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Physics-Based Analysis of Articulatory Player Actions in Single-Reed Woodwind Instruments

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Summary

Musicians use various articulation techniques during expressive performance. In the case of single-reed woodwind instruments these may involve tongue strokes to the reed or modulation of the blowing pressure. To analyse the emerging transient phenomena, a time-domain physical model of the player-instrument interaction is employed. In order to avoid adding new terms and complexity to the model, the effect of tonguing is simulated by allowing temporal variation of existing, physically meaningful parameters. Experimental measurements show differences between tones separated using the tongue or the blowing pressure and comparisons with numerical simulations are carried out. In particular the synthesised mouthpiece pressure and reed displacement are compared with data obtained under real playing conditions. In an attempt to understand how articulatory actions affect the excitation mechanism of the instrument, the physical model parameters that are required to resynthesise the recorded sounds are estimated. This allows tracking the evolution of parameters that evade direct measurement.

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1. Introduction

Physical modelling can be used for both simulation and analysis of the oscillations of musical instruments. The latter allows to study the interaction between the player and the instrument. In woodwind instruments in particular, control of the excitation mechanism is achieved via changes in the player's embouchure. During the steady state of a note, the underlying physics have been extensively studied [1, 2, 3]. On the other hand, transient phenomena have not yet undergone such an extensive analysis. For reed woodwind instruments, the oscillation and extinction threshold have been studied, both experimentally and theoretically [4, 5], and attack and decay transients have been recently investigated for both woodwinds [6, 7] and brass instruments [8]. Note to note transitions have drawn some attention on studies focusing on lip slurs on brass instruments [9, 10] or vocal tract adjustment on saxophones [11, 12, 13]. In these works several measurements have been carried out under real playing conditions. However, some signals, e.g. the reed displacement, remain difficult to track. In this context, inverse modelling attempts provide insight on the physical model parameters [14, 15, 16, 17, 18, 19], but are mostly limited to steady state tones. The attempts in [20] to simulate horn transients illustrate the challenge of physical modelling of articulatory actions.

This paper deals with different articulation techniques during single-reed woodwind performance. The main objective is to determine whether existing time-domain models can be adapted to reliably capture transient phenomena, in order to enhance our understanding of the actions of the player. This is achieved by allowing temporal variation of model parameters, without adding further terms to the model (as done e.g. in [21]). To this cause, physical model parameters are estimated from measured steady-state signals, using a flexible, non-intrusive experimental setup. Subsequently, a time variation of certain parameters is introduced in an attempt to resynthesise the emerging transients. These are very important when it comes to identifying [1] or evaluating [22] musical instruments, as they are associated with the character of a certain instrument and how easy it can be played.

Articulation in woodwind instruments is usually performed by tonguing [23]. To modify the instrument oscillations, the player can use his tongue to dampen the oscillations of the reed. Furthermore, forcing the reed closer to the mouthpiece lay may render the reed-lay interaction more significant, without the reed closing completely, as explained e.g. in [24]. Articulation is thus achieved by direct modification of the reed vibrations, which results in a modulation of the flow through the reed channel. A second articulation technique involves modulating the air flow through the mouthpiece by controlling the blowing pressure. Such air-separated tones can result in a similar, yet not identical musical phrasing compared to the tongued tones. Therefore, a physical model attempting to capture the above articulation techniques should be able to differentiate between tongue- and air-separated tones.

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The differences between tongued and air-separated articulation are highlighted using measurements under real playing conditions, as described in section 2. In order to capture the non-stationary nature of the oscillations, a time-domain model has to be formulated, as explained in section 3, followed by an inverse modelling approach to estimate steady-state control parameters. Section 4 presents an attempt to resynthesise the measured transient signals and section 5 gives some final remarks and conclusions.

2. Experimental measurements

The experimental setup consists of a clarinet mouthpiece (Maxton NA-1) attached to a cylindrical tube (length $l = 0.33$ m; radius $r = 7.5$ mm), two piezo-resistive pressure transducers (Endevco 8507C-2) and a synthetic clarinet reed (Légère, German cut, reed strength 3.75) with a strain gauge sensor attached to it. Both piezo-resistive pressure transducers are operated with the accompanying DC differential voltage amplifier (Endevco Model 136).

