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Clarinet tonguing: the mechanism for transient production

André ALMEIDA[1]; Weicong LI[1]; Lauren INWOOD[1]; John SMITH[1]; Joe WOLFE[1]

[1] School of Physics, UNSW Sydney, Australia

Abstract

Players coordinate tongue release and variation in blowing pressure to produce a range of desired initial transients, *e.g*. for accents and *sforzando*, players use higher pressures at release to give higher rise rates in the exponential stage. The mechanisms were studied with high-speed video and acoustic measurements on human and artificial players of clarinets and simpler models. The initial mechanical energy of the reed due to deformation and release by the tongue is quickly lost in damping by the lip. The varying aperture as the reed moves towards equilibrium produces proportional variations in flow and pressure via a mechanism resembling the water hammer in hydraulics. Superposition of this signal with returning reflections from the bore give complicated wave shapes with variable harmonic content. When the reed gain more than compensates losses, a stage of nearly exponential increase follows until the last few oscillations before saturation. Maximal exponential decay rates (in tongue-stopped *staccato* notes) agree with losses measured in the bore impedance spectrum. Including estimates of the negative reed resistance explains semi-quantitatively the rise rates for initial transients. Different rates for higher harmonics contribute to different wave shapes and spectral envelopes, which are illustrated and modelled here.

Keywords: Clarinet, Transients, Tonguing

1 INTRODUCTION

The initial transients of wind instrument notes have a rapidly varying waveform amplitude. Further, their frequency components—harmonic, nearly harmonic, inharmonic and broadband—grow at different rates, which gives the transient a complicated, time-varying spectrum. So it is not surprising that wind instrument transients are associated with highly salient dimensions of timbre and are important in distinguishing instruments [1,2].

Initial and final transients and other aspects of articulation are judged by musicians to be important in expressive and tasteful performance and are consequently much discussed by teachers. To start a single note or phrase on a clarinet, pedagogues typically advise that the tongue tip should touch and quickly release the reed, as though pronouncing ‘te’ or some similar syllable.

A tongued initial transient has three stages. In the first stage, which lasts ~several ms, the tongue and the consequent reed motion vary the aperture, admitting varying flow and thus varying the mouthpiece pressure. This provides the initial amplitude for a second stage, lasting ~10 ms. This stage has approximately exponential growth, and usually begins roughly when the first reflected wave returns from the bore. Stages 1 and 2 are seen in Fig 2. In the third stage, seen in Figs 3 and 5-7, the sound pressure amplitude in the mouthpiece becomes comparable with the blowing pressure. In this stage, the non-linear pressure-flow relation has effects including a fall in the rate of increase of the amplitude of the fundamental and mode-locking of partials. These lead to an exactly harmonic spectrum, with amplitude clipping producing a rapid increase rate for some harmonics.

The blowing pressure usually increases during the attack. The blowing pressure, lip forces and reed and mouthpiece properties together determine a gain for the reed. This competes with losses in the bore and mouth and (smaller) losses to radiation; this competition determines the exponential rise rates for the spectral components, which have typical values of hundreds to thousands of $\mathrm{dB.s^{-1}}$.

The combinations of different shapes and characteristic times of stage-1 reed motion with different periods of standing waves in the bore lead to a wide variety of different initial waveforms and spectra and therefore, with different exponential rise rates for each component, to a very wide range of different possible transients. The control parameters mentioned above are under the musician’s control, and thus can contribute to a player’s range of expressive articulations.

The steady part of a clarinet note has been well studied [*e.g.* 3-6]. Studies of transients between successive notes

[1] a.almeida@unsw.edu.au, weicongli@outlook.com, Lauren.Inwood2@det.nsw.edu.au, john.smith@unsw.edu.au, j.wolfe@unsw.edu.au

on wind instruments have been reported elsewhere [*e.g.* 7-10].
This paper first reviews our recent work on tonguing and transients, some involving human players [11-13] and some using a simplified clarinet playing system with mechanical tongue and independently controlled parameters [14,15]. It then presents simple models for transients illustrating some of the complications mentioned above and compares these with reanalysis of the measurements.

2 EXPERIMENTS ON PLAYERS

Figure 1 is a schematic for the experimental setup used by Li *et al.* [11] and Inwood *et al*. [12]. Sensors are attached to a Yamaha YCL 250 clarinet with a Yamaha CL-4C mouthpiece and a Légère synthetic clarinet reed (hardness 3). This is a Bb clarinet, and the written pitch is reported, *e.g*., written C5 sounds Bb4.

