Trumpet and Trumpet Player: Model and Simulation in a Musical Context

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Abstract

This paper presents a physical model of trumpet-like instruments aimed at sound synthesis. In the long term, the goal is to deliver to the musician a genuine musical instrument behaving like a brass instrument while offering more freedom and new possibilities of expression.

1 Introduction

For several years, we have been developing and studying computer-simulated models of brass instruments (including the player's lips) aimed at sound synthesis. Starting from a model derived from the Elliott and Bowsher brass model (cf. section 2), part of our work has consisted in developing this model until obtaining sufficiently realistic behavior to allow a musical use. Improvements concern the model of the exciter part (lips oscillation and air flow through the lips, cf. section 3) and of the resonator part (acoustical propagation in the bore of the instrument, cf. section 4).

However, a data-processing program cannot be compared to a musical instrument in the traditional sense of the term. Therefore, in order to give to the musician the feeling of playing an instrument, we also seek to ensure a real-time functioning of the numerical simulations and to propose relevant control interfaces (cf. paragraphs 5.1 and 5.2). Finally, the control is investigated in 5.3 in terms of optimal command of the parameters of the model. The work presented in this paper is part of a Phd thesis (Vergez 2000).

2 Minimal Brass Model

An important goal of this work is to identify what must be taken into account to model the sound production, and what can be neglected without harming the realism of the sounds and the behavior of the model.

2.1 Exigence of simplicity

One could indeed think that a more complete model would be a better choice. However, there are several arguments against this proposition:

- Care has to be taken in order to propose models with similar levels of approximation for each component. For example, a complex aerodynamical model, applied to a geometry of lips that is too simplified, is likely to give worse results than a simple aerodynamical model, but adapted to the smoothness of the geometrical description (Hirschberg 1999).

- A real-time model, essential so that a musician/instrument relation can be established with the model, demands a relatively simple model.

- The control of the model requires to identify relevant parameters to be modified. It seems that this is very difficult, when the complexity of the model is increased (discussions with S. Adachi (Adachi and Sato 1996), Di Federico (Federico and Borin 1997) and Ph. Depalle (Rodet et al. 1990)).

These reasons encouraged us to choose, as a start, one of the simplest known models representing the basic behavior of brass instruments, derived from the model of Elliott and Bowsher (Elliott and Bowsher 1982).

2.2 Description of the Model

The lips model includes a single parallelepipedic mass m attached to a spring k and a damper r. The acoustic pressure field inside the bore is decomposed into outgoing and incoming travelling waves p_o and p_i. The bore of the trumpet is modelled by its time-domain reflection function $r'(t)$, derived from its complex input impedance measured in an anechoic room (Vergez and Rodet 1997b).

The air flow is supposed laminar in the mouth and in the lips channel. An air jet formed after the lips is supposed to dissipate by turbulence all its kinetic energy in the cup of the mouthpiece without pressure recovery (Hirschberg 1995). Therefore, nonlinear coupling between the lips and the bore is represented by the Bernoulli equation linking volume flow between the lips $u(t)$, lips aperture $x(t)$ and pressure difference between the mouth and the mouthpiece $(p_m - p(t))$ (air velocity in the mouth is neglected).

Finally, this basic physical model is described by the following system of equations for positive $x(t)$:

$$(1)\ \begin{cases} m\ddot{x}(t) + r\dot{x}(t) + kx(t) = \sum F_{\text{aero-acoustics}} \\ p_i(t) = (r' * p_o)(t) \\ u(t) = l\, x(t) \text{sgn}(p_m - p(t)) \sqrt{\frac{2}{\rho} |p_m - p(t)|} \\ p(t) = p_o(t) + p_i(t) \\ u(t) = \frac{1}{Z_c}(p_o(t) - p_i(t)) \end{cases}$$

where l is the length of the mass in the transversal dimension, $Z_c = \frac{\rho c}{A_{cup}}$ is the characteristic impedance at the entry of the

mouthpiece (ρ is the air density, c the sound velocity and A_{cup} is the cross section area of the mouthpiece entry).

When lips are closed ($x(t) \leq 0$) the lower lip is taken into account by additional stiffness and damping coefficients $3k$ and $4r$, and the volume flow is set to zero.

