INFLUENCE OF THE TRUNCATION LENGTH OF THE OBOE CONE ON THE REED CLOSING TIME

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ABSTRACT

Proponents of the Pulse Forming Theory (see for instance [1] and [2]) claim that the reed closing time of wind instruments remains approximately constant over their playing range. The theory presented in [3] might provide an explanation for this phenomenon in terms of the geometry of the resonator. This paper aims to test the hypothesis that, for a conical instrument, the closing time of the reed is proportional to the truncation length of the cone. This is done by simulating (through physical modelling) and recording an oboe with a normal staple and with a short staple, assuming that the staple at the top of the instrument is part of the resonator. While the simulations confirm the hypothesis, the recordings show interesting results that invite us to postulate other possibilities.

1. INTRODUCTION

Wind instruments are often shortened or lengthened in order to change the pitch. This results in a different resonance curve for every note. It would be logical to deduce that every note has therefore its own unique sound colour. Nevertheless, the perceived sound colour of wind instruments seems to remain constant across much of its playing range [4]. The reason for this seems to lie both in the sound production mechanism and in the resonance and radiation characteristics of the resonator itself.

Proponents of the Pulse Forming Theory including [1], [2], [5] and [6], found that the spectra of wind instruments have constant spectral gaps and constant formant areas in between these gaps. Fransson [7] used an ionophon instead of a reed to excite the resonator, and changed the pulse length per period until the radiated sound was as close as possible to that of the instrument played with the reed. Voigt [1] used a high speed camera to record the movement of a bassoon reed. Both concluded that the reason why there are gaps in the spectrum is that the closing time τ of the reed remains approximately constant independently of the playing frequency. The ratio between the reed closing time τ and the signal period T determines the position of the spectral minima: When the reed is closed e.g. 1/10 of the complete period, the spectrum will show minima on the 10$^{\text{th}}$, 20$^{\text{th}}$, 30$^{\text{th}}$, etc. harmonic, in other words, the spectral minima lie on the $\frac{T}{\tau}^{\text{th}}$ harmonic and its integer multiples. With his ionophon experiment, Fransson found a closing time of 0.4 ms for the oboe. Likewise, Heptner [8] quotes a closing time of 0.45 ms.

It is well known (see for instance [9], [10]) that the spectrum of a bowed or plucked string strongly depends on the position at which the string is excited. Plucking or bowing near an antinode for a particular mode will excite it, whereas plucking or bowing near a node for a particular node will suppress it. Thus, if the string is excited at 1/2 of its length, the spectrum will have missing harmonics: 2$^{\text{nd}}$, 4$^{\text{th}}$, 6$^{\text{th}}$, etc. If it is excited at 1/5 of its length, the missing harmonics will be the 5$^{\text{th}}$, 10$^{\text{th}}$, 15$^{\text{th}}$, etc, and so on. According to Ollivier et al. [3], changing the position of the string excitation is equivalent to changing the length of the truncation for conical woodwinds, such as the oboe. A crucial difference between string and woodwind players though, is that woodwind players cannot control this parameter, since the length of the truncation is fixed. Let $T = t_o + t_c$ be the signal period, t_o and t_c the opening and closing times respectively, L_b the length of the truncated cone, and L_a the length of the truncation. If $\frac{t_o}{t_c}$ or $\frac{t_c}{t_o} = \frac{L_b}{L_a}$, the oscillation is called "Helmholz motion", in which case the ratio of the durations of the two parts of the signal is determined by the resonator [11].

The constant closing time (and therefore the missing harmonics) found in the Pulse Forming Theory can be explained by this analogy as follows: Since at every note the length of the resonator changes, the ratio $\frac{L_b}{L_a}$ changes as well, however, the length L_a remains constant independently of the playing frequency. Assuming a Helmholz motion scenario, the ratio $N = \frac{L_b}{L_a}$ is equal to the ratio $N = \frac{t_o}{t_c}$, and since the signal period $T = t_c + t_o$ is directly proportional to the total length of the cone $L = L_a + L_b$, then it follows that t_c remains constant independently of playing frequency (as does L_a) and is directly dependent on the length of the truncation L_a (see Appendix). From this theory, the closing time t_c depends only on the geometry of the cone, specifically on the length of the truncation L_a.