To measure the pressure inside the mouthpiece, a pressure transducer is directly inserted into the chamber of the mouthpiece through a drill-hole, insulated using a soft rubber ring to avoid leakage. The second pressure transducer is connected to a probe, that is mounted at the side of the mouthpiece. That probe ranges into the player's oral cavity to measure the blowing pressure supplied by the player (see Figure 1). Note that the blowing pressure is only required to ensure that the player is performing the desired articulation technique. The exact value of this measurement is not inserted into the model, hence an extensive analysis of the probe characteristics (as the one carried out in [12]) is not necessary in this study.

A standard industry foil strain gauge sensor (2 mm, 120 Ohm), glued to the tip of a synthetic clarinet reed, measures the bending of the reed. Synthetic single reeds are well suited for research applications because their non-hygroscopic material properties are designed to keep them always in playing condition. This allows direct comparisons of measurements from different times without caring about the wetness, as would be the case for wooden cane reeds. The sensor is mounted on the flat side of the reed, so that the player does not touch it with his lip or tongue during performance (see Figure 2). The strain gauge is part of a quarter Wheatstone bridge circuit with 5 Volt DC power supply with additional output level amplification (INA 126). The reed sensors were calibrated using a force-displacement measurement, while tracking the output voltage of the strain gauge sensor (see [25] for details), by comparing the sensor signals with the displacement curves. A normalisation is performed on the measured voltage, so that a zero value of the bending signal corresponds to the reed being mounted on the mouthpiece (before playing begins) and a unity value corresponds to the reed being forced to close completely (in a distributed manner). Note that neither of these states is achieved during the recorded performance, as illustrated in Figure 3.

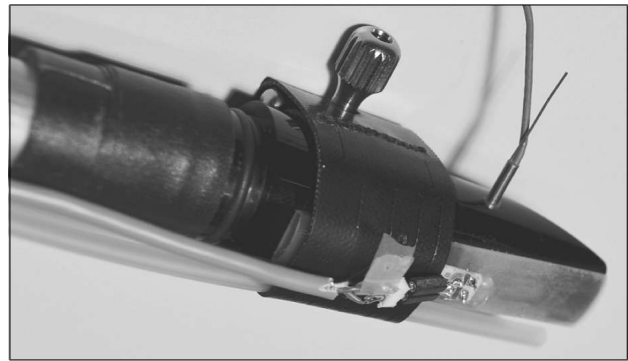


Figure 1. Clarinet mouthpiece with two attached pressure transducers, connected to a cylindrical tube of 330 mm length and 7.5 mm radius.

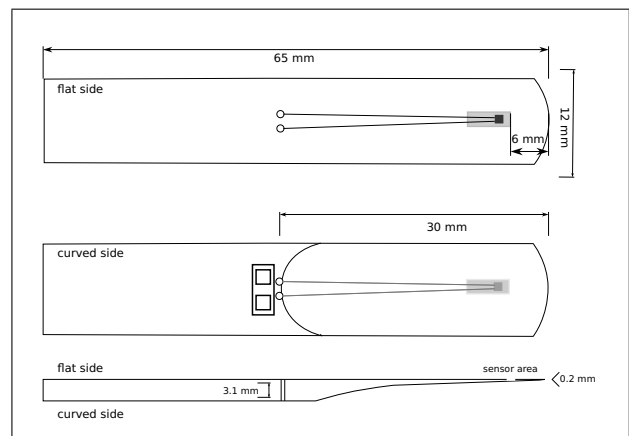


Figure 2. Synthetic clarinet reed equipped with a 2 mm strain gauge.

During the playing experiment, the mouthpiece is connected to the cylindrical tube. The sensors are connected via BNC cables to a data acquisition board (National Instruments PCIe-6351). All signals are recorded with a sampling frequency of 44.1 kHz (16 bit).

A professional woodwind player performed two common types of note transitions, with mezzo piano dynamics. In the first case (*tongue-separated* tones) a portato sequence is performed, where the player uses the front area of the tongue to directly interact with the reed (“te”) in order to separate the tones [23], while the pitch remains unchanged. Note that the reed channel does not close completely. The blowing pressure in this case is approximately constant, as shown on the top of Figure 4. In the second experiment (*air-separated* tones) the same tone sequence is produced, but this time the player is rising the hump portion of the tongue, to strike the roof of the oral cavity (“ke”), which stops the air flow from the larynx [23]. The modulation of the measured blowing pressure is plotted on the bottom of Figure 4. The duration of the measurement for each playing technique is approximately five seconds.