In spite of the crude approximations we made, sonic results show that some of the essential characteristics of brass instruments (including transitions between modes) seem to be captured in this basic model. The following improvements allow us to reach a better sound quality.

3 Improvements of the exciter model

3.1 Lips oscillation

First improvements concern the collision of the lips. Indeed, instead of the alternance between a closed-lips phase and an opened-lips phase, the progressive opening/closing has been taken into account by time-varying spring stiffness and damping coefficient.

Moreover, a one dimensional model for the lips is a crude approximation. In fact, it has been shown in (Vergez and Rodet 2000a) that this approximation leads to a discontinuous volume flow derivative at lips closure. To cope with this problem, the length of the mass l is made dependent on x for small openings. This accounts for the fact that lips begin to close from the corners (Jorno 1995). Practically, l is replaced by $l\Theta_1(x)$ with $\Theta_1(x) = \tanh(\frac{b}{l}x)$. Then the air flow partial derivative becomes continuous and a significant part of disturbing high frequencies in the sound is eliminated.

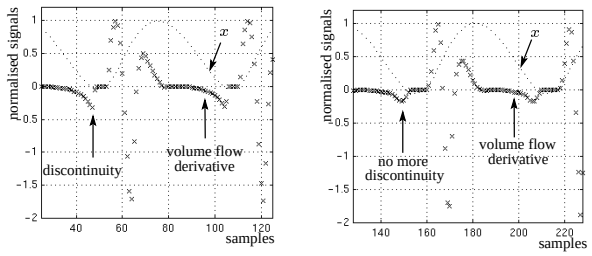

Figure 1: Effect of a varying lips length $l\ \tanh(\frac{6}{l}x)$ on the volume flow derivative at exact lips closure.

3.2 Air Flow Through the Lips

Just after the opening of the mass, a rapid alternation (apparently non realistic) of a strongly positive and a strongly negative volume flow has been observed. This occurs since the air flow model ignores viscothermal losses and inertia.

The hypothesis of a Poiseuille flow under the mass has then been studied (while neglecting inertial effects). Considering the 2D-geometry of the model and the coupling between the mouth and the bore, an analytical expression for the volume flow u has been derived (Vergez and Rodet 2000a). However, viscous effects are only significant for small apertures. In fact, for large x, the Bernoulli equation is a good approximation since viscosity can be neglected. Therefore, we have shown that the following model allows us to switch smoothly between a Poiseuille flow (for small openings) and a viscousless flow (for large openings):

$$u = \Theta_2 \times \frac{-1}{2\ Z_c}\xi A(x)\left[A(x) - \sqrt{A^2(x) + 4|p_m - p_h|}\right] \quad (2)$$

with $\Theta_2 = \tanh\left(\alpha_1 x^{\alpha_2}(p_m - p_h)^{0.5}\right)$, and $\alpha_1 = \frac{1}{12\eta e}\sqrt{\frac{\rho}{2}}$ ($= O(10^5)$), and $\alpha_2 = 2$, η is air dynamic viscosity, e is the width of the mass and $A(x) = lZ_c x\sqrt{\frac{2}{\rho}}$. Practically, it is interesting to let the player vary α_1 and α_2 around these values. This allows a finer control on the timbre of the sound. For example, figure 2 shows the influence of α_1 (α_2 being set to 3). The smaller α_1, the softer the sound.

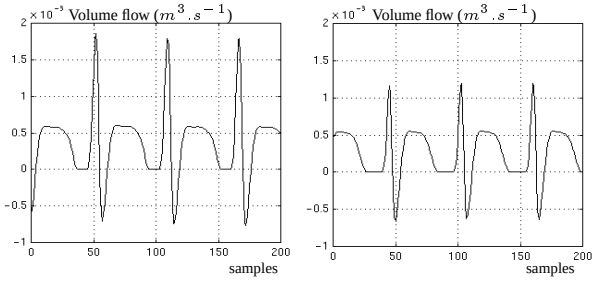

Figure 2: Volume flow calculated according to equation (2) with $\alpha_2 = 3$. From left to right $\alpha_1 = 10^6$, $\alpha_1 = 2.10^5$.