The aim of this paper is to test the hypothesis that the closing time of the oboe is directly proportional to the truncation length. This is done as follows:

- increase the truncation length of a normal oboe by cutting the staple in half, and compare its closing time to that of a normal oboe with a normal staple: Is the closing time with the modified staple longer, as expected?
- simulate the above with a physical model with a simplified version of a real oboe: one straight cone for the main body of the instrument, another straight cone for the staple.

This paper is organised as follows: Section 2 describes a method to measure the closing time from the mouthpiece pressure waveform. Section 3 describes the physical model used for the simulations, the geometry of the instruments that were simulated with two different truncation lengths, and the experimental setup to obtain the recorded signals from an oboe with a normal staple and with a short staple. Section 4 presents the results obtained from the simulation and recordings presented in Section 3, and Section 5 presents a general discussion and the conclusions drawn from the results obtained in Section 3.3.

2. MEASURING THE CLOSING TIME

According to [3], the reed opening and the mouthpiece pressure have the same phase, so one can measure the reed closing time by looking at the mouthpiece pressure, which can be measured with a microphone. Since the oboe reed is so small, the place at which the microphone is placed becomes problematic. A compromise has been found between the proximity to the reed and the practicality of placing a microphone: The first hole of the oboe body from the top is opened, which corresponds to the second octave key hole, located approximately 2 cm below the bottom end of the staple, where a 1/8" microphone can be inserted. Placing a microphone closer to the tip of the reed would involve either drilling a hole in the instrument or in the staple, however the staple has a bottom diameter of 4.8mm, and in the oboe used, the bottom 1 cm of it is inserted in the instrument. Trying to insert a microphone in the middle of the staple would mean making a hole on a 3 mm diameter tube, adapting the microphone with a tiny probe, and disturbing the flow of air into the instrument, should the probe minimally protruded inside the air channel. Special consideration has to be made on the choice of microphone due to the high sound pressure levels inside the oboe while being played.

2.1. Signal Analysis

From the mouthpiece pressure signal it is possible to find out the opening and closing times of the reed. This is done as follows: The mean value of the pressure over a period must be zero [3]. The pressure $P_{ref} = P_{max} + P_{min}$ is calculated. The time in which the pressure is below P_{ref} is then the closing time [12].

Each period of the steady state of the time domain signal is found by looking at the pressure maxima. Then P_{ref} is calculated, and the number of samples that fall above and below P_{ref} are counted and saved as opening N_o and closing N_c samples respectively. The opening t_o and closing t_c times are calculated from the number of samples as follows: $t_o = \frac{N_o}{f_s}$ and $t_c = \frac{N_c}{f_s}$, where f_s is the sampling frequency.

The mean and standard deviation of t_o and t_c throughout the duration of the steady state of the recorded note is then calculated. Figure 1 shows an example of how the mouthpiece pressure would look like (taken from a recording with the microphone at the top of the instrument), and where P_{ref} would be in that case.

3. SIMULATION AND EXPERIMENT

This Section describes the physical model used to obtain the simulated mouthpiece pressure, as well as the experimental setup to record the pressure inside the oboe as close as possible to the mouthpiece.

The oboe is usually played with the aid of a mouthpiece that consists of a conical brass tube called staple, to which two cane reed blades are bound. If we consider the staple as being part of the geometry of the resonator, we could shorten the staple so as to make the length of the truncation longer. By doing this the hypothesis is that the closing time will increase, since according to the theory, it is proportional to the truncation length.

3.1. Physical Model

The details of the model used to make the simulation is described in [13]: It is a time domain lumped reed model that incorporates mass, damping and stiffness. Since the reed displacement of the double reed is symmetrical [14], the double

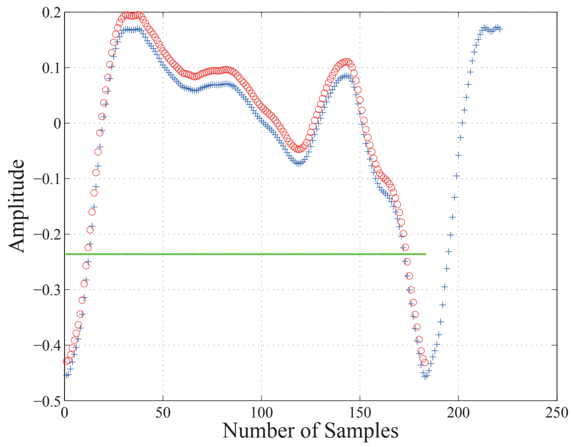

Figure 1: Method to extract t_o and t_c from the time domain signal: The blue crosses show the time domain samples of a segment of the signal, the red circles show the time domain samples of one period with mean pressure value of zero taken from maximum to maximum amplitude, and the green dots show the threshold pressure $P_{ref} = P_{max} + P_{min}$. Samples that are above P_{ref} are counted to calculate t_o, samples below P_{ref} are counted to calculate t_c. The data shown in this plot comes from a recorded signal.