The obtained mouthpiece pressure and reed bending signals are presented in Figure 3, focusing on a single note transition for each articulation technique. A difference in the emerging transients can be observed, depending on the

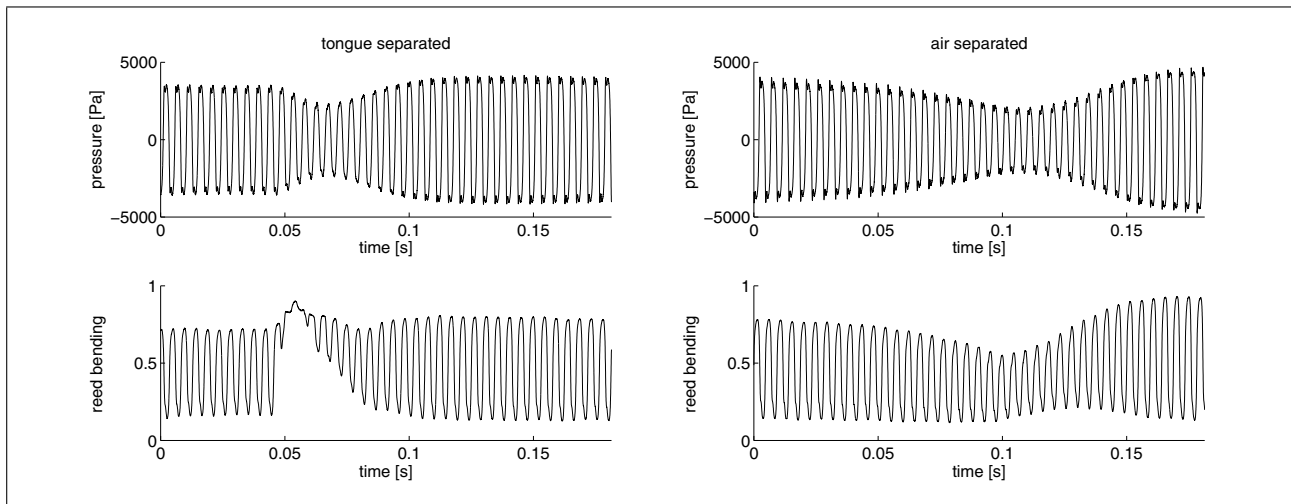


Figure 3. Measured mouthpiece pressure (top) and reed bending signal (bottom) for a single note transition for tongue separated (left) and air separated (right) tones.

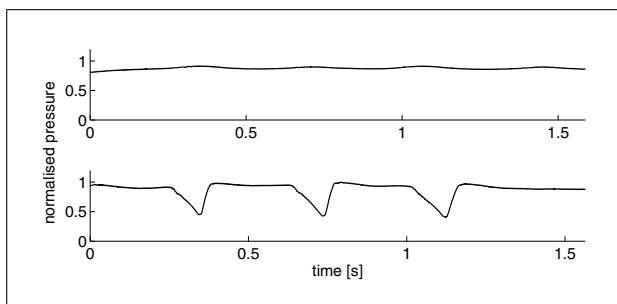


Figure 4. Normalised blowing pressure measured during the performance of tongue-separated (top) and air-separated (bottom) tones.

way that the player controls the oscillations of the instrument. From the reed bending signal it is possible to deduce that tonguing results in a stronger modification of the reed vibrations, compared to the case of air separated tones. Differences also appear in the envelope of the pressure signals. Furthermore, tongue-reed contact results in a smoother waveform of the pressure signal during the note transition, for this particular articulation style. The trends observed in Figure 3 are characteristic of all measurements obtained during the experiments. It should be noted here that the reed bending signal does not directly correspond to the displacement of the reed. Nevertheless it provides useful information on the nature of the reed oscillations and can thus be qualitatively compared with reed displacement signals measured under artificial blowing conditions [26] or calculated using physical modelling.