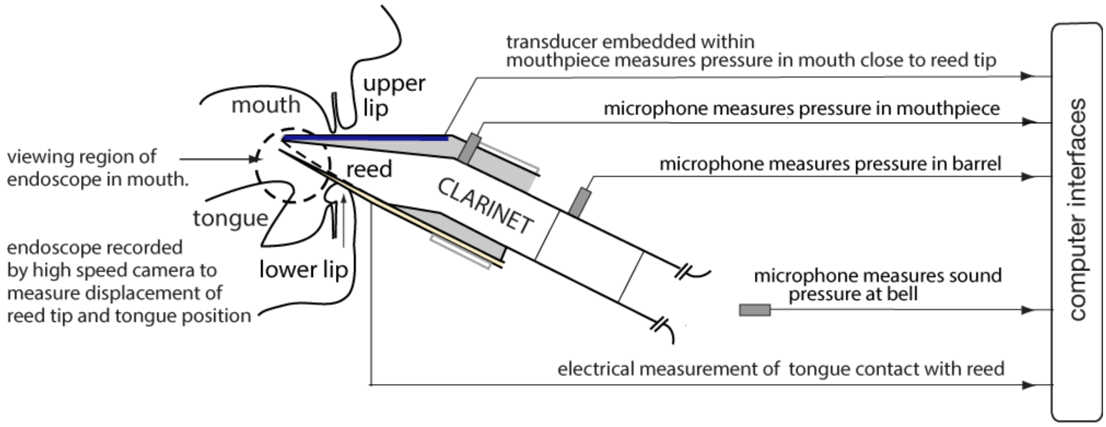

Figure 1 – A schematic of the experimental apparatus for measuring human players.

