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4aMU5. Modeling articulation techniques in single-reed woodwind instruments
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Time-domain simulations of wind instruments can, in principle, deal with non-linear oscillations and are also capable of modeling both the steady-state and the transient behavior of a system. The starting transient is usually an important identifying feature of the instrument that is played. Subtle control of articulation is required from skilled musicians to modulate transients during expressive performance. Focusing on single-reed woodwind instruments, the physical phenomena that underlie different articulation techniques are analyzed. A saxophone player is recorded during portato playing, where articulation is achieved either by the use of the tongue, or by modulating the air flow into the mouthpiece. The bending of the reed and the pressure inside the mouthpiece are measured and a physical model is formulated with the aim to capture the transient effects. Instead of adding new terms (and complexity) to a single mass-spring model, in order to simulate the player's tongue, existing physically meaningful parameters are allowed to vary. In particular, the effect of tonguing is modeled by modulating the equilibrium position of the (lumped) reed and its internal damping, whereas, in the case of air-separated tones, only a variation of the blowing pressure is required.

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INTRODUCTION

Physical modeling of wind instruments enables digital sound synthesis based on a set of parameters that have a direct physical interpretation (e.g. [1, 2, 3]). Going beyond sound synthesis applications, such models can be exploited in order to analyze the mechanism of sound generation [4, 5, 6, 7]. Both frequency-domain and time-domain methods provide a simulation framework for synthesis of steady-state oscillations. The latter, also suited to non-linear applications, are capable of yielding the transient behavior of the system. Of particular interest is whether the waveforms calculated using a physical model are in agreement with measurements, and how the control parameters are manipulated by the player during note onsets.

Transients are very important when it comes to identifying [8] or evaluating [9] musical instruments, as they are associated with the character of a certain instrument and how easy it can be played. Recent attempts to understand the subtleties of transient effects in wind instruments range from elaborate measurements [10] to simplified models [11] and deal with both attack and decay transients. In this paper the transition between two steady-state saxophone tones during portato playing is analyzed, using measurements of the mouthpiece pressure and the reed bending. In an attempt to resynthesize similar tones, the parameters of a state of the art physical model are adapted accordingly.

Articulation

Articulation in woodwind instruments is usually performed by tonguing. Even though it is often considered that the tongue is used to interrupt the air flow towards the mouthpiece [12], such an assumption is not adopted in the present study. Instead it is assumed that the tongue presses the reed upon the mouthpiece lay, but without necessarily closing it completely. Articulation is thus achieved by direct modulation of the reed oscillations, which results in a modification of the flow through the reed channel. A second articulation technique is to directly modulate the air flow by controlling the blowing pressure ($p_m$) applied to the reed. Such air-separated tones can result in a similar, yet not identical musical phrasing. Therefore a physical modeling attempt to capture the above articulation techniques should be able to differentiate between tongued and air-separated tones.

EXPERIMENTAL MEASUREMENTS

Experiments were carried out on an alto saxophone using a Vandoren AL3 mouthpiece and a synthetic reed (Légère). In fact, to simplify the air-column model of the next section, only the neck of the saxophone was used. The bending of the reed was measured using a strain gauge, as explained in [13]. The inner mouthpiece pressure ($p$) was measured by inserting a condenser microphone (G.R.A.S. - 40DP, 26AS) into the mouthpiece in such a way as not to affect the player’s embouchure [14]. In order to verify that the blowing pressure remained constant in the case of the tongued tones and varied for the air-separated tones, it was measured using a Technoterm 5402 probe.

Measurements for the mouthpiece pressure and the reed bending are shown in Figure 1 for both articulation techniques. It can be observed that during the tongue-reed interaction, the oscillations of the reed are not completely stopped and the same holds for the mouthpiece pressure. The action of the tongue seems to increase the damping ($g$) of the reed (an effect similar to that of the player’s lip [15, 16]) and change its equilibrium position ($y_m$), resulting in a much smaller vibration amplitude. Closer investigation (see Figure 2) also reveals a phase inversion of the reed bending signal during tongue-reed
FIGURE 1: Measured mouthpiece pressure for tongued tones (top-left) and air-separated tones (top-right) and measured reed bending for tongued tones (bottom-left) and air-separated tones (bottom-right).

contact, which can be explained as follows: Before tonguing the reed has one clamped and one free boundary condition and an increase in the mouthpiece pressure tends to open the reed. When the tongue presses the reed upon the mouthpiece lay both ends of the reed are (approximately) fixed. In that case an increase in the mouthpiece pressure tends to deform the reed, bending it in such a way that it appears to be closing, hence the phase inversion.

