the description of the model used, simulation results are given in numerical, graphic and also sound form.

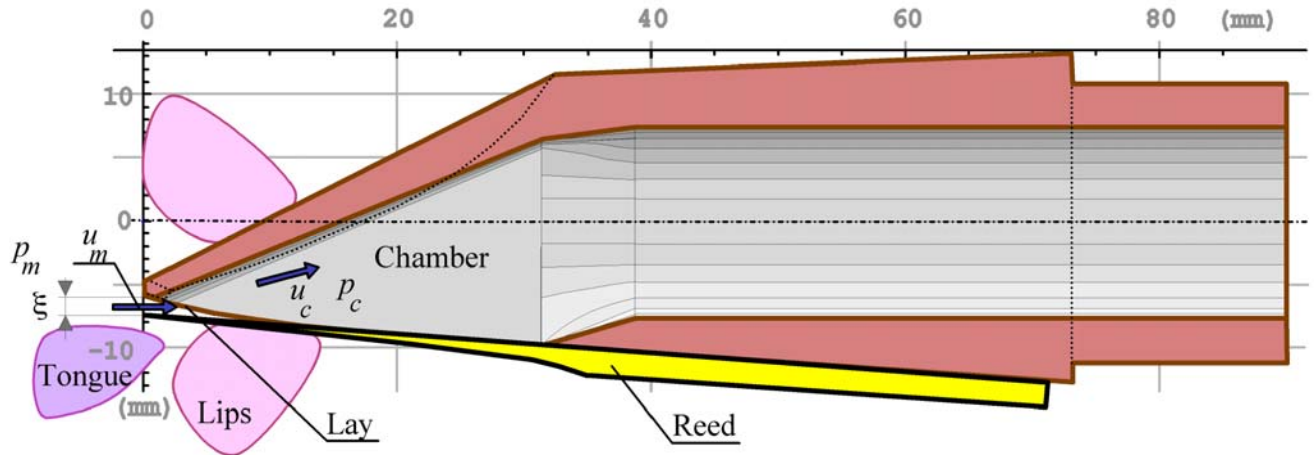# The "Reed Coupled with the Lower Lip" System: a One-dimensional Oscillator with Variable Parameters

Figure 3: *Section of the single reed mouthpiece and definition of the various physical quantities.*

The reed is modeled as a damped spring-mass system of variable mass M(ξ), damping G(ξ) and stiffness K(ξ, ξ_{eq}) with ξ, the reed slit opening (*cf*. Fig. 3). The following differential equation is taken:

$$M(\xi)\frac{d^2\xi}{dt^2} + \frac{dM}{d\xi}\left(\frac{d\xi}{dt}\right)^2 + G(\xi)\frac{d\xi}{dt} + K(\xi, \xi_{eq})(\xi - \xi_{eq}) = \sum f_{ext} \qquad (7)$$

where ξ_{eq} is the reed opening at rest.

In fact, this equation includes the influence of both the lower lip of the player and the shape of the slit. In particular, ξ_{eq} depends on the pressure exerted by the player's lip. The damping is considered as mainly due to the lip, since when a player grips the reed with the teeth, he inevitably obtains a *squeak* where the reed seems to oscillate on one of its eigenmodes (Wilson & Beavers 1974; Boutillon & Gibiat 1996). On the other hand the mass *M* and the stiffness *K* are supposed to be mainly related to the density of the reed, its longitudinal Young modulus, the reed of the Var (area of the south of France) being supposed similar to an orthotropic composite material (Shaffer 1982). These parameters also depend on the geometry of both the reed and the lay of the mouthpiece. The variability of the parameters according to ξ is in particular used to take into account the *rolling up* phenomenon causing the progressive closing of the reed on the lay. The sum of the external forces $\sum f_{ext}$ includes the force due to the difference in pressure between the two sides of the reed (an equivalent surface $S_r(\xi)$ is considered) and also the action of the tongue. Even if the results obtained seem promising from the auditory point of view, many questions remain on the mechanical behavior of the reed + lay + lip system (*cf*.

e.g. Stewart & Strong 1980; Gazengel & al. 1995). A modal analysis using finite elements on a viscoelastic model would tend to prove on the one hand that the torsion modes play a part of importance comparable with that of the flexural modes, and on the other hand that the phenomenon of rolling up is not inevitably present and that it would thus be necessary to consider a much more complex relation of contact. This point would require much more thorough work.