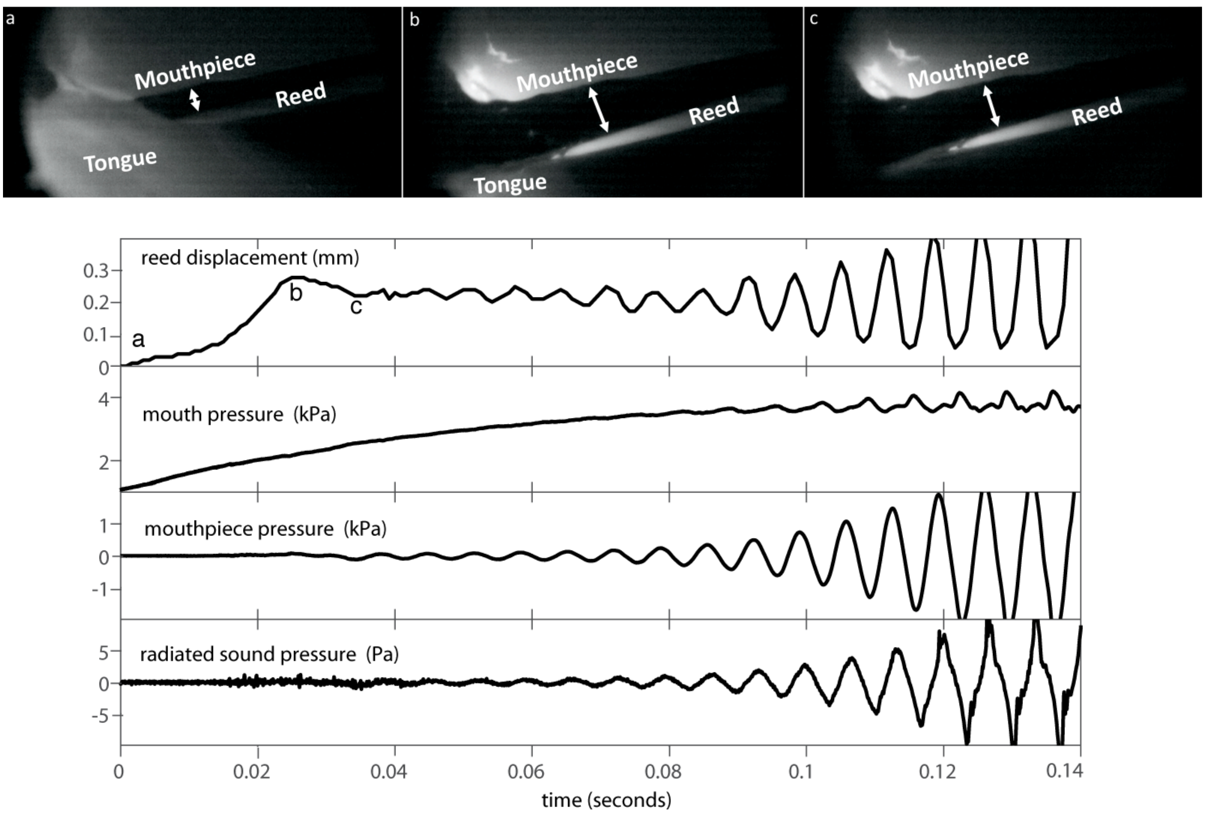

Figure 2 – The images (a, b, c) from the high-speed endoscope video show the labelled points on the graph of reed displacement from its initial position. The lower graphs show pressures in the mouth and mouthpiece and at the bell. An experienced player plays written E3, D3 concert (147 Hz), with normal tonguing. Details in Inwood *et al*. [12].

3 TONGUING: REED MOTION, BLOWING PRESSURE AND SOUND

3.1 Tongue-reed release and the pre-exponential stage

In Fig 2, an experienced player uses normal tonguing for low E on a Bb clarinet, increasing blowing pressure throughout the transient. For about 20 ms, (endoscope images (a) to (b)), the reed follows the wet tongue, which pulls it past its mechanical equilibrium position for this blowing pressure and lip force. The reed leaves the tongue at (b) and its elasticity returns it to equilibrium (c). Overdamped by the lip, the reed loses all the mechanical energy of its initial displacement. Its motion is relatively slow, considering the reed's natural frequency (> 1 kHz). The overdamping also reduces the probability that the reed will squeak. The varying aperture (b–c) at first admits an airflow and produces a mouthpiece pressure change which is, as we discuss later, proportional to the aperture. (This is not visible on the scale of Fig 2, but shown on Fig 5.)

For low notes like this one, the impedance spectrum of the bore has strong peaks at nearly harmonic frequencies, so partials approximating the first, third and fifth harmonics quickly dominate in the mouthpiece. The resonances in the vocal tract are not harmonically related and not tuned for this note [16], so the acoustic component of the mouth pressure is small. The bell radiates high harmonics better than low, giving the more interesting, nearly periodic waveform at right. It also shows inharmonic sound in the early attack.

Sometimes players begin a note without using the tongue; this has been simulated in playing machine studies by Bergeot *et al*. [17]. Interestingly, there is a hysteresis region on the plane of (blowing pressure, lip force) in which regenerative oscillation is not produced spontaneously by simply increasing the blowing pressure. In this hysteresis region, tonguing can initiate a note at lower pressure [11], thus making the start of the note more predictable.

3.2 Reed gain and the exponential stage

Once the reed has approached mechanical equilibrium at (c) in Fig 2, its later motion is driven by the varying air pressure difference across it. Consider a small pulse of low pressure arriving from the bore: it tends to close the reed, reducing the flow from the mouth and thus further lowering the pressure. Conversely, a pulse of high pressure opens the aperture, admits more flow and is thus amplified on reflection. So the reed amplifies pulses coming from the bore (or, in exotic cases, from the mouth [16,18]).

Provided the reed gain exceeds the losses in the bore and mouth, the pulse grows exponentially, until its magnitude approaches the blowing pressure, at which point reed motion and pressure approach saturation. In a simple small-signal model, the reed can be assigned a resistance, R_{reed}, whose negative value is given by the slope of a pressure-flow curve measured on a mechanical system in the absence of resonant loads [19]. R_{reed} is in parallel with the effective resistance R, compliance C and inertance L of the fundamental's bore resonance. (The instrument plays near a peak in the bore's impedance spectrum and this peak can, for this purpose, be empirically modelled as a parallel RLC circuit, where the values are determined from its frequency, magnitude and bandwidth.) For the exponential stage, with $p = p_0 e^{-t/\tau}$, the time constant τ and exponential rise rate r in $\mathrm{dB.s^{-1}}$ are given by

$$\tau = \frac{2R_{bore}R_{reed}C}{R_{bore} + R_{reed}} \quad \text{and} \quad r = -10\log_{10} e \,.\frac{R_{reed} + R_{bore}}{R_{reed}R_{bore}C}$$

This model and the measurements are further explained elsewhere [14]. The empirical circuit model is simplified when the reed is immobilised by the tongue, which can preclude flow between mouth and bore. This situation occurs in the final transient of *staccato* notes, which are therefore briefly discussed next.