4 Improvements of the resonator model

Nonlinear propagation effects which occur at high playing levels are finally taken into account. Indeed they are mainly responsible for the characteristic brassy sound obtained when a trumpet or another brass instrument is played fortissimo (Gilbert and Petiot 1996).

A new algorithm to simulate waveform distortion due to nonlinear propagation of an air pressure wave has been developed. This algorithm is derived from the simple-wave differential equation (Burgers equation without dispersion or dissipation), which assumes that the solution is always a C^1 function. However, a physically-based supplementary constraint included in our computational model, allows us to simulate shock-waves (see figure 3).

The extension of this method to the nonlinear propagation of a wave in a resonator made of a succession of cylindrical tubes has then been studied and applied to the real-time model in (Vergez and Rodet 2000b) and a pattent has been obtained. Reflection/transmission at junctions are treated in the linear hypothesis, which seems justified since nonlinear propagation is a cumulative phenomenon and reflection/transmission at junctions may be considered instantaneous.

Such a model reproduces the spectral enrichment observed when sonic level is increased. However, the number of cylinders required to approach the input impedance of a real trum-

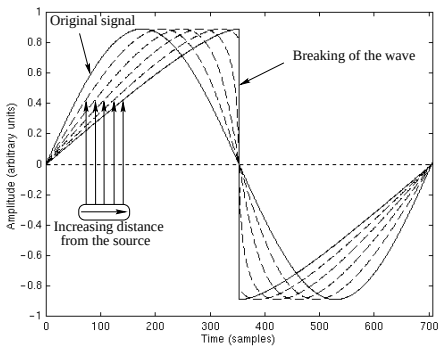

Figure 3: Simulation of the nonlinear propagation of a sinusoidal wave.

pet (at low playing levels) is too high to allow for real-time calculation. Therefore, a *hybrid* linear/nonlinear formulation has been tested to include visco-thermal losses and a more accurate geometrical description: the inner dynamics is simulated using a measured reflection function (linear acoustics) while the sound at the bell is calculated through the nonlinear propagation algorithm (Vergez 2000). This model was inspired by measurements made on an artificial mouth with water-filled latex lips. Indeed, as shown in figure 4 (next page), spectral enrichment when sonic level is increased is far more sensible at the bell than inside the mouthpiece (the note played is the fourth mode of a B^b trumpet, no valve pressed, note C5). This model is both perceptively convincing and less demanding in terms of computational cost.

5 Control of the Model

A main objective of this work is to give to the physical model the attributes of a traditional musical instrument: real-time execution, interaction between the musician and the instrument and richness of control. This requires a man-machine interface adapted to the problem (Cook 1992), (Wanderley 2000). The question is made complex by the number of factors influencing the quality of a trumpet sound (Bertsch 1997). Various means to "play" the model are now presented.

5.1 Real-time MIDI Playing Interface

The MIDI interface includes a MIDI sax Yamaha WX7 or WX5, and three foot pedals. The musician can modify, in real-time, mouth pressure, stiffness of the lips, viscous damping, as well as valve positions (Vergez and Rodet 1997a).

5.2 Towards a Meta-Trumpet

An interface for trumpet players has been conceived. It is made of a set of sensors mounted on a real trumpet[1] (figure 5). First of all, the position of each valve is deduced from a force sensitive resistor (FSR) fixed on the top of each valve. Secondly, blowing pressure is measured inside the cup of the mouthpiece. Moreover, contraction of the lips has been checked to be a monotonous (increasing) function of the pressure force of the mouthpiece on the lips of the player. Therefore, contraction of the lips is quantified through the measurement of the pressing effort transmitted by the body of the mouthpiece.

