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MODELLING THE SPECTRAL EVOLUTION OF TRANSIENTS IN WIND INSTRUMENTS

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Notes produced by self-sustained musical wind instruments are characterised by relatively long stretches of sound where the waveform has limited variation. However, for notes begun by tonguing, the initial transient or attack is characterised by a rapid, nearly exponential rise in the amplitude of the pressure oscillations. In recent articles, we have studied and modelled tonguing in the clarinet, played by human or machine players. Here, the initial displacement of the reed creates a pressure pulse with a mechanism rather like that of the 'water hammer' in hydraulics, giving pressure and flow proportional to aperture—until the first reflection returns from the bore. Superposition of the reed effect and the reflection makes the spectral content of the early transient strongly dependent on details of the reed motion and the extent of overlap with the returning reflection. The feedback gain of the reed then produces an exponential rise in amplitude until saturation is approached. The shape and characteristic times of the sound envelope are modelled as a function of the details of how the opening valve is changed during the initiation of the sound. During the attack, the oscillations change not only in amplitude but also in shape, and the gain and rise times for different harmonics and other partials may vary. This paper investigates how the time course of the initial displacement of the reed produces different initial wave shapes, and how the spectral content is shaped by reed motion and its overlap with returning pulses from the resonator.
Keywords: transients, reed instruments, time-varying spectrum, clarinet, articulation

1. Introduction

The initial transient or attack of a musical note is very important to timbre and instrument identification [1,2]. On wind instruments, the tonguing that starts a note is considered very important in good playing.

Notes produced by tonguing on a clarinet start as a small oscillation that grows more or less rapidly to a quasi-stable oscillation. When played by a mechanical player, the steady-state limit oscillation is quite stable. The growth of the oscillation is, at the beginning, very close to exponential. The current team has shown experimentally that, for a given reed and note, the exponential rise rate (or the time constant in the exponential) is dependent on the blowing pressure and lip force applied by the player to the reed [3]. A simple model of the reed and its operating gain can show why this is so [3].

In an experimental study using a mechanical player, the starting amplitude of a tongued oscillation was linked to the reed motion following tongue release. When released, the reed moves rapidly towards mechanical equilibrium, losing its mechanical energy in damping from the lip. Its motion gives a rapid change in reed aperture, which allows a rapid change in air flow into the bore of the instrument [4]. Before the arrival of the first wave reflected at the other end of the bore, the amplitude of this change in pressure and flow is, in the simple theory, proportional to the change in reed opening. Often, however, the initial reed motion is not complete before the reflected pulse returns. In this case, the variation in pressure and flow due to reed motion overlaps with that due to the reflected pulse [4]. Different time-variations of reed opening thus produce different starting wave shapes, often different from the time-variation of the reed opening because of overlaps with the reflected pulse. This is shown in figure 1.

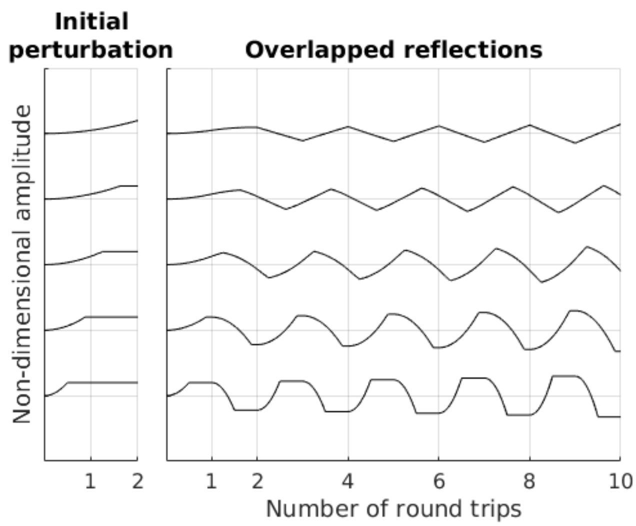


Figure 1. Reed-wave interactions modelled for a simplified clarinet-like instrument. The ratio $\beta = t_r/t_t$, where t_r is the duration of the initial reed motion and t_t the round-trip time in the tube. Here β varies from 2 (top row) to 0.4 (bottom). (Reproduced with permission from [4])

Figure 1 also shows that the different extents of overlap give rise to different amplitudes of the starting wave and also different starting waveforms for the oscillation. Different initial waveforms mean different spectral composition. Further, in a real instrument, the partials at different frequencies have different growth rates, for instance because of frequency-dependent losses in the bore. The combination of different starting amplitudes at different frequencies and different growth rates means that different initial reed motions can produce considerable variation in the starting transient. Such differences are expected to be perceptually very important to the overall perception of the note [1, 2].