3.3 Final transients, *staccato* and losses

At the end of isolated notes or phrases, notes are usually terminated by reducing the blowing pressure until the reed gain falls below the threshold value at which it just compensates the losses in the bore, mouth and radiation. Below this threshold, standing waves decay, as shown in Fig 3a-c, with rates controlled by the blowing pressure and its decrease during the decay. At the end of *staccato* notes, however, the tongue immobilises the reed. Without reed gain, waves in the bore are no longer amplified, and with losses in the mouth disconnected, the exponential decay rate is fixed by the bore: Fig 3d . The exponential decrease rates (~$400\ \mathrm{dB.s^{-1}}$) are consistent with the resistance calculated from the bandwidth of peaks in the measured impedance spectrum of the bore [11,20].

3.4 Comparing different articulations

Figure 3 shows measurements of tongue contact and the pressure in the mouth, mouthpiece and bell for four different articulations. Accented and *sforzando* (and to a lesser extent *staccato*) transients have greater blowing pressure at the instant of tongue release and consequently higher exponential rise rates (~$1300\ \mathrm{dB.s^{-1}}$) than normal articulation. Note that tongue release and blowing pressure are coordinated so that the latter is increasing at the instant of tongue release (as also in Fig 2).

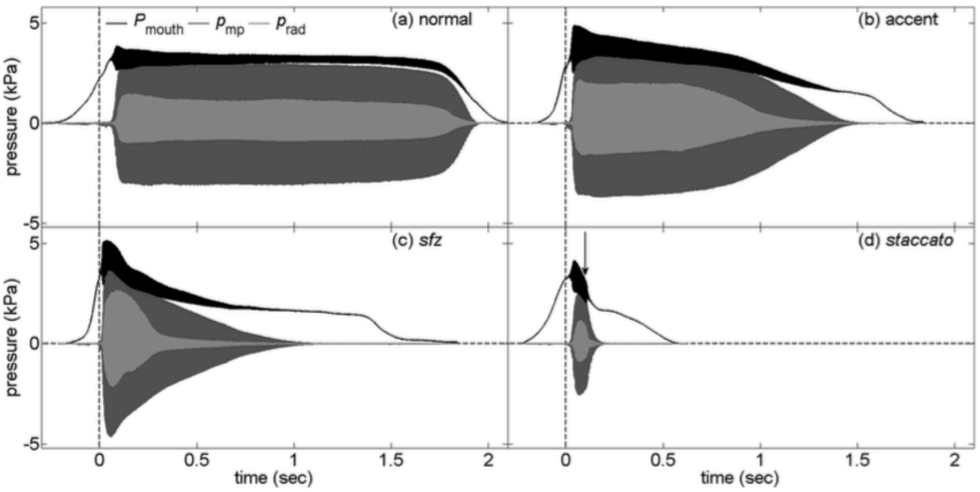

Figure 3 – An expert tongues (written) C5 with four different articulations. Mouth pressure, in black, includes the DC component (the blowing pressure) and the mouth AC signal. Mouthpiece pressure is in mid grey and bell pressure in pale grey. The vertical dotted line shows the instant of tongue release and the arrow (in *staccato*) the instant of tongue contact. From Li *et al*. [11].

3.5 The pre-exponential stage

In the absence of a reflection from the bore, the variation in mouthpiece pressure is simply proportional to the variation in aperture past the reed, because of an effect analogous to the water hammer in hydraulics: an increased aperture admits proportionally more flow from the high pressure source in the mouth and the increase in mouthpiece pressure follows from Newton's second law applied to the pressure pulse in the duct. We demonstrated this experimentally by replacing the clarinet with a tube long enough (L) to make the time for the initial pulse to travel along the tube and return (t_t) longer than the time (t_r) for the reed to reach mechanical equilibrium, thus enabling detailed study [15]. ($t_t = 2L/c = T/2$ where T is a period of the note.)

Depending on tongue motion and reed properties, the reed equilibration time (t_r) may be several to tens of ms so, for practical cases, the initial reed motion effect and the returning waves are in superposition, which is approximately linear for small signals. Some resultant superpositions are illustrated schematically for a simple hypothetical case in Fig 4. Here the aperture has constant acceleration until it reaches equilibrium. The bore is cylindrical. The effect of different ratios $\beta = t_r/t_t$ gives rise to effects that make the pre-exponential amplitude and spectrum complicated functions of the reed motion and t_r.