reed is modelled as a single mass-spring system, where the reed-lay interaction is modelled with a conditional contact force based on a power-law:

$$m\frac{d^2y}{dt^2} + mg\frac{dy}{dt} + ky + k_c(\lfloor y - y_c \rfloor^{\alpha}) = \Delta p, \quad (1)$$

where m is the effective reed mass, g is the damping per unit area, k is the effective reed stiffness per unit area, Δp is the pressure difference $p_m - p$, p_m is the mouth pressure, p is the mouthpiece pressure, k_c and α are power-law constants, and y_c represents the displacement value above which the contact force becomes active, i.e.:

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

The flow into the mouthpiece consists of two components: the flow through reed channel u_f, which is assumed to be governed by Bernoulli's law, and the volume flux u_r induced by the reed motion [15]:

$$u_f = \lambda h \sqrt{\frac{2\Delta p}{\rho}} \quad (3)$$

where λ is the effective width of the reed, $h = y_m - y$ is the reed opening, y_m is the reed opening at rest, y is the reed displacement, and ρ is the air density, and

$$u_r = S\frac{dy}{dt} \quad (4)$$

where S is the effective reed surface.

The response of the resonator can be calculated via convolution of the forward-travelling pressure wave p^+ at the mouthpiece entry with the bore reflection function (see Appendix of [13]):

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

where p^- is the returning wave. The relationship with the mouthpiece flow is:

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

where Z_0 is the characteristic impedance at the mouthpiece entry [10].

In all the simulations shown below, the input impedance Z_{in} is calculated with the program VIAS[1] using the bore geometry, and the reflection function r_f is then calculated from it according to [16].

3.2. Instruments

The geometry of the instruments used to do this simulation is based on measurements on a real oboe: First it is assumed that the staple is a straight cone with a top diameter of 2.38mm (when round), a bottom diameter of 4.8mm and a length of 47mm. These measurements were taken from a standard Guercio D12/47 staple. Likewise, the body of the oboe is assumed to be a straight cone, where its angle can be calculated taking the top diameter, the bottom diameter at the bottom of the bottom joint, and the length. The oboe used for these measurements is a full Conservatory professional automatic oboe (Stencil oboe marked Reisser Musik, made by Hans Kreul in Tübingen, Germany in the early 1980's, model 9111VA), for which the (half) angle is approximately 0.7°.

The instruments are built as follows: The top of the original instrument has the same dimensions as a standard oboe staple (Guercio D12/47). The main cone continues from the staple with a (half) angle of 0.7° to a length L_M which, together with the staple, give a first impedance peak close to the frequencies that correspond to the notes C_4, E_4, G_4 and B_4. Since the impedance peaks of cones are inherently inharmonic, the volume of the missing part of the cone has to be replaced [17], [18] in order to regain harmonicity. In order to do that, an equivalent angle θ_E for each cone was calculated, taking the top diameter of the staple and the bottom diameter of the main cone and the total length L_T. Then the truncation length L_a is calculated using that equivalent angle and the top diameter of the staple. A cylinder of length $L_c = \frac{L_a}{3}$ is added to the top of the instrument, which replaces the volume of the missing part of the cone of length L_a and diameter D_T.

The modified instruments should have a longer truncation. To achieve this, the staple is cut to half its length L_s, and its top diameter is measured. The staple section of the original instrument is then replaced with the dimensions of the short staple to make the modified instruments. The main cone of the modified instruments has the same dimensions as those of the original instruments. The top cylinder has a length $L_c = \frac{L_a}{3}$, and the diameter is the same as the top diameter of the short staple.

Table 1 shows the dimensions of the top of the two instruments, and Table 2 shows the dimensions of the main cones, giving 8 instruments in total. Figure 2 shows the configuration of staple plus main cone corresponding to note B_4 of both instruments. The reed parameters were the same for all instruments, and are presented in Table 3.