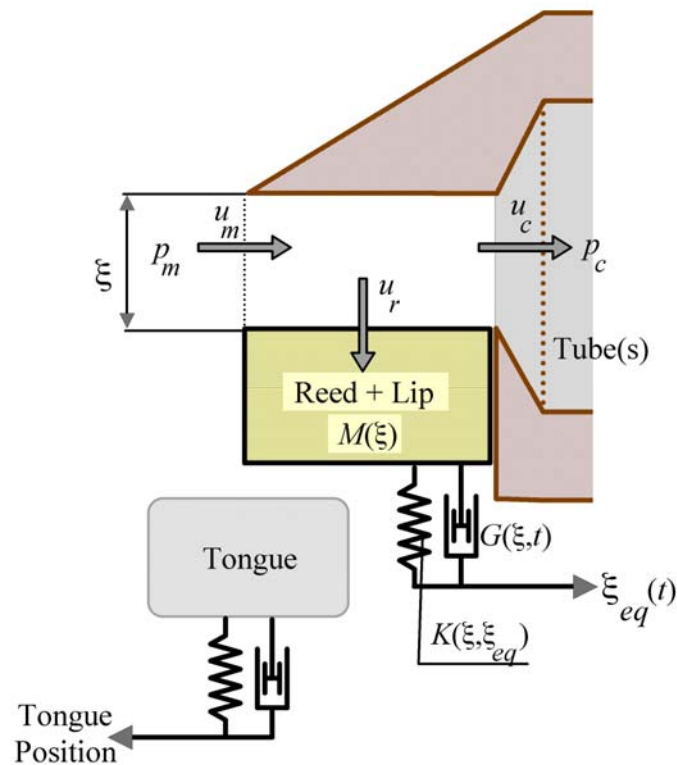## The Tongue and its Interaction with the Reed

Figure 4: *Simplified representation of the system reed+lower lip and the tongue.*

The tongue plays an important role in phrasing. It is modeled by a damped spring-mass system (*cf*. Fig. 4) whose equilibrium position is controlled. It can touch the reed with a perfectly soft shock: just after the shock, the reed and the tongue form a single system whose momentum is the sum of the two momenta before the shock. An adhesion model is introduced for the separation: the tongue and the reed separate only if the force that they mutually exert on each other is higher than a given threshold. This threshold, as well as the other parameters of the tongue model, can vary in time in order to obtain various effects of phrasing.

Air and its Interaction with the Reed

Conservation of Flow

The pressure difference between the mouth of the player p_m and the mouthpiece volume p_c acts on the reed, with a force equal to $S_r(\xi)(p_c - p_m)$ and causes a flow u_m through the reed slit. u_m is an increasing function of both ξ and the pressure difference $(p_m - p_c)$. It was usually considered in an empirical relation given by Backus (1963) as proportional to $(p_m - p_c)^{2/3} \xi^{4/3}$. Although this relation was used for our simulations until 1990, u_m is now calculated by applying the Bernoulli equation, with given assumptions (Stewart & Strong 1980; Hirschberg 1995; Kergomard 1995): $\left| u_m \right| = w(\xi) \, \xi \, \sqrt{2 \left| p_c - p_m \right| / \rho_0}$ where w is the equivalent width of the opening, increasing with ξ. The other involved flows are the flow due to the reed motion $u_r = S_{eq}(\xi) \, d\xi/dt$ and the flow entering into the mouthpiece $u_c = u_m - u_r$. Since these relations involve total pressures and flows, each one includes both quasi-static and acoustic component.

Separation of Mean Flow and Volume Velocity in the Coupling with the Resonator

In the mouthpiece, the flow entering into the tube (remaining part of the mouthpiece and body of the instrument) is written $u_c = u_c^0 + u_c^a$ and total pressure, $p_c = p_c^0 + p_c^a$. Acoustic components p_c^a and u_c^a are connected by the equations (1) and (3) of the tube. Quasi-static components u_c^0 and p_c^0 characterize the air flow in the instrument and depend on its shape. Pressure p_c^0 is very close to zero (Kergomard 1995). Quasi-static u_c^0 and acoustic u_c^a components of the total flow u_c are separated by a pair of filters, transmittances of which are $(1 + s/\sqrt{2})/(1 + \sqrt{2} \, s + s^2)$ and $[(s/\sqrt{2}) + s^2]/(1 + \sqrt{2} \, s + s^2)$ in reduced frequencies, *i.e.* $s = i \, f/f_c$ where f is the frequency and f_c the cut-off frequency, close to 20Hz. The introduction of a flow impedance Z_{00}, with $p_c^0 \approx Z_{00} \, u_c^0$ and small compared to the characteristic acoustic impedance, has been carried out but the study of its effects remains to be done.