Figure 4 shows that, when the reed time t_r is shorter than the return time t_t from the bore, the resultant waveform has a clipped shape, and so is expected to have strong higher harmonics, especially odd harmonics. For more realistic cases, with $t_r > t_t$, the shape more closely approximates a triangle wave, suggesting odd harmonics again but with less power in the higher harmonics. The effect of β on the pre-exponential spectrum for a simple system is modelled in more detail by Almeida *et al*. [13].

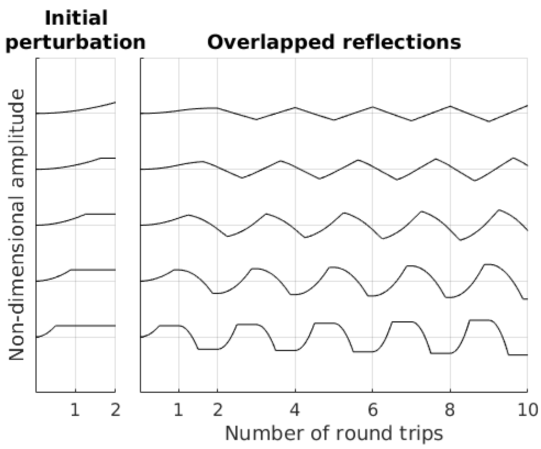

Figure 4 – Reed perturbation effects with the superposition of waves returning from a cylindrical bore. The ratio t_r/t_t varies from 2 (top) to 0.4 (bottom).

In a real clarinet, the impulse response function, and therefore the reflections, are more complicated than a single reflection. For the fingerings for the lowest notes, the bore impedance has several impedance peaks in nearly harmonic ratios (odd number times f_o), so reflections are expected to be nearly periodic. For notes in the second and higher registers, however, there are no or few nearly harmonically related impedance peaks [20], so linear superposition of reflections in the early transient produces strongly non-periodic waves and therefore inharmonic spectra.

4 ANALYSIS OF SPECTRAL EVOLUTION

Transients measured by earlier studies in this lab [11, 14, 15] were analysed using the heterodyne detection technique described by Almeida *et al.* [13]. The microphone recordings were sampled at 50 kHz. A complex exponential with constant frequency equal to that of the partial being analysed multiplies the recording, which is summed over Hann windowed bins of 1024 samples, as an example. If the frequency of the partial is constant within the bandwidth of 50 kHz/1024, then the sum is proportional to the average amplitude of the partial, and the angle of the sum gives the phase difference with respect to the reference signal over the window.

4.1 Analysis of transient measurements on a simple model system

A playing machine with controlled tongue parameters was used to generate reed motion with varying durations on a simplified ‘clarinet’, which was a cylindrical pipe 89 cm in length [14]. Figure 5 shows in the top row the sound pressure measured in the barrel (chosen instead of the mouthpiece for reduced turbulent noise). The second row shows the amplitudes of the first five (nearly harmonic) partials, and the last row the ratio of the amplitude of the third partial to the fundamental (H_3/H_1). As for many human players, the tongue in its initial position pushed the reed towards the mouthpiece, then accelerated away from the mouthpiece with controlled acceleration rates (respectively 23.5, 14.7, 3.2 and 0.9 $\mathrm{mm.s^{-2}}$). The tongue in this case was dry, however, and did not draw the reed past its equilibrium position, so in this case the aperture increased as the tongue accelerated. (Contrast this with Fig 2, where the aperture decreases once the reed breaks free from the wet tongue.) The zoom inset shows the first 10 ms, which is approximately the period of the note. The different acceleration rates produce values of $\beta = t_r/t_t$= 0.3, 0.4. 0.9 and 1.8.

As $\beta = t_r/t_t$ increases (left to right in Fig 5), the relative amplitude of higher partials (for $t \geq 0$) decreases, with qualitative similarity to the calculations in Fig 4. We also see (second row) the nearly exponential growth of the fundamental following the tongue-dominated pre-exponential stage. During this exponential stage, the growth of H_3 and H_5 is slower than that of H_1. This is in part due to visco-thermal losses in the bore that increase in proportion with the square root of frequency. Another reason is frequency-dependent gain: the simple model for reed gain neglects the mass of the reed, which is a more severe approximation at high frequency.