3. Physical modelling

In the previous section it has been shown that different articulation techniques result in different transient signals during note transitions. In order to analyse the details of the measured transient signals and the underlying physics, a time-domain model is formulated that allows temporal

variation of the physical model parameters. Two nonlinearities are taken into account in this model, one due to fluid dynamical effects and one due to the collision of the reed with the mouthpiece. Using a steady-state portion of the recorded sound, it is possible to extract the model parameters that are required to resynthesise the measured mouthpiece pressure. These parameters can subsequently be used as a starting point for the numerical modelling of transients.

3.1. Time-domain modelling

The clarinet reed acts as a pressure controlled valve, driven by the difference between the blowing pressure p_m and the mouthpiece pressure p . Following [27], it is modelled as a second order oscillator in the displacement y , with a nonlinear term representing collision with the mouthpiece

$$m \frac{d^2 y}{dt^2} + m g \frac{dy}{dt} + k y + k_c [y - y_c]^\alpha = \Delta p, \quad (1)$$

where m is the effective reed mass per unit area, g is the damping and k the effective stiffness per unit area and k_c and α are power-law constants. The reed-lay interaction, which is effective before the reed closes completely, as explained in [24], takes place when the displacement exceeds the value y_c , hence

$$[y - y_c] = \begin{cases} y - y_c & \text{if } y > y_c, \\ 0 & \text{otherwise.} \end{cases} \quad (2)$$

The choice of $\alpha = 2$ for the power-law exponent is made, in agreement with quasi-static simulations using a 2D distributed model [28], as explained in [27]. The flow through the mouthpiece consists of two components [29]; the Bernoulli flow u_f and the reed induced flow u_r ,

$$u = u_f + u_r = \sigma \lambda h \sqrt{\frac{2|\Delta p|}{\rho}} + S \frac{dy}{dt}, \quad (3)$$

where σ is the sign of the pressure difference Δp , λ the effective width of the reed, ρ the air density and S the effective reed surface. The reed opening h is equal to $y_m - y$, where y_m is the equilibrium opening of the reed, after the player positions his lip (see [21]), with $y_c = 0.6y_m$ (see Figure 5).

This nonlinear element represents the excitation mechanism of the instrument. To simulate clarinet tones, it needs to be coupled to a digital representation of the bore. Assuming plane wave propagation, the reflection function of the bore (r_f) can be calculated using wave digital modelling [30]. This requires an axially symmetric representation of the resonator (mouthpiece plus cylinder). Following [30] the mouthpiece is modelled using a cylindrical and a conical section. The numerical bore profile and the calculated reflection function for the dimensions of the experimental setup of section 2 are shown in Figure 6. Assuming that the mouthpiece pressure is a superposition of a forward and backward travelling wave,

$$p = p^+ + p^-, \quad (4)$$

then convolution of the forward travelling wave with r_f yields the (linear) acoustic response of the bore,

$$p^- = r_f * p^+, \quad (5)$$

with

$$Z_0 u = p^+ - p^-, \quad (6)$$

Z_0 being the characteristic impedance at the mouthpiece entry. The complete algorithm to discretise equations (1) through (6) and compute the mouthpiece signals, subject to a given blowing pressure, is outlined in [27, Appendix A1].

3.2. Inverse modelling

A method to estimate clarinet control parameters under real playing conditions has been presented in [27]. In that study, accurate resynthesis of steady-state tones is achieved based on both pressure and flow signals in the mouthpiece. These are obtained using three microphones placed inside the clarinet barrel, and a wave separation algorithm, including an adaptive calibration of the system [31]. In the present study, a simpler inversion technique is employed, aiming on a qualitative comparison of experiments and simulations, on the basis of a single pressure measurement. The use of a cylindrical tube, that can be accurately modelled, allows to infer the required information on the flow through the mouthpiece, assuming no time-variations in the wave propagation conditions.