This effect is not present in the case of air-separated tones. In fact, the pressure waveforms are significantly different for each articulation technique, something that has been verified by a series of measurements. This points towards the fact that the effect of the player’s tongue is not confined to modulating the air flow towards the mouthpiece. It is the objective of this study to formulate a physical model that can capture this effect. The physical nature of the model can be subsequently used to analyze and understand the instrument oscillations during transient behavior.

FIGURE 2: (a) Observed phase inversion during tongue-reed contact (both signals are high-pass filtered and normalized for comparison purposes). (b) Closed reed at minimum mouthpiece pressure. (c) Deformed reed at maximum mouthpiece pressure during tongue-reed contact. (d) Open reed at maximum mouthpiece pressure.
PHYSICAL MODELING

Time-domain simulations were developed by McIntyre and Woodhouse [17] for string instruments and their methodology was applied by Schumacher on wind instruments [18]. In that work the tube of the instrument is assumed to be a linear resonator, coupled to a non-linear excitation mechanism that represents the reed-mouthpiece system. Using this technique, the calculation of the oscillations of the system is not limited to the steady state of the sound. There are several publications discussing such models (e.g. [1, 3, 19, 20]). In this paper we adopt the model presented in [4] that consists of a lumped mass-spring model with a non-linear collision term, coupled to the impulse response of the tube. The equation of motion for the reed is

\[ m \frac{d^2 y}{dt^2} + m g \frac{dy}{dt} + k y + k_c (|y - y_c|)^\alpha = \Delta p, \]

where \( m \) is the effective reed mass and \( k \) the effective stiffness per unit area, \( y \) the reed displacement, \( k_c \) and \( \alpha \) are power-law constants and \( y_c \) is the displacement value above which contact forces due to reed beating become active. The reed is driven by the pressure difference across it \( \Delta p = p_m - p \).

The flow into the mouthpiece is the sum of the Bernoulli flow \( u_f \) and the reed induced flow \( u_r \):

\[ u = u_f + u_r = \lambda h \sqrt{\frac{2\Delta p}{\rho}} + S \frac{dy}{dt}, \]

where \( \lambda \) is the effective reed width, \( h \) the reed opening, \( \rho \) the air density and \( S \) the effective reed surface. The total mouthpiece pressure can be decomposed into a forward and a backward-traveling wave (\( p = p^+ + p^- \)). The coupling with the bore is achieved via convolution of the forward traveling wave with the impulse response of the tube, as proposed in [18]. The relationship between pressure and flow in the mouthpiece is given by \( Z_0 u = p^+ - p^- \), where \( Z_0 \) is the characteristic impedance at the mouthpiece end of the resonator.

Numerical Discretization

Equation (1) is discretized using the finite-difference method:

\[ m \frac{y^{n+1} - 2y^n + y^{n-1}}{\Delta t^2} + m g \frac{y^{n+1} - y^{n-1}}{\Delta t} + \frac{k}{2} (y^{n+1} + y^{n-1}) + k_c (|y^n - y_c|)^\alpha = p_m - p^n \]

where \( y^n \) denotes the value of variable \( y \) at time \( n\Delta t \), with \( \Delta t \) being the sampling interval. Solving for \( y^{n+1} \), it is possible to calculate \( h^{n+1} = y_m - y^{n+1} \) and \( u_r^{n+1} = S(y^{n+1} - y^n)/\Delta t \).

The resonator consists of the mouthpiece and the saxophone neck. The former is modeled as a cylindrical plus a conical section [21] and the latter as a cone with the same angle, both assuming an axisymmetric geometry (see Figure 3). The bore reflection function can be calculated using digital waveguide modeling [21, 22]. Assuming a cylindrical bore entry (with zero instantaneous reflection) the value of the returning pressure wave at the “next” time step can be obtained by convolution of the forward traveling wave with the reflection function of the tube:

\[ [p^-]^{n+1} = \sum_{i=1}^{N_f} r_f(i) [p^+]^{n-i}, \]

where \( N_f \) is the length of the reflection function \( r_f \). Rewriting equation (2) as

\[ \text{sign}(\Delta p)u_f^2 + 2\frac{(\lambda h)^2 Z_0}{\rho}u_f + \frac{2(\lambda h)^2}{\rho}(2p^- + Z_0 u_r - p_m) = 0 \]
yields a single physically meaningful solution for $u_{n+1}$, as explained in [4, Appendix A1], so that the total pressure and flow in the mouthpiece can be calculated at time $(n + 1)\Delta t$.