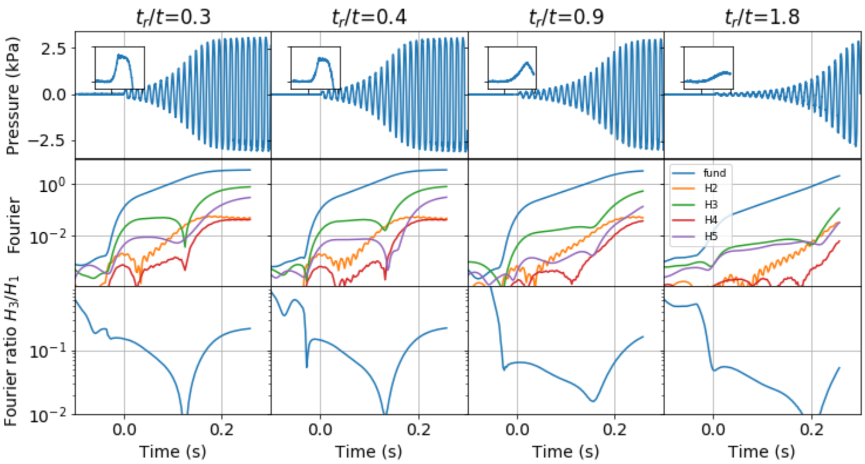

Figure 5 – Barrel pressure and its frequency components in transients on a playing machine.

Saturation occurs over several cycles before the signal reaches its steady or quiescent amplitude. As the amplitude of the sound wave in the bore becomes comparable with the blowing pressure, the reed gain falls below its small-signal value. In this stage, the nonlinearity in the flow-pressure curve for the reed becomes more significant, leading to clipping of the signal, and mode locking of the frequency components begins. The evolution of H_3 and H_5 shows complications in this regime.

The pre-exponential waveform and spectrum are determined by the initial tongue and reed motion, giving rise to the pressure waveform in the insets. This sets the initial magnitudes and phases of the partials, which are not exactly harmonic, and whose relative phases therefore change slowly over time during the linear superposition of the exponential stage [13]. During saturation, however, exactly harmonic H_3 and H_5 are generated by clipping, with phases locked to that of H_1. In the first example of Fig 5, it appears that the H_3 due to the growing linear transient and that due to clipping have a period of destructive interference, before the latter dominates.

4.2 Analysis of transients played by clarinettists

Most notes on the clarinet have the return time (t_t, a half-period) rather shorter than the reed equilibration time. Figure 6 shows the evolution of partials in the note (written) C5, 463 Hz, near the bottom of the clarion register, whose fundamental uses the second resonance of the bore. The figure is a re-analysis of data from Li *et al*. [11]. Notice that the *sforzando* example has a larger pre-exponential amplitude, largely because of the higher blowing pressure at the moment of tongue release. H_1 has a clear exponential stage for both attacks. For *sforzando*, the higher blowing pressure also produces a higher exponential rise rate. The larger pre-exponential amplitude and the larger rise rate together yield a shorter exponential stage for *sforzando*. In neither case is this accompanied by a sustained exponential rise in the other partials: instead, the rapid but smooth rise in some of the partials occurs only during the stage leading to saturation; it is therefore due to non-linear clipping rather than linear gain at the reed. In the *sforzando* attack, it is interesting to observe the strong but brief inharmonic partials at 764 and 1227 Hz (*i.e.* 1.65 and 2.65 times H_1). These are initially strong during the exponential stage, but are suppressed in the saturated steady note, when the third and higher harmonics (both even and odd) dominate the spectrum. Of the two strong inharmonic partials, the first corresponds with the strong third peak in the bore impedance and the latter with the weak fifth peak [20].