This paper analyses the evolution of each partial in the initial transient, first in a simplified clarinet-like system, mechanically played, and later in a slightly modified clarinet played by real musicians. In both cases, a heterodyne method is used to determine time-evolution of each partial (described in section 2). We then apply this model to mechanically played simple clarinets (section 3) showing that the model parameters can be easily described. In section 4, the same method is applied to signals played by real musicians in real clarinets, and the two cases are compared.

2. Simplistic model: simple overlap

Following [4], we start by considering a resonator that produces just a simple delay, linear amplification by the reed and superposition of reflected waves. With this simple model, we predict the waveform generated by a few simple initial perturbations. As can be guessed from the example in figure 1, any abrupt perturbation in pressure and flow would give rise to an approximately square wave, which has significant power at higher harmonics, especially odd ones. For successively slower rates of rise, keeping the same time-variation profile, the waveform comes to resemble a triangular wave, which has less power in high harmonics.

This effect can be displayed graphically using a Fourier analysis of one of the periods of the waveform after a few reflections. The relative amplitudes of the first 5 harmonics are shown in figure 2, taken a few periods into the oscillation. Relative amplitude values remain constant in this simple simulation, because the growth rate is the same at all frequencies. The x axis is the ratio $\beta = t_r/t_t$, where t_r is the time taken for the initial reed displacement and t_t is the round-trip time for a wave in the pipe, which equals half a period for oscillations in this open-closed pipe. (β=1 corresponds to a reed motion that stops just as the first reflection arrives.)

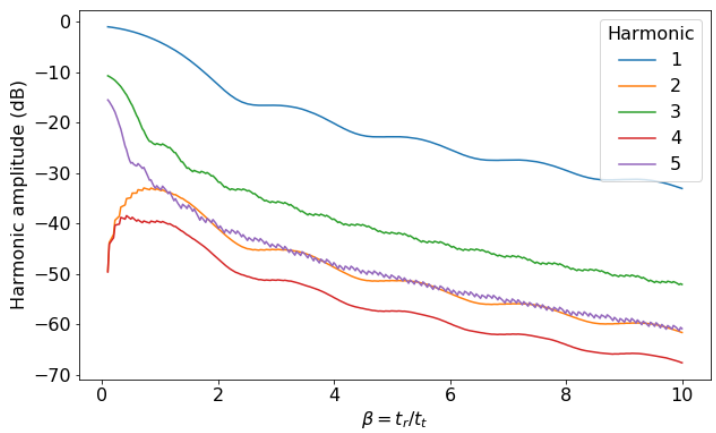


Figure 2. Amplitudes of harmonics as a function of $\beta = t_r/t_t$ for parabolic perturbations with different durations. From the top, the graphs show harmonics 1, 3, 5, 2, 4.

For different perturbation shapes, we expect the harmonic content to have different dependence on β. Figure 3 shows how the ratio of the third harmonic to the fundamental changes for 4 different profiles. All profiles start off with the same ratio -9.54 dB (1/3), which is the ratio for a square wave.