Results

Some results have been obtained ten years ago at the IRCAM with language FORTRAN™ by using a Digital Waveguide modeling of the tubes, the formula of Backus for the reed/air coupling, and by solving the non-linear differential equation representing the mouthpiece by the Adams predictor-corrector method of order 4. More recent simulations have been carried out on MATHEMATICA™ using the Bernoulli equation, employing the Runge-Kutta method of order 4 with constant step. In this second case it is only a validation of the algorithms before an optimized and finalized software development.
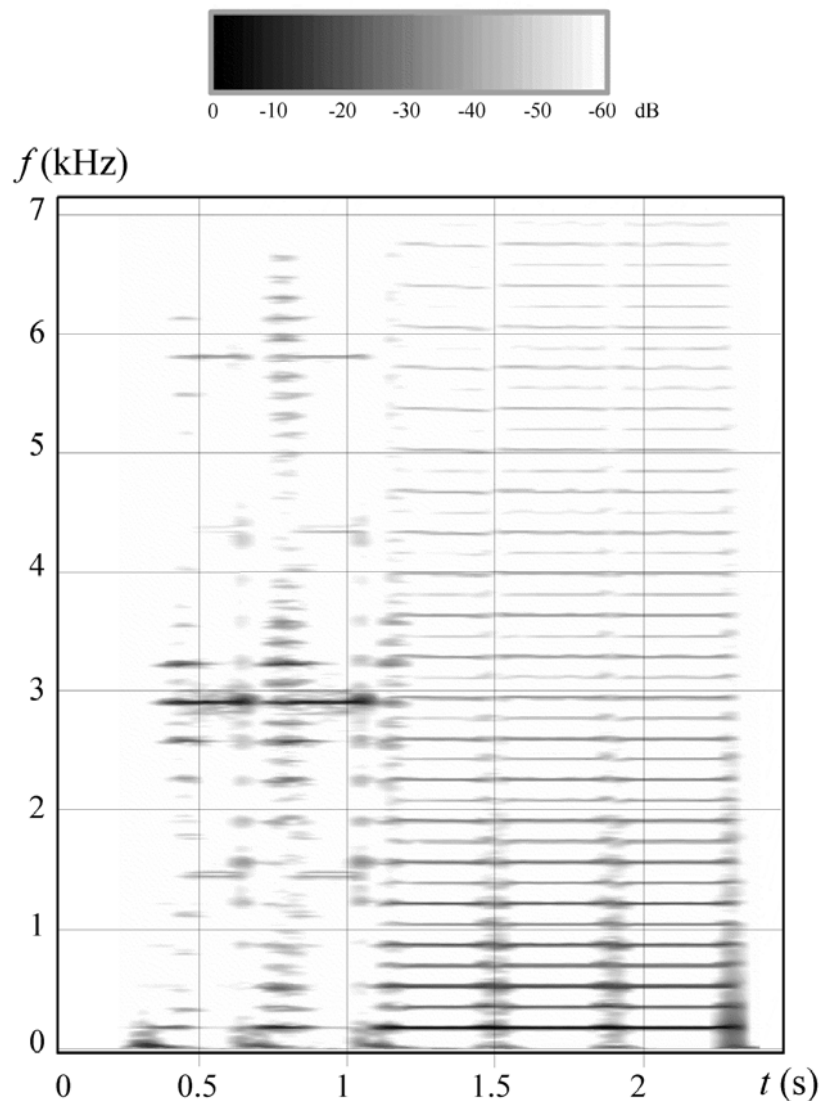
Figure 5: *Time frequency analysis (spectrogram) of a squeak on a virtual instrument (sound of Track 1).*

Obtaining Squeaks on Virtual Instrument and the Difficulty in Controlling the Mouth

One of the first sounds generated by the virtual instrument was a squeak such as a beginner can obtain sometimes on his real instrument, owing to the difficulty in controlling the playing parameters (*cf.* Track 1, time frequency analysis of which is given Fig. 5; on this spectrogram, one can observe, between 0 and 1.1s, in addition to the prominent reed frequency, close to 2.9 kHz, the combinations of this one with the pipe resonance frequencies). This phenomenon is similar to the *mouth tones* on the flute (Castellengo 1999). The reed dynamic plays a prominent part, as is well-known by players and instrument makers, and its driving is as delicate on the virtual instrument as in reality. Various modes of oscillation, more or less stable, are obtained when the damping of the reed coupled with the lower lip is varied (*cf.* Track 2 & Fig. 6).
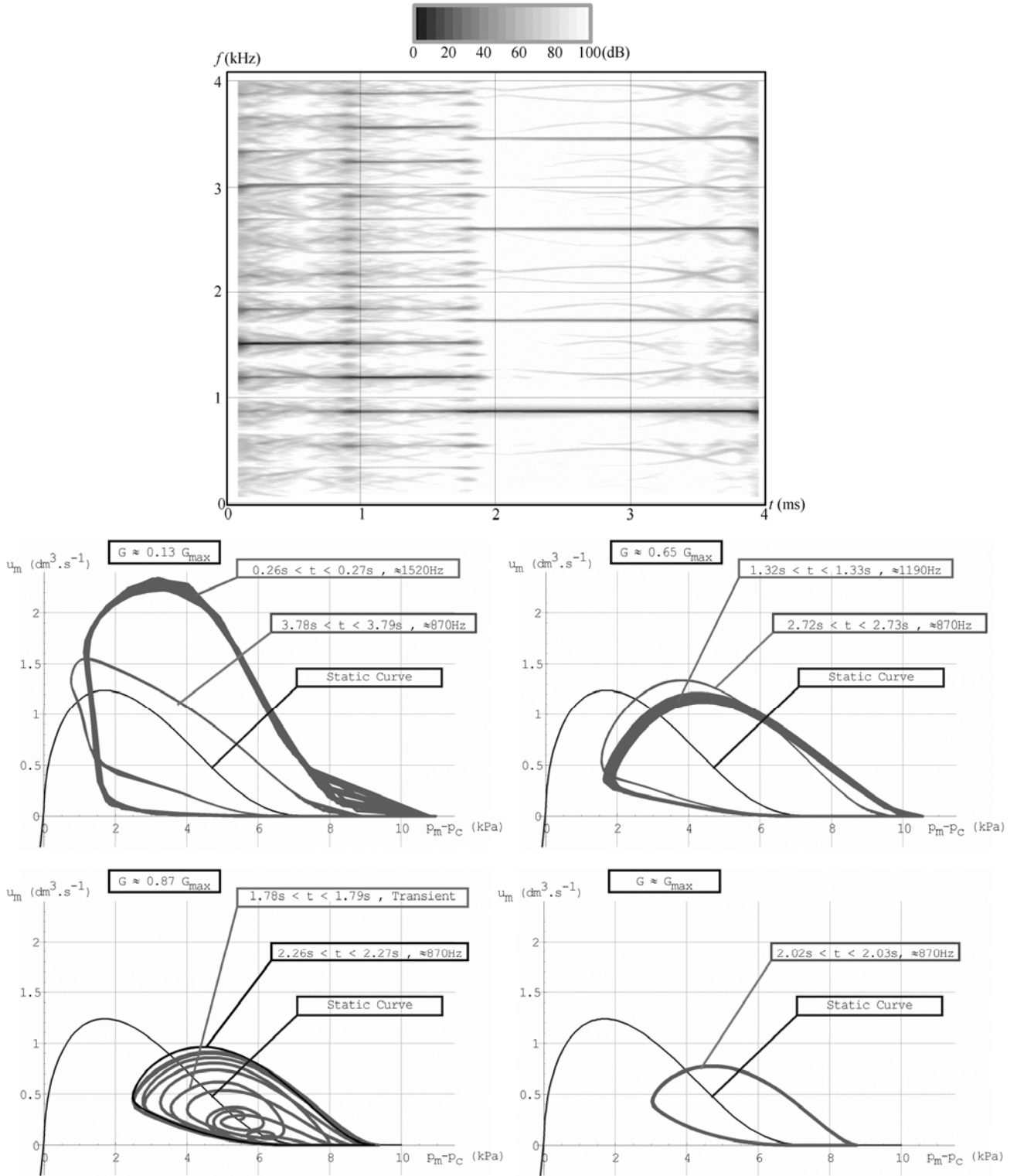
Figure 6: *Time frequency analysis (spectrogram) and phase diagrams* $(p_m - p_c) \Leftrightarrow$ *flow u_c of the sound recorded on Track 2 for the three modes of oscillation (partials 9, 7 and 5) and the transient between 2nd and 3rd modes. On each figure, adjustments are rigorously identical; only their past differs.*

