Sound synthesis of bowed string instruments using a gesture based control of a physical model

Demoucron Matthias, Caussé René
IRCAM, CNRS-UMR STMS, 1 place Igor Stravinsky, 75004 Paris, France
{demoucron, causse}@ircam.fr

Abstract

Sound synthesis of bowed strings instruments using physical models offers the possibility of simulating the vibration of the string from the main parameters controlled by the violinist: bow pressure, bow velocity and position on the string. A specific study of gestures that are performed on real instruments would improve the realism of these devices and would make them easier to use.
After a brief description of the physical model that has been used during this work, we will present some setups dedicated to the measurement of the gesture parameters applied by the violinist. The data collected from different bowing techniques such as *tremolo*, s*piccato*, *détaché* or *martelé* permit to extract characteristic features and to build parametric gesture patterns that can be used to control the physical model.

INTRODUCTION

Sound production using traditional musical instruments results both from the mechanical properties of the instrument and from the control that the player exerts on it. In the case of sustained instruments such as the violin, the player has a continuous control of the sound that enables him to achieve a great variety of different bow strokes and expressivity.

Sound synthesis based on physical modelling uses input parameters that are more or less relevant from a player point of view. In many cases, this advantage turns into a weakness: a poor knowledge or an empirical choice of the input parameters that have to be used to achieve a given musical idea results in sounds that are judged as non realistic.

Compared to theoretical studies, very few works have concentrated on quantifying and characterizing control strategies of instrument players. The particular case of bowed string instruments has begun to be explored a few years ago (Askenfelt, 1986 and 1989).

The present work intends to test the relevance of controlling a simple physical model with realistic gesture parameters. It focuses on modelling bow velocity and pressure profiles in some typical situations encountered in musical performances.

PHYSICAL MODEL

The theoretical behaviour and the mathematical modelling of the bowed string has been widely described and commented (Woodhouse, 2004). In its simplest formulation, the equation describing the motion of the string (linear density ρ, tension T) driven by an external force $F_l(x,t)$, can be written with:

$$\rho\frac{\partial^2 y}{\partial t^2} - T\frac{\partial^2 y}{\partial x^2} = F_l(x,t) \quad (1)$$

In the case of bowed string instruments, the player excites the string by rubbing it with a ribbon of horsehair that is stretched between the tip and the frog of the bow. The friction force that drives the string involves a specific slip-stick motion: during the sticking period, the string velocity is supposed to equal bow hair velocity, whereas during the sliding period the string slips on the bow hair, slowed down by a friction force that depends both on the normal contact force between the bow and the string, and on their differential velocity.

Several mathematical formulations of this friction force have been proposed for numerical simulations (Serafin, 2004). In this work, it has been modelled by the following equation (hyperbolic model):

$$F = F_N\left(\mu_d + \frac{(\mu_s - \mu_d)v_0}{v_0 + |\Delta v|}\right)Sign(\Delta v) \quad (2)$$

The numerical implementation of equation (1) related to adequate extremities conditions (string fixed at $x = 0, L$) has been done using a modal formulation (Adrien, 1991; Antunes, 2000): the displacement of the string and the external force that drives it are expressed on an adequate base of spatial modes $\varphi_n(x)$:

$$y(x,t) = \sum_{n=1}^{\infty} a_n(t)\varphi_n(x) \quad (3)$$

Using (3), equation (1) reduces thus to a second order differential equation on the components $a_n(t)$ depending only on time that can be more easily numerically solved.

A version of this physical model has been implemented as a Max/MSP object. This allows a real-time control of the synthesized sound and a practical way of testing its response to specific input parameters.

MEASUREMENT METHOD

The motion of the bow is measured using a dual axis accelerometer (AnalogDevices ADXL202) fixed on the bow frog. This device permits to measure the acceleration along the bow stick direction (bowing direction) and orthogonally to the bow in the vertical direction.