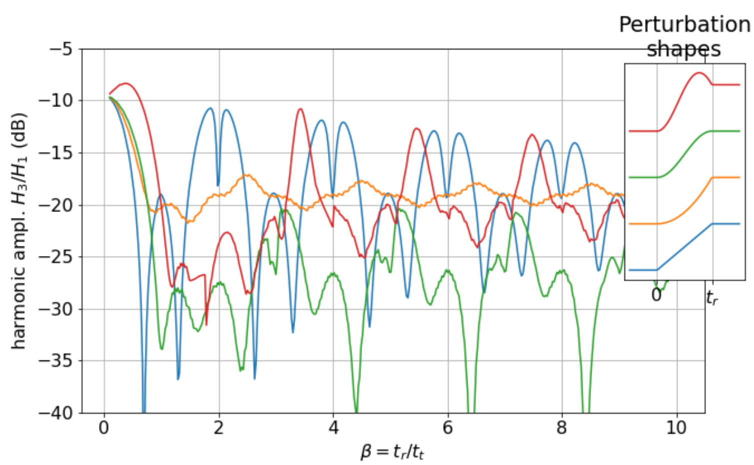


Figure 3. Ratio of harmonic amplitudes H_3/H_1 as a function of β for perturbations with four different shapes of the perturbation (blue $x = \frac{t}{t_r}$, orange $x = \left(\frac{t}{t_r}\right)^2$, green $x = \frac{1-\cos\left(\pi\frac{t}{t_r}\right)}{2}$, red $x = \frac{1-\cos\left(1.3\pi\frac{t}{t_r}\right)}{2}$).

Are similar patterns observed in real conditions? This is the object of section 4. The next section introduces the experimental methods used for the measurements shown in that section.

3. Materials and methods

The data shown in this article were acquired in previous studies [3,5], and are analysed here with new methods. The apparatus used for data acquisitions is briefly described in the following two subsections, followed by the analysis method that is new to the present paper.

3.1 Mechanical playing device

The data described in section 4 were acquired using a mechanical playing device [3], whose basic operation resembles that of a clarinet. A clarinet mouthpiece is mounted at one end of a straight cylindrical tube. Tubes of different lengths were used, one much longer than a clarinet to minimise overlap of reflections with the perturbation generated at the reed. The other end seals to large chamber, allowing a radiation boundary condition. The chamber is pumped to a pressure below atmospheric to create a positive blowing pressure across the reed in the usual direction. The exposed mouthpiece allows easier control of the lip and tongue actions.

The lip force is provided by a constant mass that hangs from the upwards-facing reed. The force is distributed over an area comparable with that of a real lip by means of a soft pad of Sorbothane.

The tip of the tongue is simulated by a thinner pad on the tip of a lever. To start a note with varied acceleration in the size of the aperture, the operator presses the opposite side of the lever either with another mass or his finger. Tongue and reed motion are recorded using a high-speed camera, and automatic image analysis retraces the reed position (y) *vs* time (t). This curve is used to check that the motion is an approximately parabolic increase in time, and to calculate the average acceleration of the reed.

Instrument bore pressure shown in figures below is measured in the barrel of the instrument, 7 cm downstream of the reed. (This position reduces turbulence at the microphone.)

3.2 Sensor-fitted clarinet

Human-played data are acquired on a real clarinet, where the barrel is replaced by a cylinder of equivalent length and diameter, which allows fitting a microphone with negligible intrusion in the musician's gesture. A small pressure sensor is also fitted to the clarinet mouthpiece; this is almost imperceptible to the musician. Data from this sensor are not used in the current article.

Six musicians played a series of exercises, from which only the isolated notes with different attack indications were used in the present study.

3.3 Estimation of partial amplitudes

The analysis of partial amplitude is performed on the microphone signals (sampled at 50 kHz) using the method of heterodyne detection:

The original signal is multiplied by a complex exponential at a constant frequency, matching the frequency of the partial under study. This signal is the summed using windows of 1024 samples, multiplied by a Hann window: this was the window length that produced minimal ripple while conserving a reasonable transient time. Slopes of more than 40000 dB/s cannot be detected using this method, because the size of the window will smooth out the steep slope. Such quick transient times usually arise for partials above the 3rd harmonic in the human data).

If the frequency of the partial is constant within a band of 50000/1024 = 50 Hz, then the absolute value of the sum for each window is proportional to the average amplitude of the partial over the window, and the complex angle of the sum corresponds to the average of the phase difference relative to the reference signal over the window.

4. Mechanically played transients (long pipe)

In a recent article [4], the authors were able to control the release of the reed in a simplified clarinet-like instrument described in the previous section. The reed opening followed an approximately parabolic profile. This generated a parabolic increase in the reed aperture, until it opened to its equilibrium position, or until the first reflection returned. A slight overshoot was sometimes observed but this decayed rapidly due to the high damping of the lip on the reed. The pressure perturbation could be observed most clearly in long pipes, where the first reflection occurred much later than the duration of the initial reed motion. Because of the 'water hammer' effect discussed above, its time course was similar to that of the reed opening—a parabolic profile (see figure 4).