With identical parameters different modes can be obtained, depending on what occurred previously. On the example Track 2, damping G is gradually increased by a factor of 200 while all other parameters are held constant. Three successive modes of oscillation appear but when the damping is decreased symmetrically, the oscillation remains stable on the lower mode, which was obtained initially with a high damping. This shows, as confirmed by players, that the attack has an important influence on the sound quality obtained. The various regimes can be described for example by the phase diagrams $(p_m - p_c) \Leftrightarrow$ flow u_c (cf. Fig. 6). A study similar to that of Cullen & al. (2000) would allow determination of the possible modes of oscillation according to the adjustment of the various parameters in order to facilitate the choice of the driving parameters of the model.

Design of Imaginary Instruments such as the Transverse Saxophone and the Network of Tubes of the Type

"Radiator"

On the musical level, one of the possible applications of Physical Modeling Synthesis is the building of physically unrealizable instruments. An example is the transverse saxophone for which a theoretical study shows that one must obtain a signal of Helmholtz whose characteristic ratio N is the ratio of the lengths of the two tubes (Dalmont & Kergomard 1995): during a period T, the value of the rectangular signal is P_o during $NT/(N+1)$ and $(-NP_o)$ during $T/(N+1)$. It is difficult to realize such an instrument which requires a mouthpiece volume equal to zero. Simulations carried out (*cf.* Tracks 3, 4 and 5) are in agreement with the theory and when the length ratio is close to 5, the sound obtained is similar to that of a saxophone. One can also adapt a single reed mouthpiece to a tube network of the type "central heating radiator" (*cf.* Tracks 6, 7, and 8 which illustrate also the following point).

Importance of the Tongue on the Phrasing

The player can obtain a large range of attacks and articulations by using the tongue. Thus, the modeling of the tongue gives much more realism to the sounds produced. It can be verified that the rough model is sufficient to obtain sound effects characteristic of single reed instruments (*cf.* Tracks 1, 6, 7 and 8 for a given resonator, Tracks 9 and following for complete models with tone holes).