Bow velocity cannot be easily computed from the data that are collected. Due to the physical principle based behind the accelerometer (a mass-spring system, the signal being computed from the displacement of the mass from its rest position), it is sensitive to gravitational acceleration, therefore to the inclination of the bow. Small changes in the angle, such as angle due to the bending of the stick when pressing the string with the upper part of the bow, string changes or violinist's motions, will move the offset of the signal, and involve a drift when integrating it (figure 1).

Different solutions have been proposed in order to settle this problem, including detection of the zero crossing velocity and offset correction using a video camera (Schoonderwaldt, 2006). However, the great dynamic accuracy of this device is extremely useful to describe highly dynamical variations during performance, such as attacks or transitions.

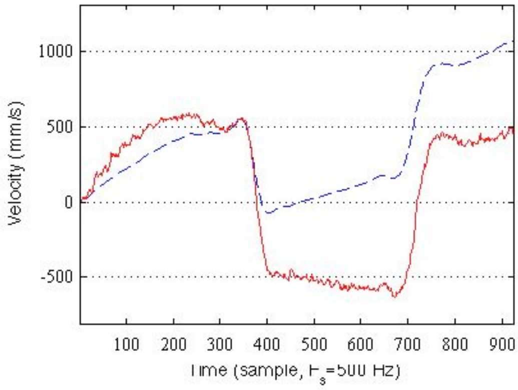

Figure 1. Velocity drift (dashed line) when trying to reconstruct velocity from acceleration data. Velocity reference (solid line) has been measured with an optical system.

A custom sensor has been developed to measure bow pressure (figure 2). A thin metal plate is fixed at one's extremity on the frog of the bow with an appropriate ring. A small circular piece is placed between the other extremity and the bow hair, so that the hair exerts on the plate extremity a varying constrain that depends on bow pressure. Finally, two gages are glued on the plate in order to measure the deformation involved by these constrains.

Forces are applied at different positions of the bow in order to calibrate the sensor. By interpolating between these reference positions, the bow pressure at the contact point can be deduced from the measure that is done at the frog. This device combined with bow position measurement permits to measure bow pressure with ±3% error. Without any information on the position this error has been measured to be around ±20%.

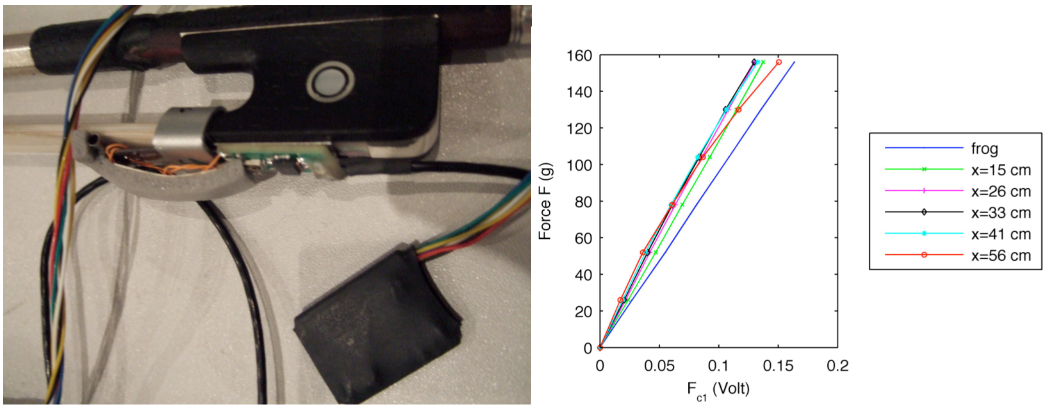

Figure 2. Right: bow pressure sensor and accelerometer used during the experiments. Left: calibration charts for the bow pressure sensor.

In addition to previously described sensors, some experiments have been done that coupled the measurement setup with motion capture data. A Vicon System 460 optical motion capture system was used to measure the movement of the bow relatively to the violin. The use of six M2 cameras around the instrumentalist assured the spatial resolution to be below 1mm with a framerate of 500 Hz.