Neglecting reed beating, inertia and damping in equation (1), the reed displacement is proportional to the pressure difference across the reed

$$y = \frac{\Delta p}{k}. \quad (7)$$

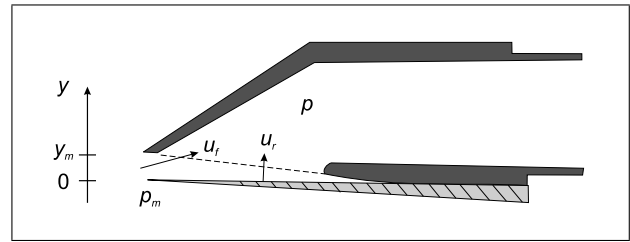


Figure 5. Sketch of the reed-mouthpiece system, where p_m and p represent mouth pressure and mouthpiece pressure and u_f and u_r reed channel flow and reed induced flow respectively. The reed tip displacement is denoted with y and the equilibrium reed opening (after the player positions his lip) with y_m .

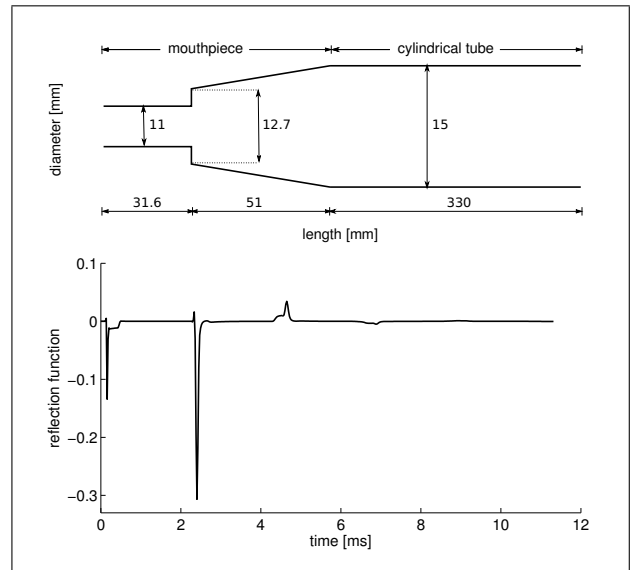


Figure 6. Schematic bore profile (not to scale) of the simplified clarinet (top) and its simulated reflection function (bottom).

Then, following [27], the total flow can be written as a function of pressure only

$$\begin{aligned} u &= \sigma \lambda (y_m - y) \sqrt{\frac{2|p_m - p|}{\rho}} + S \frac{dy}{dt} \\ &= c_1 q |p_m - p|^{\frac{3}{2}} + c_2 q |p_m - p|^{\frac{1}{2}} + c_3 \frac{dp}{dt}, \end{aligned} \quad (8)$$

where $q = \sigma \sqrt{2/\rho}$ and

$$c_1 = -\lambda/k, \quad c_2 = y_m \lambda, \quad c_3 = -S/k. \quad (9)$$

The theoretical flow u from equation (8) can be calculated, given the pressure p , subject to the parameters c_i ($i = 1, 2, 3$) and converted to a frequency-domain variable U (henceforth, capital letters denote frequency-domain variables). Given the reflection function of the resonator, it is possible to calculate its input impedance

$$Z = \frac{1 + R_F}{1 - R_F} Z_0. \quad (10)$$

and subsequently obtain a theoretical pressure

$$\tilde{P} = Z U, \quad (11)$$

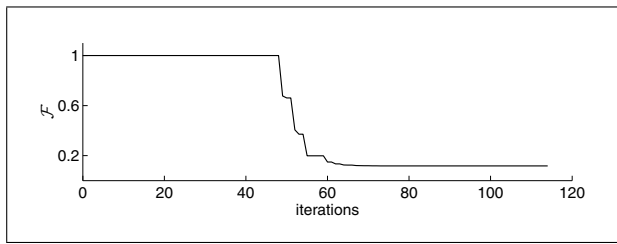


Figure 7. Evolution of the objective function \mathcal{F} during the optimisation algorithm.