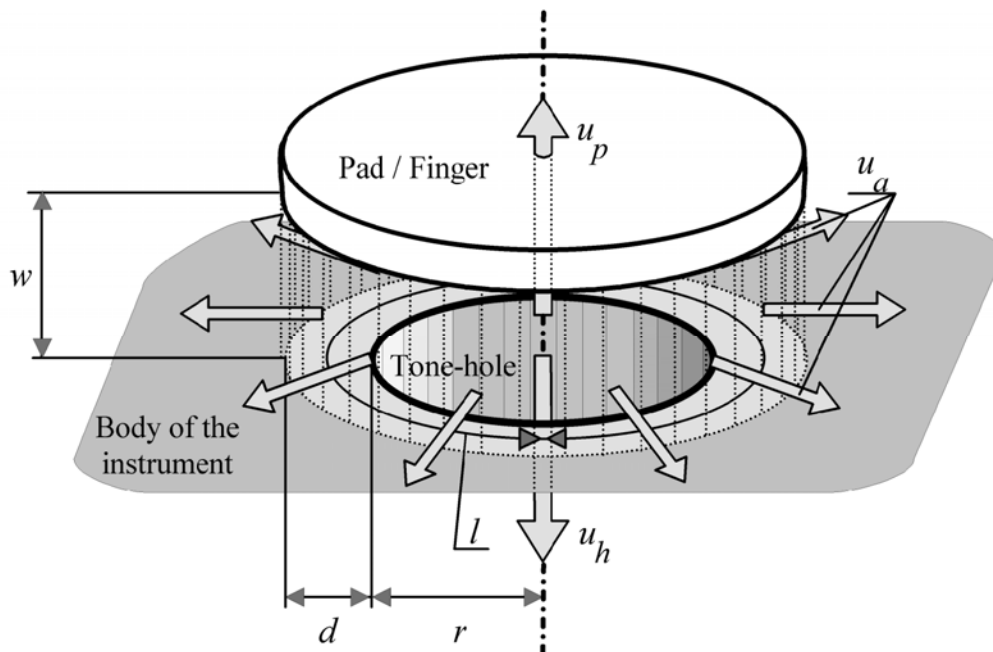# The Tone hole and the Finger of the Player

The Model

Figure 7: *Definition of the various physical quantities concerned in the closing system (key or finger) of a tone hole: l is the "length" of the opening (in fact an average perimeter), w its "width" (the distance cover / body of the instrument) and d its "depth". The flows are u_h, entering into the tone hole, u_a outgoing by the opening and u_p due to the displacement of the cover. The acoustic pressure at the input of the tone hole is noted p and the external acoustic pressure is considered as negligible. The radiated output signal is taken proportional to the flow u_a, assuming a monopolar radiation.*

Many works on open and closed tone holes have been published (*cf. e.g.* Nederveen & al. 1998; Keefe 1983; Dubos & al. 1999); some were concerned with the role of the finger of the player or the pad of the key (Nederveen 1998-2), sometimes important in playing situations. The formula used by Stewart & Strong (1980, Eq. (7) referring to Van den Berg & al. 1957) to model the mouthpiece gives the acoustic resistance of a rectangular opening, width l, low height w and depth d. It is roughly adapted for the opening in the shape of ring, with rectangular section, located between the cover (pad or finger) and the body of the instrument (*cf.* Fig. 7). The acoustic pressure under the cover is noted p and the external acoustic pressure is supposed to be negligible. As for the bell, the signal radiated in far field is considered as proportional to the flow u_a outgoing through the opening. External correction length phenomena are not taken into account. The flow entering into the hole is noted u_h and the displacement of the cover, surface S_p, generates a flow u_p, in a way similar to the modeling of the reed.

The following equation system is chosen:

$$\begin{cases} u_h + u_a + u_p = 0 \\ u_p = S_p \dfrac{dw}{dt} \\ p = 12\mu\dfrac{d}{lw^3}u_a + 0.438\dfrac{\rho_0}{(lw)^2}u_a^2\ sign(u_a) \end{cases} \tag{8}$$

where μ is the dynamic viscosity coefficient of the air.