MEASUREMENTS AND MODELLING OF BOWING PATTERNS

Violinists were asked to play different typical bowing techniques such as *détaché*, *martelé*, *sautillé* or *tremolo*. The full measurement device combined with the Vicon system gave a complete set of data including bow velocity and pressure, position on the string, bow angle, player's motion. In this work, we focused on velocity and bow pressure. From the measurements, typical patterns were extracted and modelled. They had to be characterized by a few parameters that are relevant from a user's point of view. Two specific situations will be presented here: jumping bow strokes and short *martelé*.

Jumping bowing patterns

Bow strokes in which the bow bounces on the string provide a first illustration of this "real gesture" based synthesis. Those sounds are produced by giving a vertical impulsion to the bow, and by letting it bounce on the string. At the same time, the bow moves quite slowly in the bow stick direction, in order the string to be rubbed.

This gesture family offers little control to the violinist, compared to sustained sounds. The technical challenge consists in keeping up the motion of repeated rebounds and in coordinating bow stroke changes and rebounds (Guettler, 1998). Different sound dynamics can be obtained by increasing the horizontal and vertical velocities or going closer to the bridge. The regularity and the more or less long contact time are achieved by finding the right place on the bow.

The figure 3 presents bow pressure profiles that have been measured during several rebounds on the string.

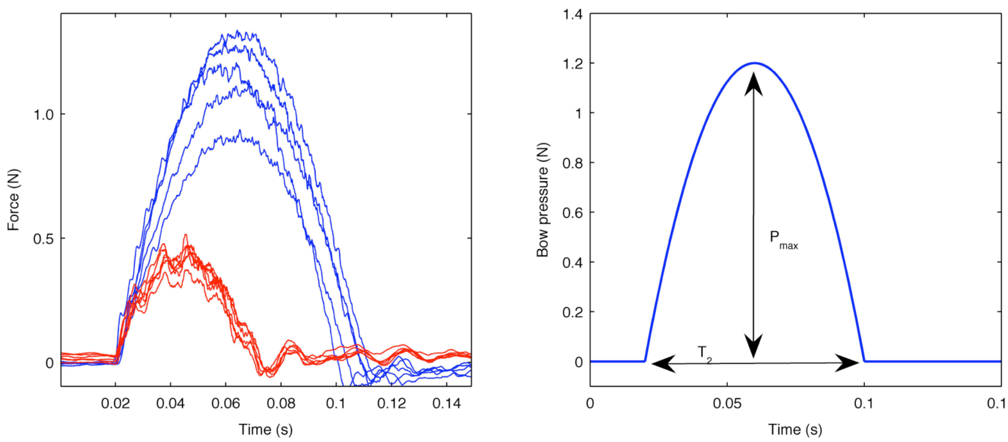

Figure 3. Bow pressure profiles measured during sautillé at two bow positions (blue: middle of the bow, red: closer to the tip)

A parabola has been used to fit these data. This allows the model to be controlled by two parameters: the maximal bow pressure during the rebound P_{max}, related to bow vertical velocity given by the player, and the contact time T_2, mainly related to the position of the contact point on the bow:

$$P = -\frac{4P_{\max}}{T_2^2}t^2 + \frac{4P_{\max}}{T_2}t \quad \text{for} \quad t \in [0:T_2] \tag{4}$$

Because the contact time between the bow and the string is usually very short, the velocity can be considered constant for a first approximation, alternatively negative and positive for a *sautillé*, or constantly positive for bow strokes such as *ricochet*. However, more developed model of bow velocity could be considered for repeated notes. In the present work, a sinusoid, period T and amplitude V has been used to represent bow velocity:

$$v_b = V \sin\left(\frac{2\pi}{T}t\right) \tag{5}$$

Finally, the complete model offers the possibility of playing with several parameters that are more or less related to player's considerations. For example, a rather long contact time of 0.1 seconds permits to simulate rebounds played at the middle of the bow, whereas a very short one would produce sounds like impact of the bow stick on the string. Playing with the relation between the maximal bow pressure and the velocity gives the possibility of producing light or crushed sounds, and the number of rebounds during each bow stroke simulates different techniques such as *sautillé*, *ricochet*, or *spiccato* (figure 4).