Table I. Physical model parameters used in the resynthesis process, obtained through inverse modelling estimation (E), direct measurement (M) or from the literature [32, 33] (L).

stiffness/area	$k = 1.79 \cdot 10^7$ Pa/m	E
reed surface	$S = 9.86 \cdot 10^{-5}$ m ²	E
equilibrium	$y_m = 4.1 \cdot 10^{-4}$ m	E
blowing pressure	$p_m = 3637$ Pa	M
reed width	$\lambda = 0.012$ m	M
reed mass/area	$m = 0.033$ kg/m ²	L
damping	$g = 3000$ s ⁻¹	L
contact stiffness	$k_c = 2 \cdot 10^{10}$ Pa/m ²	L

which can be converted back to a time-domain variable \tilde{p} using an inverse Fourier transform. The inverse model is based on an optimisation routine that minimises the difference between the above calculated (theoretical) pressure signal and the one obtained from the experimental measurements. For their comparison an l^2 -norm is employed in the construction of an objective function

$$\mathcal{F} = \frac{\|p - \tilde{p}\|_2}{\|p\|_2}, \quad (12)$$

which the optimisation routine attempts to minimise. This routine estimates the parameters c_i , so that the theoretical flow u in equation (8) yields a pressure \tilde{p} that approximates the mouthpiece pressure p .

Applying the above routine to a steady portion of the recorded sound (approximately 20 periods long), the blowing pressure p_m can be considered constant and is approximated by the maximum value of p . Using the Nelder-Mead simplex method, and initialising $c_i = 0$, the optimisation algorithm converges after 114 iterations. The termination criterion is a change of an order smaller than 10^{-9} for both the estimated parameters and the objective function. The evolution of the objective function \mathcal{F} is shown in Figure 7. From the estimated parameters c_i , using (9) and setting λ equal to the actual width of the reed, k , y_m , and S are calculated, as shown on Table I. These approximations are quite close to theoretical values given in the literature (as a reference, Schumacher [32] gives $k = 1.25 \cdot 10^7$ Pa/m, $S = 1.46 \cdot 10^{-4}$ m² and $y_m = 4 \cdot 10^{-4}$ m), where one should also consider the effective nature of these parameters, which are influenced by the player's embouchure, as well as the fact that synthetic reeds were used in this study.

For the remaining model parameters, theoretical values obtained from the literature have been used. m is calcu-

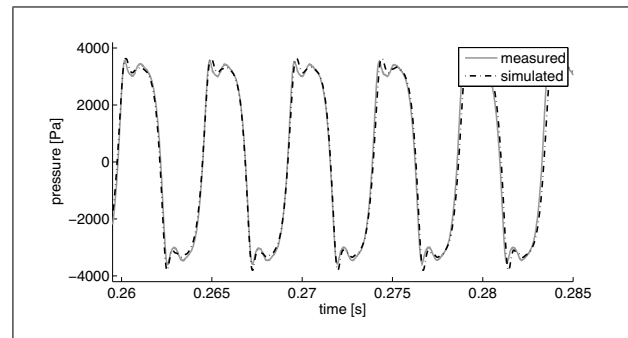


Figure 8. Measured mouthpiece pressure, compared to a numerical simulation using the parameters on Table I.

lated using $\omega_0 = 23250$ Hz for the reed natural resonance frequency [32], g is also taken from [32] and k_c is calculated using the collision parameter $\omega_1 = 632$ given in [33], where in analogy to the presented formulation $k_c/m = \omega_1^3/y_m$. Using the above parameters the physical model can approximate the measured mouthpiece pressure, as depicted in Figure 8.

4. Articulation modelling

In order to capture the vibrations of the reed and the pressure fluctuations in the mouthpiece during articulation, it is necessary to consider a time-dependent variation of the physical model parameters. The control of the system is achieved by the player by means of changes in the embouchure that affect the excitation mechanism accordingly. As discussed in section 2, two different articulation techniques are analysed, namely tongue and air separated tones.

An attempt to incorporate the effect of the player's tongue has been presented by Ducasse [21], who makes use of a second mass-spring system that interacts with the oscillating reed. In the present study the objective is to avoid adding further elements to the physical model, so that both articulation techniques are directly comparable in terms of the variation of the model parameters. Therefore the effect of tonguing, or modulating the blowing pressure, is simulated by allowing a temporal variation of physically meaningful parameters [34, 35] for the model presented in section 3.1. The steady-state values of these parameters are obtained by the inverse model of the previous section. The fact that all parameters have a direct physical interpretation, allows to fine-tune them during the transients, according to the expected actions of the player.