Results

With only one tone hole in a cylindrical tube, it was possible to calculate (*cf.* Track 9) rather realistic sound effects and in particular a glissando (*cf.* Fig. 8) obtained by progressive opening of the key, which is accompanied by a difficulty of emission well-known by players. The effect of the flow due to the displacement of the finger or the key becomes obvious if one plays the same fingering without blowing in the instrument (*cf.* Track 10, and also Track 16). The instrument then functions in free oscillations. On Track 11, a melody line of the type "4th Variation" in Weber Opus *posth*. emphasizes, on a clarinet with 5 tone holes, a typical characteristic of the timbre of the clarinet in the case of a very fast succession of open/close fingerings. The chromatic scale of Track 12 required the modeling of the 20 main tone holes of a clarinet; the absence of phrasing renders it not very spectacular despite the complexity of the model directly drawn from geometrical measurements of a real instrument. Some interpretations of the theme "*The Pink Panther*" (Tracks 13 to 16), played by a virtual beginner on a virtual bass clarinet highlight the effects obtained with a tongue more or less hard and *sticking* and a bad control of the reed. Finally, some tests on a conical instrument (Tracks 17 to 20, Digital Waveguide modeling) put the accent on the particular difficulties of stability, overblowing or others, well-known on instruments of the saxophone type (Grand & al. 1997).
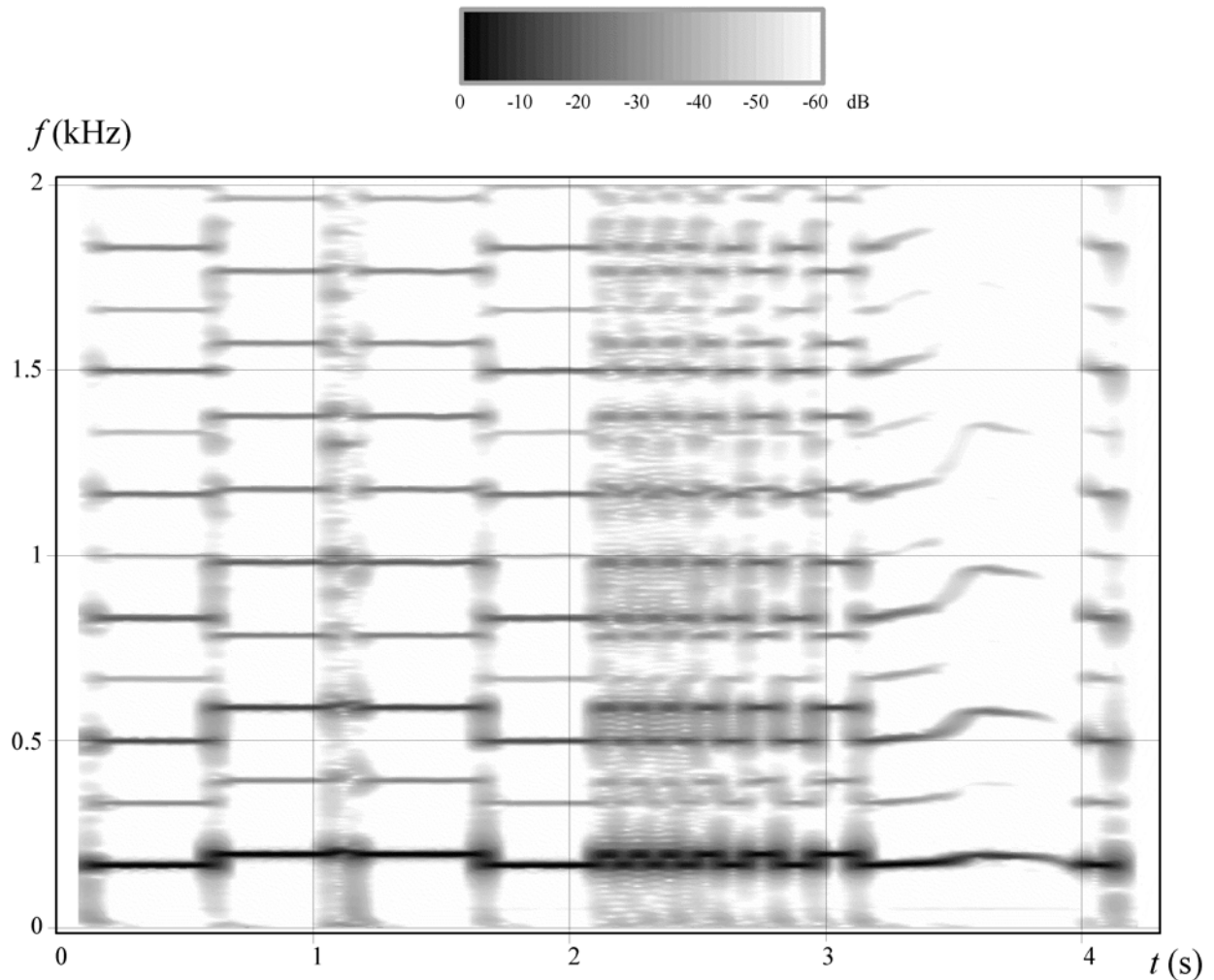
Figure 8: *Time frequency analysis (spectrogram) of Track 9 obtained with a cylindrical tube with a tone hole. At the end of the sound, the progressive opening of the key makes it possible to obtain a glissando.*

Conclusion and prospects

The results obtained illustrate the fact that in order to obtain synthesized sounds of good quality it is more relevant to take into account the most important phenomena related to the instrument and the player than to search for a high degree of accuracy in relation to one particular phenomenon. For example, it is less important for the realism of the sound produced to improve the modeling of the acoustic phenomena in the mouth than to model - even in a simplified way - the action of the tongue of the player.

The interest and the feasibility of the Physical Modeling Synthesis approach for the single reed instruments are confirmed, in particular by the listening to the sounds obtained ten years ago. However, it is necessary to continue the improvement of the models and the algorithms. This work could lead to software developments with several aims, one being to provide an additional tool to instrument makers. Sound synthesis application will require a focusing on the aspects of real time and gestural interfacing with the player, well-known to the

research teams working on the subject (*e.g.* Cook 1992, Cadoz & al. 1993), in particular to overcome the difficulty of driving the models. The extension to other types of excitations (double reed, flute, brass instruments) will have to be carried out. Then, it might be possible to build, starting from physically and perceptively identified elements of the original, virtual instruments sources of unheard sounds.

Sounds

The sounds created ten years ago at the IRCAM are marked with "#" and the more recent simulations, carried out on MATHEMATICA™, with "% ". Warning: the level was standardized for each sound and so there is no common reference for the sound levels.

Track 1[#]: This squeak with attack was one of the first sounds obtained on a cylindrical tube without tone holes, and shows well that a still rather rudimentary model gives a high perceptive realism because all the major elements of the instrument are modeled.