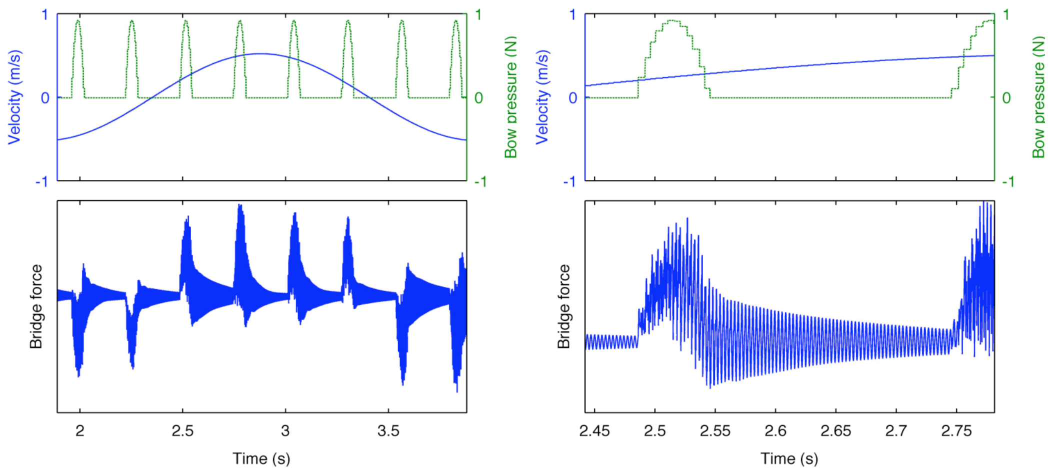

Figure 4. Simulation example of sautillés

Short *martelé*

Menuhin described the short *martelé* as one of the three fundamental bow strokes that constitutes the violinist's "menagerie". Again, this is a very dynamic and short bow stroke (generally less than 0.5 s) that is obtained by following the next procedure: the bow first presses the string, without moving, then the attack begins from the relaxation of this tension, the bow being quickly moved at the same time. Very high bow velocity can be obtained during these bow strokes (up to more than 2 m/s) and its evolution has a typical bell shape profile (figure 5, left).

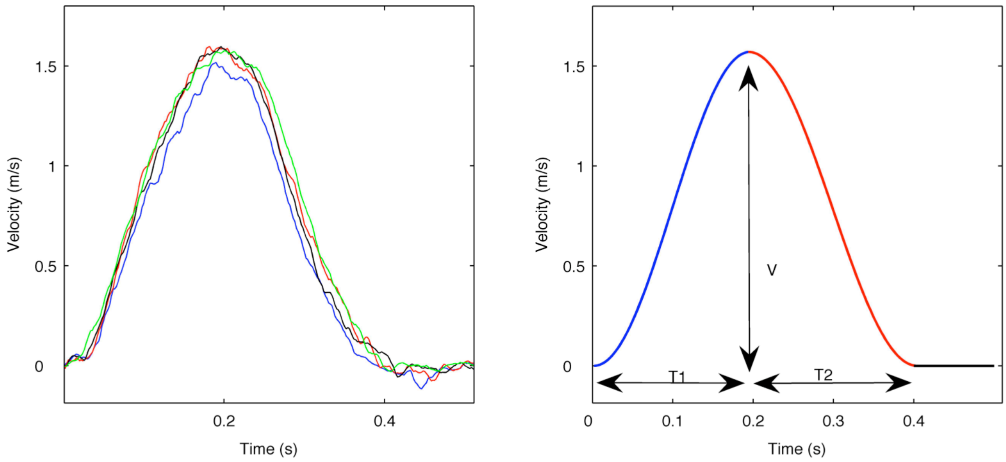

Figure 5. Short martelés. Velocity profiles measured for repeated notes with the same violinist.