In that article, the observations showed that, if the reed opening happens slowly so that the reflected pulse overlaps the initial perturbation, the initial amplitude of the exponentially growing envelope of the pressure oscillation became smaller, because of that negative superposition (see figure 1).

The same measurements can be analysed in terms of spectral composition, showing patterns that share features with those shown in section 2.

4.1 Observations

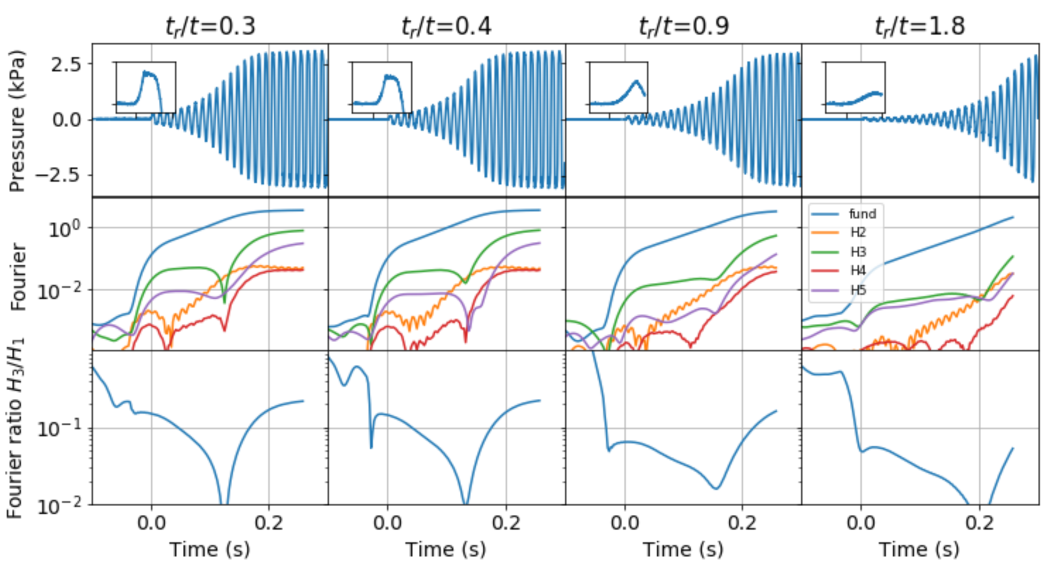


Figure 4. Transients on a long, cylindrical, 'clarinet' for perturbations of different duration

Figure 4 shows the first 3 tenths of seconds of the oscillation in a cylindrical resonator of total length 0.89 m driven by a clarinet reed and mouthpiece. The oscillation is triggered by the mechanical tongue at 4 different values of the acceleration: respectively 23.5, 14.7, 3.2 and 0.9 $\mathrm{mm} \cdot \mathrm{s}^{-2}$. The insets show the first 1/100$^{\text{th}}$ of second, as measured by the barrel pressure sensor—roughly the first oscillation. The second row of plots shows the amplitude of the first five harmonics (blue is the fundamental, then orange, green, red and purple). The third row shows the ratio between the third harmonic and the fundamental (H_3/H_1).

4.2 Discussion

Figure 4 shows that the initial ratio of 3$^{\text{rd}}$ harmonic to fundamental (at t=0) decreases as the value of $\beta = t_r/t_t$ increases from left to right. The difference is not as dramatic as predicted, however.

Additionally, the figure also shows that the increase in the amplitude of the fundamental is very close to exponential for the first several oscillations, after which the signal starts to saturate. Saturation corresponds to a regime where the amplifying effect of the reed can no longer be considered linear. Approaching saturation, the amplification of the first harmonic is reduced, while the amplitudes of the third and fifth harmonics rapidly increase, because of the non-linearity (clipping). This corresponds to the time where the green and the purple curves (3rd and 5th harmonics) undergo a sharp increase in slope. The slower rise in the 3rd and higher harmonics during the exponential phase is partly due to visco-thermal losses in the bore, which increase in proportion with $\sqrt{f}$. Higher frequencies are also expected to have a lower reed gain, because the model for reed gain neglects the mass of the reed, whose influence is greater at higher frequencies.