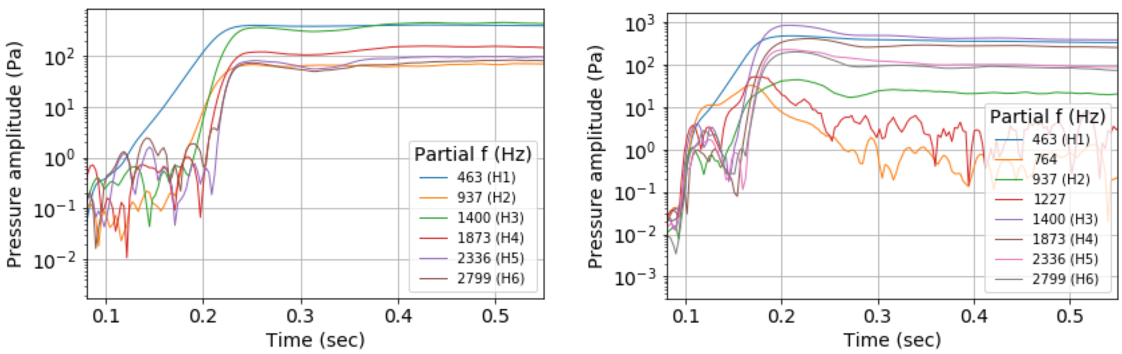

Figure 6 – Evolution of partials as an experienced player plays C5 (463 Hz) with normal articulation (left) and *sforzando* (right). Observe the strong inharmonic partials at 764 and 1227 Hz for *sforzando*.

4.3 From transient to steady note

Figure 3 showed that, after the transient, the mouthpiece pressure is several times larger than the mouthpiece pressure. In this quiescent state, one can use the Wilson [21] method to determine the vocal tract impedance at that frequency: continuity requires that the flow into the bore is minus one times that into the mouthpiece, so the vocal tract and the bore are therefore in series, and the ratio of acoustic pressure in the mouth to that in the mouthpiece pressures is the negative ratio of their impedances ($p_m/p_{mp} = -Z_m/Z_{mp}$), in the quiescent state. However, Figs 3 and 7 also show that p_m/p_{mp} may equal or exceed one during the transient.

In the steady note, players sometimes tune a vocal tract resonance to the note that they are playing to achieve advanced techniques, including pitch bending and altissimo playing [16,18] and the ratio p_m/p_{mp} can identify vocal tract involvement [22]. In normal playing, clarinettists tune the vocal tract resonance not to the note played, but ~100 Hz above, over a range of up to two octaves about C5 [16]. Figure 7 shows, on an expanded scale, accented attacks on the notes C4 (well below the tuning range), G5 (within the range) and C5 (near the lower limit). As expected, the quiescent ratio p_{mp}/p_m is lowest for the note C4 but always >1.

Wilson's impedance ratio argument cannot simply be applied to the rapidly varying amplitudes of currents and pressures during the transient, however, because impedance is inherently a frequency domain parameter. Figs 3 and 7 show that, during the transient, the acoustic pressure in the mouth can be as large as or larger than that in the mouthpiece, in apparent disagreement with the impedance ratio suggested by the steady part of the note.

It is worth observing that, although the mouth sound is unheard by most listeners, it may be perceived by the player and might contribute feedback about the attack, particularly in the clarion or altissimo registers.

The harmonics in Fig 7 show that the second harmonic is substantially weaker than the first and third for the notes C4 and C5, whose impedance spectra have strong peaks at these frequencies, and not at the second harmonic. G5, like other notes in the upper clarion or high range on the clarinet, does not systematically show impedance peaks at odd harmonics and low impedance at even harmonics.