Because the stop of the bow can be more or less long, depending on the dryness that is wanted, this shape has been modelled with two successive cosines, the first one describing the attack, and the second one, the deceleration of the bow.

$$v_b = \frac{V}{2}(1 - \cos\frac{\pi}{T_1}t) \quad \text{for } t \leq T_1 \tag{6}$$

$$v_b = \frac{V}{2}(1 + \cos\frac{\pi}{T_2}(t - T_1)) \quad \text{for } t \in [T_1 T_2] \tag{7}$$

The force patterns during the same gesture performance are plotted on figure 6. As expected, the bow pressure starts high, then suddenly decreases when the player begins his gesture. Oscillations related to the bow are hardly controlled in these examples. Down-bow execution of short martelé produces often this kind of oscillation that corresponds to a sound in which the bow seems almost to bounce. This is typical from non expert musicians trying to execute very quickly this short *martelé*.

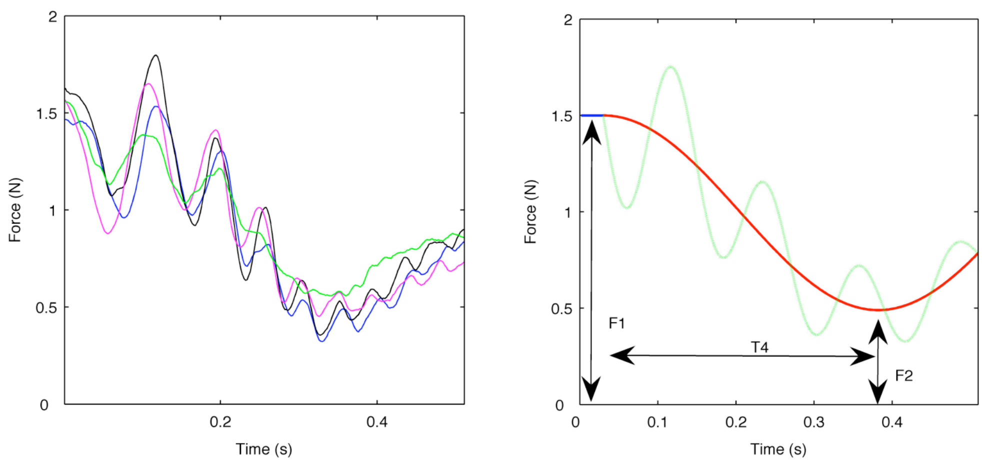

Figure 6. Bow pressure profiles during martelé.

From these measurements, we can build a first model: at the beginning the bow pressure is constant with value F_1 during a very short time T_1 (typically 50 ms), then its release will be a cosine starting from F_1 and decreasing to F_2:

$$P = F_1 \quad \text{for } t \le T_3 \tag{8}$$

$$P = \frac{F_1 - F_2}{2}\left(1 + \cos\frac{\pi(t - T_3)}{T_4}\right) + F_2 \quad \text{for } t \in [T_3 T_4] \tag{9}$$

If we are interested in reproducing the specific non expert features observed on the bow pressure shape, an additional term can be used that model the capability of the player to control and to damp bow oscillations, as seen in figure 7 (δF being the maximal oscillation of the force, δT the period of bow oscillations (around 10 Hz) and τ the damping coefficient):

$$P = \frac{F_1 - F_2}{2}\left(1 + \cos\frac{\pi(t - T_3)}{T_4}\right) + F_2 - \delta F \sin\frac{\pi(t - T_3)}{\delta T}\exp\left(-\frac{t - T_3}{\tau}\right) \tag{10}$$