3.3. Recordings

In order to confirm the simulation results, an experiment is made with an oboe played with a normal staple and with a short staple. In order to measure the sound pressure inside the oboe, a 1/8" G.R.A.S. pressure microphone model 40DP was inserted tightly inside the second octave key hole of the instrument. The microphone was connected to a G.R.A.S. preamplifier model 26AS, then to a BSWA microphone conditioning unit model MC702. The output of the latter was connected via a coaxial cable to the input of a sound card of a modern computer (Intel Core 2 Duo CPU E7400, 2.8 GHz, 4GB RAM, 64 bit). The recording was made with the program Audacity. The sampling rate was set as $f_s = 44.1$kHz.

The cylindrical section L_c used in the simulations above should account for the whole truncation volume, since the reed does not have a volume in the model. In real life, a reed is attached to the staple. If we assume that the standard oboe reed plus standard oboe staple account for the volume of the truncated cone, once the staple is cut in half, the extra missing volume has to be replaced. In order to do this, the cane is shaped in such a way that reed dimensions are somewhat bigger than those of a standard reed. The fact that this new reed plus short staple assembly plays at approximately the same pitch as the standard reed on the same oboe is an indication that both assemblies have approximately the same volume.

An amateur oboist played the oboe referred to in Section 3.2, first with a standard staple and reed assembly and then with a short staple and bigger reed. She played a diatonic C major scale from C_4 to G_5 at a mezzoforte dynamic level.

[1] www.bias.at

Parameter	Oboe	Modified Oboe
D_T [mm]	2.38	3.5
D_B Staple [mm]	4.8	4.8
L_s [mm]	47	23.5
θ_E [°]	0.8	0.75
L_c [mm]	29	46

Table 1: Geometrical parameters corresponding to the top of the instruments.

Parameter	C_4	E_4	G_4	B_4
L_M [mm]	470	330	270	190
D_B [mm]	16.3	12.9	11.4	9.44

Table 2: Geometrical parameters corresponding to the main cones, which are the same for both Oboe and Modified Oboe.

Reed Parameter	
k [Pa/m]	30×10^{6}
S [m^2]	90×10^{-6}
y_m [m]	350×10^{-6}
p_m [Pa]	4.5×10^{3}
λ [m]	7×10^{-3}
m [kg/m^2]	150×10^{-3}
g [1/s]	15×10^{3}
k_c [Pa/m^2]	85×10^{12}
y_c [m]	200×10^{-6}
α	2.5

Table 3: Reed parameters used to simulate the cones.

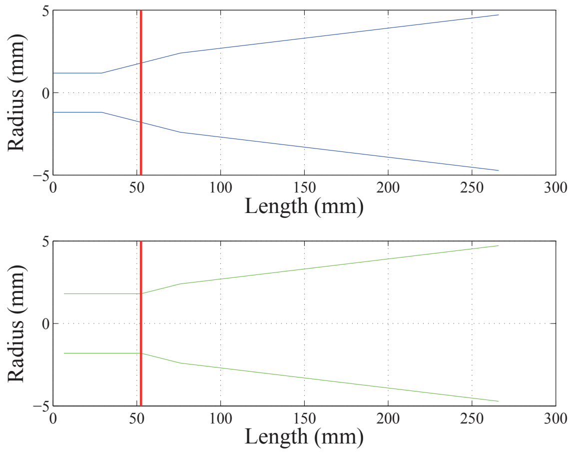

Figure 2: Configuration of staple plus main cone corresponding to note B_4 of the Oboe (top) and Modified Oboe (bottom). The red vertical line shows the point at which the normal staple was cut short.

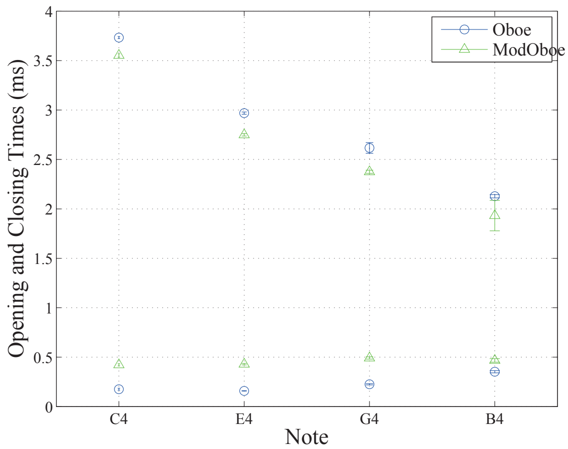

Figure 3: Opening and closing times of a simulated Oboe (short truncation) and a Modified Oboe (long truncation).