In the case of tongue-reed interaction, tongue-reed contact is modelled by increasing both the effective mass m and the damping g of the mass-spring oscillator. Furthermore, since the tongue is expected to press the reed tip towards the mouthpiece lay, the equilibrium opening y_m is decreased. The temporal variation of these parameters related to tonguing, as determined by an empirical fitting procedure, is shown in Figure 9. The blowing pressure remains approximately constant in this case, as verified by

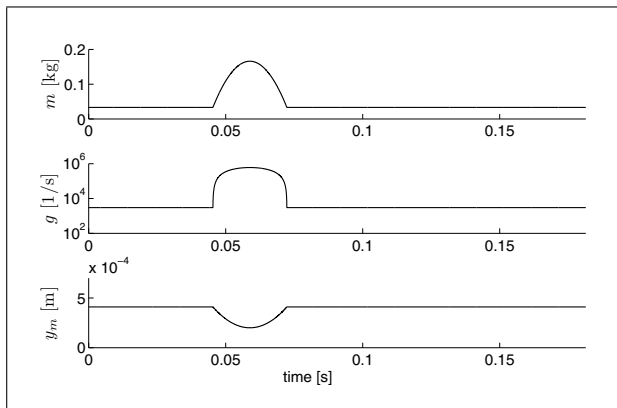


Figure 9. Temporal variation of mass m , damping g and equilibrium opening y_m , during the simulation of tongue separated tones.

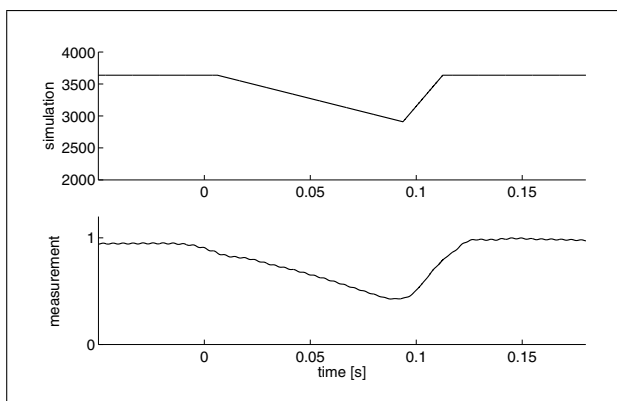


Figure 10. Evolution of the blowing pressure, during the simulation of air separated tones (top) and as observed during the experimental measurements (bottom).

experimental measurements. Thus tongued articulation is achieved via a direct modification of the oscillations of the reed.

On the other hand, in the case of air separated tones, the player controls the instrument by modulating the input (blowing) pressure. In that scenario, the reed vibrations are not manipulated directly, and as a result, the reed signal is less severely affected, as observed in the experimental measurements (see Figure 3). For the simulation of such transients, only the blowing pressure parameter needs to vary, as depicted in Figure 10, in accordance to the measured blowing pressure (Figure 4).

The simulated pressure and reed displacement signals are plotted in Figure 11 for both articulation techniques. It can be observed that the presented model can distinguish between the two articulation methods, synthesising signals that are comparable to the ones obtained by experimental measurements. In particular, in both Figures 3 and 11 the modulation of the reed oscillations is more severe when the tongue is used, due to the direct interaction with the reed. Regarding the mouthpiece pressure, a pressure envelope that is characteristic of each articulation method is apparent in the measured signals. This ‘articulation signature’ is also present in the simulated pressure signals of

Figure 11. Finally, the increase in the reed damping due to the contact with the tongue results in a smoother synthesised pressure signal during the transient, compared to the case of air separated tones. Such an effect has also been observed in the experimental measurements (see Figure 3). Sound examples generated by the above model are available at iwk.mdw.ac.at/?page_id=148&sprache=2.

5. Conclusions

Physics-based analysis of recorded sounds can provide useful information regarding the control of the player over a musical instrument. In this paper, focusing on two particular articulation techniques for single-reed woodwind instruments, physical model parameters are estimated, in order to resynthesise note transitions. The steady-state values of the parameters are calculated using an inverse modelling approach. Their variation during the transients is approximated by considering the effect of the player’s tongue and the variation of the blowing pressure during different articulation techniques. It should be noted here that, due to lack of experimental evidence, the action of the player’s tongue has been assumed to be time-wise symmetric (see Figure 9). This assumption does not seem to affect the ability of the model to synthesise waveforms similar to the measured ones, with non-symmetric envelopes. However, a quantitative comparison of the pressure envelopes is avoided, since it would require further knowledge on the (possibly asymmetric) way that time-domain parameters vary.