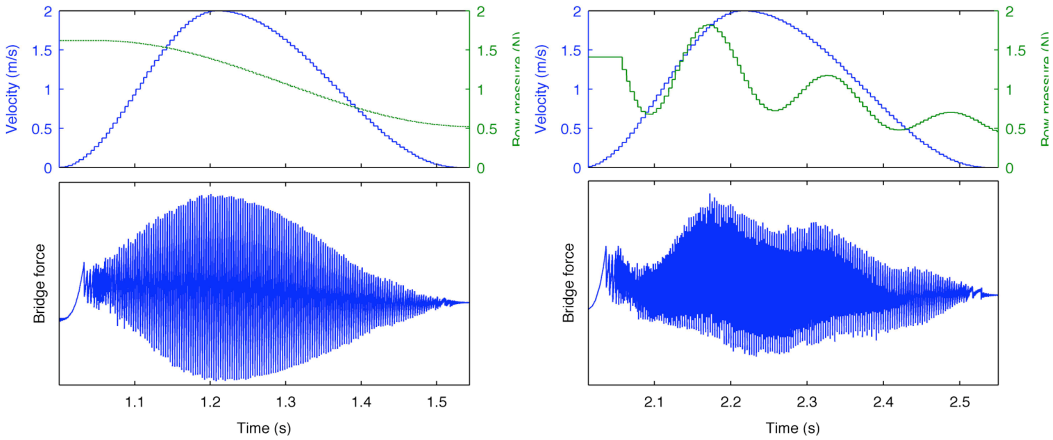

Figure 7. Simulations of short martelé.

CONCLUSIONS

We present in this paper some bow strokes models inspired by gesture measurement of violinist's performance. These models rely on a few parameters that are easier to manipulate than direct determination of inputs parameters. Consequently, they allow a higher level control of physical modelling based sound synthesis.

Two specific situations have been presented here (bouncing bow strokes and short martelé) but similar works have been done to characterize other bowing techniques such as *tremolo* or *détaché*.

The modelling of input parameters offers a practical way of describing with a few parameters bow stroke from the same family. In this work, players were asked to execute a given gesture, outside of any musical context. A next step would consist in fitting these parameters on technical strategies and musical intentions. For example, patterns have been deduced from measurements concerning a particular player. First, the question will be to check that they apply to other musicians. Secondly it will consist in examining how they adapt their gesture to some specific musical purpose such as sound dynamic.

ACKNOWLEDGEMENTS

We would like to thank Anders Askenfelt, Nicolas Rasamimanana and Benoît Fabre for discussions and support. We thank also Emmanuel Fléty, Rémy Müller and Alain Terrier for their help and interest.

Motion capture data have been recorded by Nicolas Rasamimanana at the IDMIL/CIRMMT, McGill University, Montreal with Delphine Bernardin's help.

This work is part of CONSONNES project, funded by the french Agence Nationale pour la Recherche.

REFERENCES

Adrien, J.M. (**1991**). "The missing link: Modal synthesis", in *Representations of Musical Signal,* pp.269-297

Antunes, J.; Tafasca, M.G.; Henrique L.L. (**2000**). "Simulation of the bowed-string dynamics: Part 1- A nonlinear approach", *5ème Congrès Français d'Acoustique*, pp.285-288

Askenfelt, A. (**1986**). "Measurement of bow motion and bow force in violin playing", *J. Acoust. Soc. Am. America* 80(4), pp.1007-1015

Askenfelt, A. (**1989**). "Measurement of bowing parameters in violin playing. II", *J. Acoust. Soc. Am. America* 86(2), pp.503-516

Guettler, K.; Askenfelt, A. (**1998**). "On the kinematics of spiccato and ricochet bowing", *CAS Journal* Vol. 3, No. 6 (series II), pp.9-15

Schoonderwaldt, E; Rasamimanana, N.; Bevilacqua F. ,(**2006**), "Combining accelerometer and video camera: reconstruction of bow velocity profiles", *Proc. Of the 2006 Intern. Conf. on New Interfaces for Musical Expression*, pp. 200-203

Serafin, S. (**2004**), "The sound of the friction", *PhD thesis.*

Woodhouse, J.; Galluzo, P.M. (**2004**), "The bowed string as we know it today", *Acta Acustica united with Acustica* 90, pp. 579-589