4. RESULTS

4.1. *Simulation*

Figure 3 shows the opening and closing times of the two instruments and four notes. The closing time remains approximately constant for both instruments, and in all cases it is shorter for the Oboe case than for the Modified Oboe case, which confirms the hypothesis that by increasing the truncation length the closing time increases.

4.2. *Recording*

Figure 4 shows the opening and closing times of the Oboe with standard staple and reed assembly and of the Modified Oboe with the short staple and bigger reed. The closing time of the Modified Oboe is shorter than that of the Oboe for notes C_4, D_4, E_4, F_4, and A_4, and about the same as that of the Oboe for the note G_4. By note B_4 the opening and closing times are about the same and above that, the closing time is longer than the opening time. This same recording was repeated with a professional oboist, and similar results were obtained.

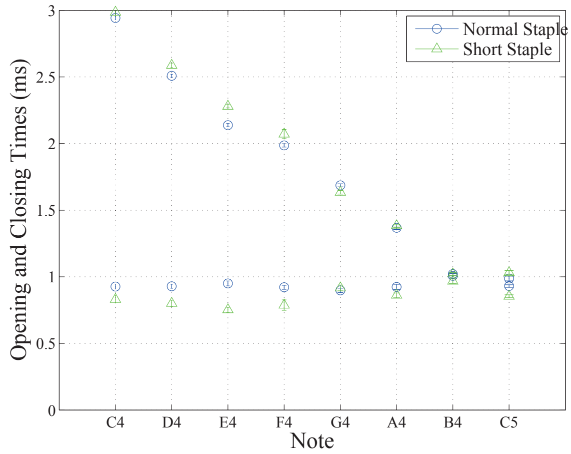

Figure 4: Opening and closing times of an oboe played with a standard staple and reed assembly and with a short staple and bigger reed.

5. DISCUSSION

The hypothesis to be tested in this paper is whether increasing the truncation of a conical woodwind instrument increases the reed closing time. While the simulations confirm this hypothesis, the recording shows the opposite for most notes. A reason why this is the case could be that the theory from Ollivier et al. [3] assumes perfect conicity. For the simulation we assumed that the bore of a real oboe is perfectly conical (straight with one taper), which might not be the case. And even if it were the case, the oboe has tone holes, which when closed, present an extra volume which would not be there in the case of a perfect cone. Also, the staple and the main cone have different tapers, that is, the simulated instruments presented here are also not one perfect cone. Furthermore, the theory from Ollivier et al. [3] is based on a lossless Raman-type model, which gives "two-step" solutions of the reed movement, that is, the reed is either completely open or completely closed. Figure 1 shows that the mouthpiece pressure is not a square waveform. Similar mouthpiece pressure waveforms were obtained in the recordings.

The discrepancies found between the simulations and the recordings lead us to believe that, while the geometry of the cone surely plays a role in the closing time, there must be other mechanisms that influence it. One possibility is the detailed geometry of the reed and the fluid dynamics of the air jet inside it. It is interesting to note that the closing time in the simulations is always shorter than that of the recordings. The reason for the discrepancies discussed here is unclear, and remains to be investigated.

A further reason for the discrepancies discussed here could be the placement of the microphone inside the oboe, which does not directly measure the mouthpiece pressure that applies on the reed, rather the pressure some distance below the mouthpiece.

6. APPENDIX

According to [3] and [11], the ratio N of the cone and its truncation is the same as the ratio of the two signal episodes:

$$N = \frac{L_b}{L_a} = \frac{t_o}{t_c} \tag{7}$$
$$t_o = N t_c \tag{8}$$
$$L_b = N L_a \tag{9}$$
$$\tag{10}$$

The signal period T is related to the total length of the cone (including truncation) by:

$$L_a + L_b = \frac{\lambda}{2} = \frac{c}{2}(t_o + t_c) \tag{11}$$

Combining equations (7) and (11) leads to

$$t_c = \frac{2}{c} \cdot La \tag{12}$$

Therefore, t_c is directly proportional to L_a, and given that L_a is constant, so is t_c.

7. ACKNOWLEDGEMENTS

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