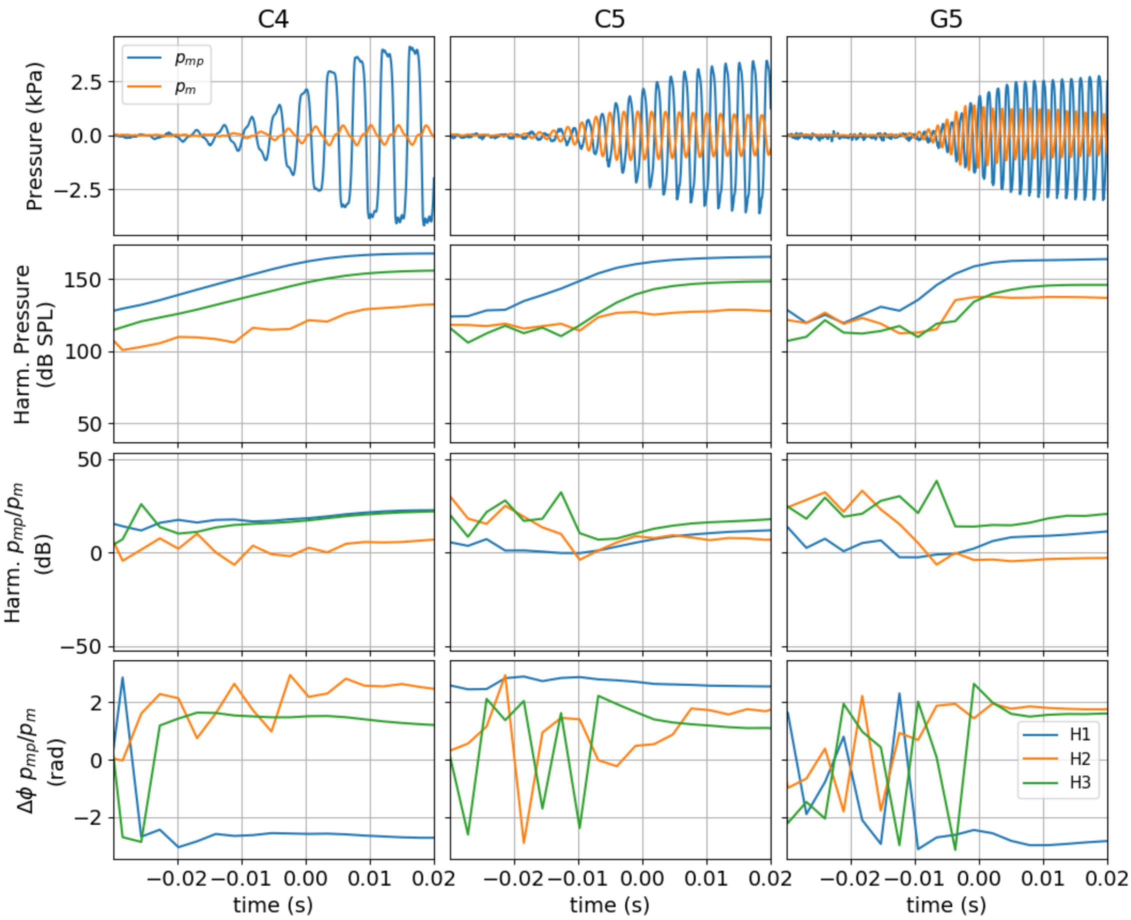

Figure 7 – The middle column shows the accented attack for C5 (Fig 3b) on an expanded time scale. For comparison, left and right columns show accented attacks of C4 and G5 by the same player. Rows show pressure waveforms, harmonics of p_{mp}, amplitude and phase of p_{mp}/p_m. Data from Li *et al* [11].

C4 shows clear exponential phases for H1, H3 and perhaps H2. For the other notes, the late start of the rise in H3 suggests that it comes from nonlinearity rather than reed gain *per se*. Note that H3 is stronger in the mouth than the mouthpiece for G5, whose bore impedance doesn't have a peak at this frequency.

Players achieve a wide range of exponential rise rates for different for different notes (*e.g.* Fig 7) and also for different articulations (*e.g.* Fig 3). Further, the high range for expert players exceeds that for students [11]. Example sound files are available online [23].

5 CONCLUSIONS

- Players coordinate tongue release and variation in blowing pressure to produce desired initial transients, *e.g.* higher pressures at release to give higher exponential rise rates for accents and *sforzando*.
- In a typical attack, the tongue releases the reed, which moves quickly towards mechanical equilibrium, losing its mechanical energy. The resulting variation in the aperture produces a proportional variation in mouthpiece pressure via a mechanism analogous to the water hammer in hydraulics. This stage, which usually ends with the first returning wave from the bore, creates the pre-exponential amplitude and spectrum. Larger blowing pressures and/or more rapid tongue and reed motion produce larger pre-exponential magnitudes.
- The reed release usually occurs when the blowing pressure already exceeds a threshold at which the reed gain compensates for losses. This produces a stage of exponential increase whose rate depends on blowing pressure, embouchure forces, and reed and mouthpiece properties. The partials generated in the preceding stage, which are in general not exactly harmonic, grow in linear superposition at different rates and varying phases. Their amplitude in the mouthpiece may briefly exceed that of the fundamental.
- The tongue can start notes at lower blowing pressures than the threshold measured with rising pressure.

- When the mouthpiece pressure amplitude becomes comparable with the blowing pressure, the reed gain falls below its small-signal value, the exponential rise rate falls, and superposition is no longer linear. Clipping and mode locking produce exactly harmonic partials; these can interact destructively with partials at similar frequency, leading to brief absences of one or more harmonics.
- Players typically coordinate tongue release with increasing blowing pressure to produce a range of different pre-exponential amplitudes and exponential increase rates for different articulation styles. The way in which players control the mouthpiece aperture in the pre-exponential stage influences the spectrum throughout the transient and thus may contribute to their characteristic articulatory styles.

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