[1]Thanks to Alain Terrier and Patrice Pierrot for the construction of the Meta-trumpet and of the electronic set up respectively

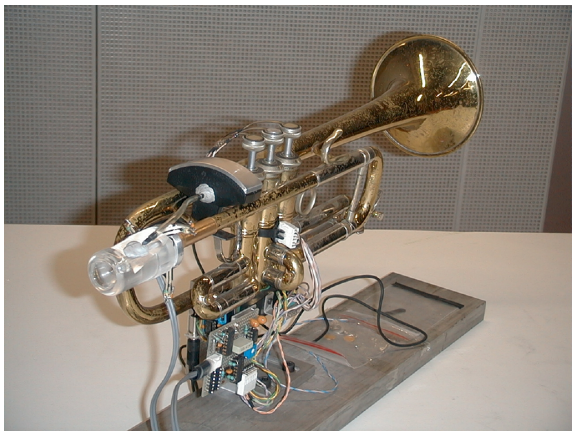

Figure 5: Playing interface for trumpet players

5.3 Optimal control: inversion of the model

Other non real-time strategies of control have also been investigated with T. Hélie. One might want to control the model in an optimal way, so that it reproduces as closely as possible a recorded trumpet sequence. The problem is to estimate time-varying parameters of a nonlinear system. This question has been studied in the case of vocal cord models, but the situation is much more complex here because of the acoustic feedback of the instrument on the lips. In the case of musical instruments, few works have been published (Wold 1987), (Cemgil and Erkut 1997), (Guillemain et al. 1997), and none to our knowledge relates to physical models of brass instruments. A first method was presented in ICMC99 (Hélie et al. 1999). In a paper accepted at ICMC2001 (Dhaes and Rodet 2001), a second approach is presented.

6 Conclusion

A physical model of trumpet-like instruments has been built, starting from a typical single-mass model. Improvements have been added after analysis of simulation results or of experiments on an artificial mouth device. The final model gives very realistic sonic results. This confirms that a rather simple model can reproduce most of the behavior of the real instrument. The trumpet model will be demonstrated in real time at the conference. During the demonstration, it will be

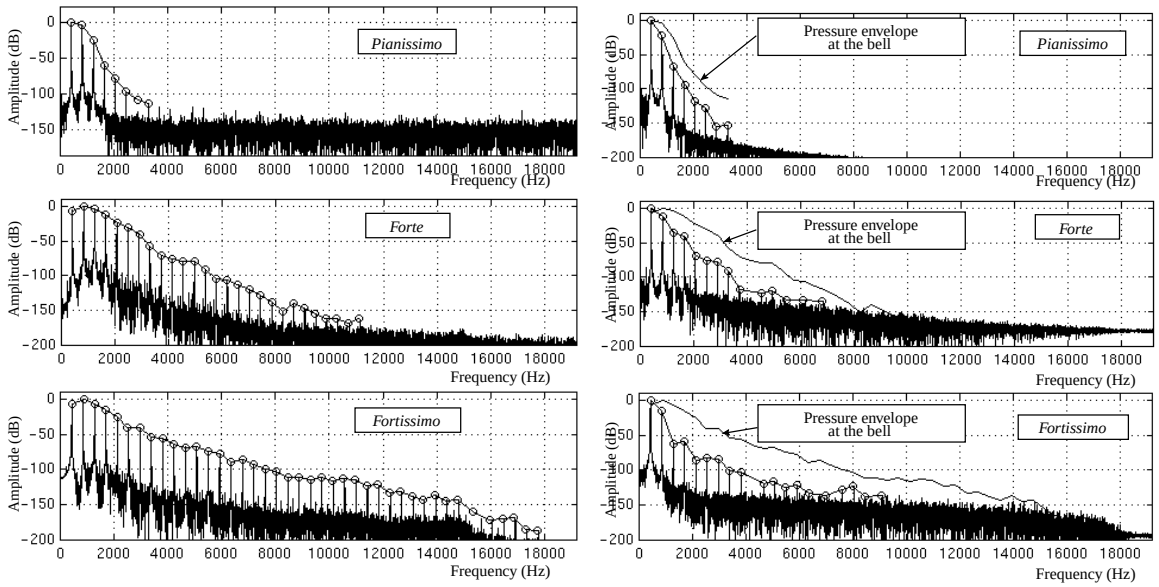

Figure 4: Experimental results obtained with the artificial mouth. Comparison of the spectral enveloppe of the air pressure at the bell (left column) and in the mouthpiece (right column) for different playing nuances (see section 4).

emphasized that this model can really be played like a traditional musical instrument. Indeed, the model will be used in 2001 by a composer (M. Lanza) in a piece for two instruments.

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