Track 2[%]: On a cylindrical tube of length 50cm and of radius 7.5mm, of fundamental frequency 170Hz, one obtains three abnormal modes (approximately 1520Hz near to the 9th partial of the tube, then 1190Hz near to the 7th partial of the tube, then 870Hz near to the 5th partial) while varying in time damping G of the system reed + lower lip. G varies linearly from $0.005\,G_{max}$ to G_{max} on the time interval [0 ; 2.025s] and then goes down linearly to $0.005\,G_{max}$ on the interval [2.025s ; 4.05s]. It should be noted that there is no change of mode during the decrease of G.

Track 3[%]: Pressure signal in the mouthpiece for a transverse saxophone with tubes of 20 and 50cm (lengths ratio of 2.5).

Track 4[%]: idem with tubes of 25 and 50cm (ratio of 2)

Track 5[%]: idem with tubes of 10 and 50cm (ratio of 5). The conical tube of the saxophone is then perceptually approached and a change of mode is obtained when the pressure in the mouth is gradually decreased.

Track 6, 7 et 8[#]: Effects of phrasing with the tongue on a resonator of the type "radiator not connected to the pipes of the central heating". The presence of tubes in arches is only slightly perceptible during the attack transient (lower resonances).

Track 9[#]: Sound obtained with a cylindrical tube with a single tone hole. After clear closing/opening motion, the key moves away very gradually from the hole in order to obtain a glissando effect, with a fall in the quality of emission similar to that obtained on a real instrument.

Track 10[#]: Same motion of key as for the sound of Track 9 but the player does not blow. This emphasizes the auditory effect created by the air volume displacement due to the motion the key.

Track 11[#]: Small melody *legato* on a clarinet with 5 tone holes. The fast succession of open/close fingerings emphasizes a characteristic of the timbre of the clarinet, obvious on the *4th Variation* in Weber Opus Posth.

Track 12[#]: Chromatic scale on a virtual instrument built with the dimensions of a real instrument. 20 tone holes were modeled. The not very spectacular character is explained by the total absence of phrasing.

Tracks 13[#] & 14[#]: Theme "*The Pink Panther*" (Henri Mancini) respectively performed *piano* then *forte* by a beginner clarinetist on a virtual bass clarinet.

Track 15[#]: Theme "*The Pink Panther*" with an abnormally hard tongue.

Track 16[#]: Theme "*The Pink Panther*" with an abnormally sticking tongue. When the tongue jams the reed, one perceives the noise of the air volume displacement created by the motion of the keys.

Track 17[#]: Detached sound produced by a saxophone type instrument with overblowing on the low fingerings. The pressure of the lower lip varies periodically.

Track 18[#]: Fluctuating sound due to strong variations of the pinching and breath of
the player on a conical instrument, with overblowing on the low fingerings.

Track 19[#]: Sound legato on a conical instrument, with overblowing on the low fingerings.

Track 20[#]: Conical instrument, with strong instability on some fingerings.

Acknowledgements

References

Amir, N., Pagneux, V., and Kergomard, J. 1997. "A Study of Wave Propagation in Varying Cross-Section Waveguides by Modal Decomposition. Part. 2: results." *J. Acoust. Soc. Am.* 101(5): 2504-2517.

Backus, J. 1963. "Small Vibration Theory of the Clarinet." *J. Acoust. Soc. Am.* 35(3): 305-313.

Backus, J. 1985. "The Effect of the Player's Vocal Tract on Woodwind Instrument Tone." *J. Acoust. Soc. Am.* 78(1): 17-20.

Barjau, A., and Agulló, J. 1989. "Calculation of the Starting Transients of a Double-reed Conical Woodwind." *Acustica* 69: 204-210.

Bouasse, H. 1929. *Instruments à vent, tome I.* Bibliothèque scientifique de l'ingénieur, reissued by Blanchard, Paris 1986.

Boutillon, X., and Gibiat, V. 1996. "Evaluation of the Acoustical Stiffness of Saxophone Reeds under Playing Conditions by Using the Reactive Power Approach." *J. Acoust. Soc. Am.* 100(2): 1178-1189.

Cadoz, C., Luciani, A., and Florens, J.-L. 1993. "CORDIS-ANIMA : a Modeling and Simulation System for Sound and Image Synthesis - The General Formalism." *Computer Music Journal* 17(1):19-29.

Castellengo, M. 1999. "Acoustical Analysis of Initial Transients in Flute Like Instruments." *Acustica* 85: 387-400.

Cook, P. 1992. "A Meta-Instrument Physical Model, and a Meta-Controller for Real-Time Performance Control." Proceedings of the International Computer Music Conference, San Francisco, pp. 273-276.

Cullen, J. S., Gilbert, J., and Campbell D. M. 2000. "Brass Instruments: Linear Stability Analysis and Experiments with an Artificial Mouth." *Acustica* 86: 704-724.

Dalmont, J.-P., and Kergomard, J. 1995. "Elementary Model and Experiments for the Helmholtz Motion of Single Reed Wind Instrument." *Proceedings of the 1995 International Symposium on Musical Acoustics*. Dourdan, France, pp. 114-120.

Dubos, V., Kergomard, J., Khettabi, A., Dalmont, J.-P., Keefe, D. H., and Nederveen, C. J. 1999. "Theory of Sound Propagation in a Duct with a Branched Tube Using Modal Decomposition." *Acustica* 85: 153-169.