The parameter estimation process is based on a single pressure signal, a fact that poses several limitations to the presented approach. In particular, having no direct information about the flow inside the instrument may result in an acoustic impedance mismatch between the experimental setup and the simulated bore. For this reason a straight, cylindrical tube is used, for which accurate models are available for both the wave-propagation and the open-end radiation (see e.g. [36]). To apply the presented methodology to different bore configurations, one has to ensure that an accurate approximation of the reflection function is obtained for the numerical model, via either measurements or modelling techniques.

The fact that a single microphone is inserted in the clarinet mouthpiece allows for a measurement setting with minimal effect on the playing conditions. This is dictated by the objective to acquire fine details regarding different performance techniques. However, such a single-microphone measurement does not allow to account for changes in the tube conditions. Fluctuations of temperature, humidity and carbon dioxide concentration affect the speed of sound [37] and hence the wave propagation inside the resonator. Therefore the recordings are confined to small time intervals, in order to limit variations in the tube conditions. For the treatment of transient signals with longer durations, an adaptive approach is required both for the experimental setup as well as for the physical model [38].

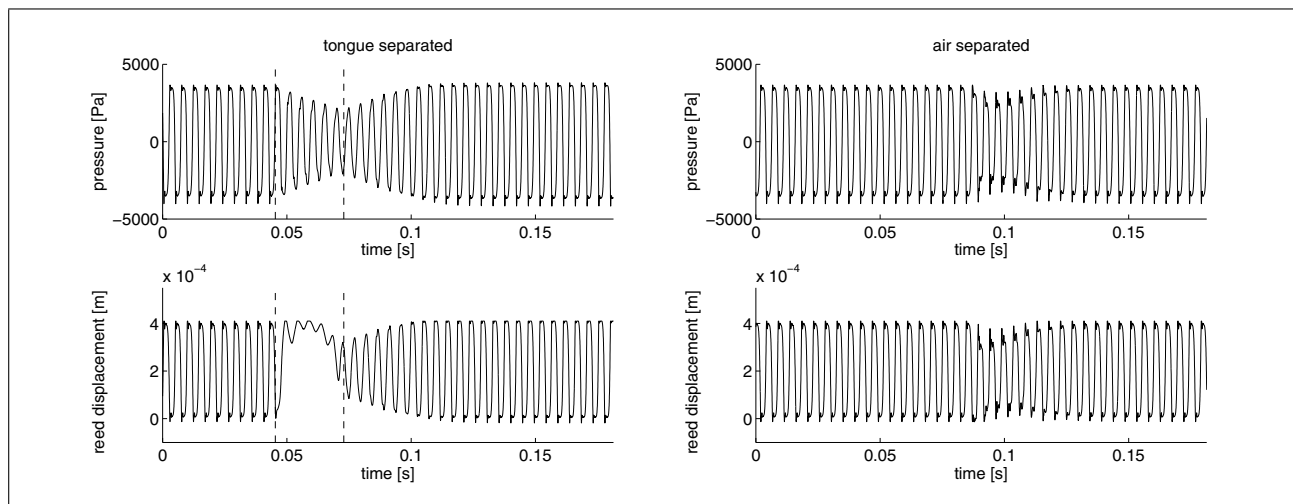


Figure 11. Simulated mouthpiece pressure (top) and reed displacement (bottom) for a single note transition for tongue separated (left) and air separated (right) tones. The dashed lines indicate the interval where the tongue is in contact with the reed.

Overall, the presented model is capable of reproducing the measured pressure signals, at least qualitatively, both during steady-state and during transient oscillations. The ability of the model to distinguish between different articulation techniques, constitutes it suitable for studying the control of the player over the instrument. The presented approach, to estimate control parameters under real playing conditions, points towards the construction of a useful numerical tool for the analysis of recorded mouthpiece signals. Towards the development of a more robust resynthesis routine, the reed bending signal needs to be directly correlated with the reed displacement. This quantitative information, along with the measured mouthpiece pressure, can significantly extend the applicability of the proposed approach to more complex bore geometries.

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