In Figure 4, the fall then rise in the third partial in the two left columns at about 0.15 s is an interesting feature. As can be seen from the insets, the tiny initial pressure perturbation has a waveform shape determined by the opening motion of the reed, which also determines its relative phase with the fundamental. . During the regime of linear reed gain (the first stage in the attack), the fundamental and third partial are in linear superposition (no phase locking), and the frequency of the latter is slightly less than three times the fundamental, so the phase difference increases gradually and their amplitudes also evolve independently of each other, being determined by the amplification rate of the exciter (see Fig. 5). Later in the attack of the note, the fundamental starts to saturate, generating higher harmonics with phases that are locked to the phase of the fundamental. If and when the 3rd partial of the linear phase is in opposition to the phase-locked 3rd harmonic, an interference minimum occurs, and is followed by the regime with rapidly growing third harmonic.

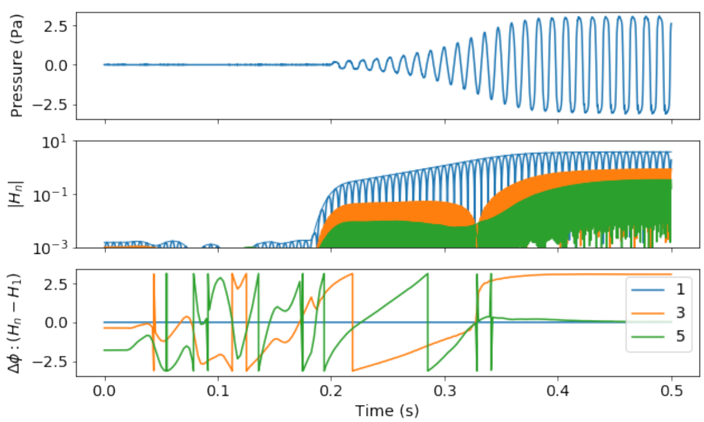


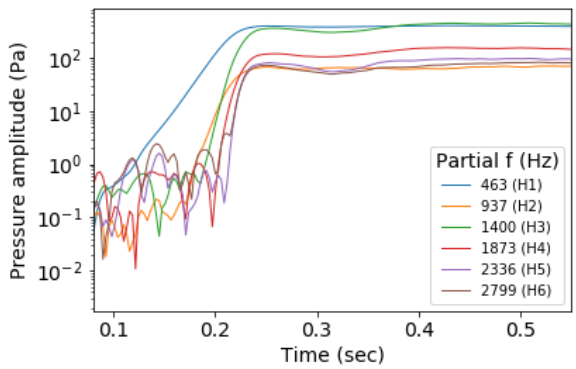
Figure 5. Evolution of amplitude and phase of harmonics relative to the fundamental phase. Notice the steady increase in the phase of H3 and H5

These do not exhibit the bifurcation delays observed by Bergeot [6] for the case of a pressure rising from zero. In such a case the perturbation is the smooth increase in pressure, and the oscillation generated by it first undergoes a reduction in amplitude before the blowing pressure reaches the oscillation threshold. In the normal tongued attack, the blowing pressure is usually above the oscillation threshold when the tongue is released, so that it grows immediately from the initial perturbation caused by the quickly varying reed motion.

5. Human played transients

For real musicians playing real instruments, $\beta = t_r/t_t$ is usually rather greater than one, partly because the lip slows the reed motion (t_r large) and the pitch is usually higher (t_t small), whereas the simplest results in the previous section are for $\beta \gtrsim 1$. For experienced players, it is thus rare to see transients that include significant power in higher harmonics in the early exponential stage. More often, we only see the higher harmonics appearing when the saturation of the oscillation begins (see for instance figure 6 which shows a normal articulation played by an experienced musician).

Notice also that the increases of the first and higher harmonics are not so exactly exponential. This is likely to be due to time variation, during the attack, of the blowing pressure [5], the force applied to the reed or possibly even the vocal tract configuration.



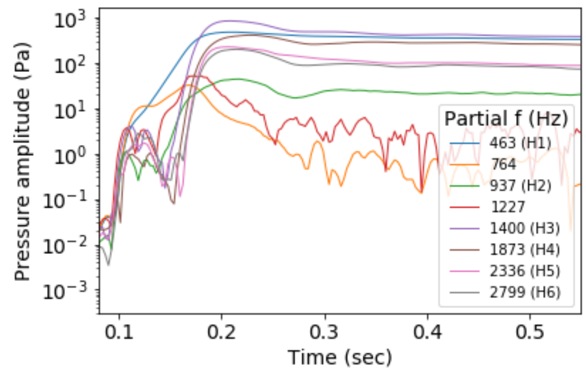


Figure 6. (left) An experienced player plays (written) C5 with a "normal" articulation. Figure 7. (right) The same player plays C5 *sforzando*

In some cases, higher partials may even briefly exceed the power of the fundamental, as seen for instance in a *sforzando* attack by the same player. (Compare figures 6 and 7).