Ducasse, E. 2002. "An Alternative to the Traveling Waves Approach for Use in Two-Port Descriptions of Acoustic Bores." *J. Acoust. Soc. Am.* (in revision).

Gazengel, B., Gilbert, J., and Amir., N. 1995. "Time Domain Simulation of Single-Reed Wind Instrument. From the Measured Input Impedance to the Synthesis Signal. Where are the Traps?" *Acta acustica* 3: 445-472.

Grand, N., Gilbert, J., and Laloë, F. 1997. "Oscillation Threshold of Woodwind Instruments" *Acustica* 83(1): 137-151.

Hirschberg, A. 1995. "Aero-Acoustics of Wind Instruments" (Chapter 7, pp. 291-369) in *Mechanics of Musical Instruments*. Wien New-York: Springer-Verlag, ISBN 3-211-82801-X.

Hirschberg, A., Gilbert, J., Msallam, R., and Wijnands, A. P. J., 1996. "Shock Waves in Trombone." *J. Acoust. Soc. Am.* 99(3): 1754-1758.

Keefe, D. H. 1983. "Theory of the Single Woodwind Tone Hole." and "Experiments on the Single Woodwind Tone Hole." *J. Acoust. Soc. Am.* 72(3): 676-699.

Keefe, D. H. 1992. "Physical Modeling of Wind Instruments." *Computer Music Journal* 16(4):57-73.

Kemp, J., Amir, N., and Campbell, D. M. 2000. "Calculation of Input Impedance Including Higher Modes." Proceedings of the 5th French Congress on Acoustics, Lausanne: E.P.F.L. , pp. 314-317.

Kergomard, J. 1995. "Elementary Considerations on Reed-Instrument Oscillations" (Chapter 6, pp. 229-290) in *Mechanics of Musical Instruments*. Wien New-York: Springer-Verlag, ISBN 3-211-82801-X.

Levine, H., and Schwinger, J. 1948. "On the Radiation of sound from an Unflanged Circular Pipe." *Physical Review* 73:383-406.

Msallam, R., Dequidt, S., Caussé, R., and Tassart, S. 2000. "Physical Model of the Trombone Including Nonlinear Effects. Application to the Sound Synthesis of Loud Tones." *Acustica* 86(4): 725-736.

Nederveen, C.J. 1998-1. "Influence of a Toroidal Bend on Wind Instrument Tuning." *J. Acoust. Soc. Am.* 104(3, Pt. 1):1616-1626.

Nederveen, C.J. 1998-2. *Acoustical Aspects of Woodwind Instruments* (*revised edition*). DeKalb, Illinois 60115: Northern Illinois University Press, ISBN 0-87580-577-9.

Nederveen, C.J., Jansen, J.K.M., and Van Hassel, R.R., 1998. "Corrections for woodwind tone-hole calculations." *Acustica – Acta Acustica* 84: 957-966.

Pagneux, V., Amir, N., and Kergomard J. 1996. "A Study of Wave Propagation in Varying Cross-Section Waveguides by Modal Decomposition. Part. 2: Theory and Validation." *J. Acoust. Soc. Am.* 100(4, Pt. 1): 2034-2048.

Shaffer, D. W. 1982. *Reed Construction*. U.S. Patent 4,355,560 for Fibracell™ reeds.

Smith, J. O. 1986. "Efficient Simulation of the Reed-Bore and Bow-String Mechanisms." Proceedings of the International Computer Music Conference, The Hague, pp. 275-280.

Smith, J. O. 1992. "Physical Modeling Using Digital Waveguides." *Computer Music Journal* 16(4): 74-87.

Smith, J. O. 1996. "Physical Modeling Synthesis Update." *Computer Music Journal* 20(2): 44-56.

Stewart, S. E., and Strong, W. J. 1980. "Functional Model of a Simplified Clarinet." *J. Acoust. Soc. Am.* 68(1): 109-120.

Van den Berg, J., Zantema, J. T., and Doornenbal, P. Jr. 1957. "On the Air Resistance and the Bernoulli Effect in the Human Larynx." *J. Acoust. Soc. Am.*29:626-631.

Van Walstijn, M., and Campbell, M. 1999. "The Wave Digital Filter Brass Mouthpiece Model." *Acustica* 85: S77.

Verge, M.-P., Fabre, B., Mahu, W. E. A., Hirschberg, A., van Hassel, R. R., Wijnands, A. P. J., de Vries, J. J., Hogendoorn, C. J. 1994. "Jet formation and jet velocity in a flue organ pipe." *J. Acoust. Soc. Am.* 95(2): 1119-1132.

Verge, M.-P. 1995. Aeroacoustics of Confined Jets, with Applications to the Physical Modeling of Recorder-Like Instruments. Eindhoven: Technische Universiteit Eindhoven, ISBN-90-386-0306-1.

Weber (von), C.M., Opus Posth. (1786-1826). "Introduction, Theme and Variations for Clarinet and String Quartet."

Wilson, T. A., and Beavers, G. B. 1974. "Operating modes of the clarinet." *J. Acoust. Soc. Am.* 56(2): 653-658.