It should be noted here that the above model is capable of synthesizing a saxophone tone while all model parameters are kept constant. The validity of such an approximation is constrained to the steady state. Including a rising and decaying blowing pressure can yield some transient behavior (see Figure 4), due to (1) pressure build-up downstream of the reed during attack and (2) since the envelope of the mouthpiece pressure signal can be approximated by the blowing pressure during decay. However, in order to simulate transients in a physically meaningful way it is necessary to vary several model parameters, including (but not limited to) the blowing pressure.

**FIGURE 3:** Schematic depiction of the experimental setup (dimensions in mm).

**FIGURE 4:** Mouthpiece pressure (top) and flow (bottom) simulated with a sample rate of 44100 Hz, using the constant parameters from Table 1 and the plotted blowing pressure variation ($p_m$).

### Modeling Articulation

Modeling the vibrations of the reed during articulation can be achieved by modulating the physical model in order to explain how the player is affecting the system while adjusting his embouchure. An attempt to incorporate the effect of the player's tongue involved adding a second damped mass-spring system that interacts with the oscillating reed [23]. In the present study the objective is to capture the tongue-reed interaction without adding further complexity to the physical model. Therefore the model itself remains unchanged and the effect of tonguing (or modulating the air flow) is simulated by allowing the model...
parameters to vary with time. In the case of tongue-reed interaction the following variations are enforced:

- The equilibrium opening of the reed ($y_m$) is reduced due to the tongue tending to close the reed.
- The internal damping of the reed ($g$) is increased while the tongue is in contact with the reed.
- A pressure build-up is assumed to take place upstream of the reed, because of the severe reduction of the reed opening. The pressure reverts to the level of the blowing pressure with the release of the reed.

In the case of the air-separated tones only the blowing pressure is adjusted. The values of the physical model parameters and their variations during the transient are given in Table 1. The resulting pressure and flow signals in the mouthpiece are plotted in Figure 5 for both articulation methods.

**TABLE 1:** Physical model parameters used in the simulations, along with their variation during articulation ([tongue] stands for the tongued tones and [air] for the air-separated tones).

<table>
<thead>
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<th>parameter</th>
<th>value</th>
<th>transient variation</th>
<th>unit</th>
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<tbody>
<tr>
<td>$k$</td>
<td>7e6</td>
<td>–</td>
<td>[Pa/m]</td>
</tr>
<tr>
<td>$S$</td>
<td>3.5e-4</td>
<td>–</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>$y_m$</td>
<td>4e-4</td>
<td>-30% [tongue]</td>
<td>[m]</td>
</tr>
<tr>
<td>$p_m$</td>
<td>1200</td>
<td>-33% [air]</td>
<td>[Pa]</td>
</tr>
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<td>–</td>
<td>[m]</td>
</tr>
<tr>
<td>$m$</td>
<td>0.05</td>
<td>–</td>
<td>[kg/m$^2$]</td>
</tr>
<tr>
<td>$g$</td>
<td>2300</td>
<td>+1900% [tongue]</td>
<td>[1/s]</td>
</tr>
<tr>
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<td>–</td>
<td>[m]</td>
</tr>
<tr>
<td>$\alpha$</td>
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<td>–</td>
<td>[1]</td>
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**FIGURE 5:** Mouthpiece pressure and flow for the case of tongued tones (left) and air-separated tones (right).

It can be observed that modeling the tonguing effect by changing the reed vibration mechanism and not the blowing pressure, it is possible to simulate a mouthpiece pressure signal that is similar to the measured one. The evolution of the signals has the same profile during both the decay and the attack transient. When only the blowing pressure is modified the simulated pressure signal is quite different, which was also the case when comparing the tongued and air-separated measured signals.
DISCUSSION

Estimation of physical model parameters from naturally performed sounds can provide useful information about how a player is controlling his instrument. A rigid, inverse modeling approach to estimate clarinet control parameters during steady state conditions has been already published [4]. In this paper an attempt is carried out to study how reed parameters are manipulated during articulation transients. Even though no estimation algorithm is presented for the model parameters, it is shown how a single mass-spring model can be modified in order to capture the transient effects during musical phrasing. Two different articulation techniques (with and without using the tongue) have been modeled and the simulated mouthpiece pressure signals compared well to measurements under real playing conditions.

REFERENCES