More often, and especially for less experienced players, oscillations at resonant modes of the instrument appear in the initial transient. For a note in the clarion register, the resonances are not harmonically related, as they would be in a straight cylindrical resonator. An example is shown in figure 8, where the fundamental is at 467 Hz and the two lines for 764 and 1238 Hz show significant level in the first 300 ms, then disappear as the main oscillation approaches saturation, and thus produces the 3rd harmonic at 1410 Hz. This is also seen in figure 7 to a smaller extent, due to the shorter duration of the attack.

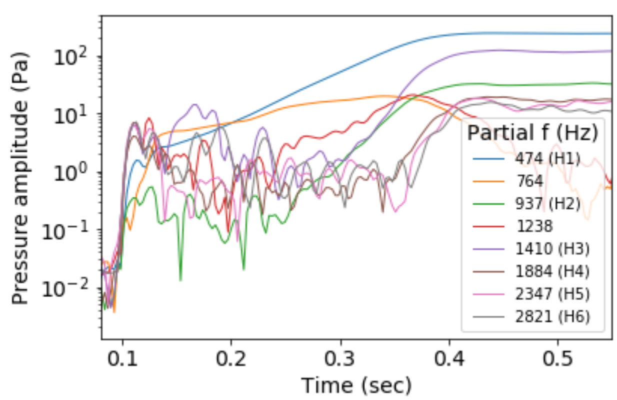


Figure 8. An intermediate player plays C5 with "normal" articulation, showing inharmonic partials in the transient.

6. Conclusions

An attack transient from silence begins when the tongue releases the reed, whose motion changes the aperture into the instrument producing, at first, proportional changes in flow and pressure. This determines the pressure variation waveform until the first reflection arrives. Thereafter, superposition produces quite complicated waveforms.

Previous works form the authors showed that the time course of the initial reed motion produces a proportional pressure perturbation, and that the fundamental component of the oscillation produced by this perturbation then rises exponentially until saturation. This article shows that the envelope of individual partials of the perturbation can be isolated from each other. For most of the transient, approximately linear gain from the reed (which must more than compensate for losses in the bore) produces an exponential rise in each of the partials until the fundamental approaches saturation. In general, higher partials produced in the early stage of the transient do not rise as quickly as the fundamental, and sometimes fall during the transient, until saturation produces rapid rises in the harmonics. Harmonics produced by non-linear saturation can interfere with partials from the initial perturbation producing dips in their amplitudes within the note attack. The spectral content in the early part of the transient is not always harmonic and is a strong function of the time-course of reed movement following tongue release. In some cases, partials unrelated to the harmonics of the played note can be initially excited and undergo some growth until the main oscillation is well established.

7. Acknowledgements

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REFERENCES

1 Berger, K. W. Some factors in the recognition of timbre, *J. Acoust. Soc. America,* **36**, 1888–1891, (1963).

2 Thayer, R. C. The effect of the attack transient on aural recognition of instrumental timbres, *Psychol. Music,* **2**(1), 39–52, (1974).

3 Li, W., Almeida, A., Smith J. and Wolfe, J. The effect of blowing pressure, lip force and tonguing on transients: A study using a clarinet-playing machine, *J. Acoust. Soc. America*, **140**, 1089–1100, (2016).

4 Almeida, A., Li, W., Smith, J. and Wolfe, J. The mechanism for initial transients on the clarinet, *J. Acoust. Soc. America*, **142**, 3376-3386, (2017).

5 Li, W., Almeida, A., Smith J. and Wolfe, J. How clarinettists articulate: The effect of blowing pressure and tonguing on initial and final transients, *J. Acoust. Soc. America*, **139**, 825-838, (2016).

6 Bergeot, B., Almeida, A., Gazengel, B., Vergez, C., & Ferrand, D. (2014). Response of an artificially blown clarinet to different blowing pressure profiles. *The Journal of the Acoustical Society of America*, *135*(1), 479-490.