Some secrets of good musicians: the physics controlling articulation and timbre in reed instruments

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ABSTRACT

Sometimes, the beauty of a single note identifies a good musician: The initial and final transients are controlled appropriately, as is the harmonic content of the sustained part. This study reports first how several control parameters are varied by accomplished players of clarinet and saxophone. It then uses measurements on a clarinet-playing machine to determine the effects of these parameters independently. In the sustained part of a note, mouth pressure P and lip force F applied to the reed affect both sound level and harmonic content. Further, good players can control the spectral envelope using the vocal tract: peaks in the acoustic impedance of the tract enhance the amplitude of harmonics in the played note at nearby frequencies. The highly salient initial transients produced by good human players have an approximately exponential increase in the amplitude of the fundamental at rates r about 1000 $\mathrm{dB{\cdot}s^{-1}}$ that is achieved by varying both the rate of increase in P and the timing of tongue release during this increase. On the playing machine, when P is above the oscillation threshold, initial reed displacement decays quickly after tongue release, but tongue release rapidly changes the airflow into the bore. This initiates an exponential increase in the sound at rates r that can range from several tens to several hundreds of $\mathrm{dB{\cdot}s^{-1}}$, and that, over the range used, increase with increasing P and decreasing F. Finishing notes either by decreasing P below a threshold, or by tongue contact with the reed, produces an exponential decay in the final transient. The amplitude of the fundamental decreases exponentially at rates ~400 $\mathrm{dB{\cdot}s^{-1}}$ when notes are stopped by human tonguing. This is consistent with the measured bandwidths of the bore resonances, which indicate the dissipated energy. A simple energy accounting model explains the exponential rises and falls in the initial and final transients: A static flow-pressure curve for the mouthpiece has positive and negative slopes corresponding to positive and negative AC conductances respectively. In the playing region, negative AC conductance converts steady pressure from the DC flow into acoustic energy. This oscillatory energy contributes to the energy stored in the reactive components of a resonance in the bore, from which the losses in the bore and the reed are sinks. The energy budget produces the observed behaviours.

1. INTRODUCTION

A beautiful note requires appropriate and elegant control of the beginning, middle and end. Wind musicians control the initial and final transients with time variations in the blowing pressure, coordinated with the motion of the tongue (*e.g.* Sadie, 1984; Sullivan, 2006). They control the pitch and spectral envelope with blowing pressure and what they call embouchure, a term that includes the forces applied with the lips and the shape of the vocal tract. The clarinet and its cousin, the saxophone, have been well studied experimentally and theoretically (*e.g.* Wilson & Beavers, 1974; Bak & Dolmer, 1987; Gilbert *et al.*, 1989; Idogawa *et al.*, 1993; Grand *et al.*, 1997; Nederveen, 1998; Kergomard *et al.*, 2000; Facchinetti *et al.*, 2003; Atig *et al.*, 2004; Ollivier *et al.*, 2004; Dalmont *et al.*, 2005; Dalmont & Frappé, 2007; da Silva *et al.*, 2007; Guillemain, 2007; Chen *et al.*, 2009; Guillemain *et al.*, 2010; Almeida *et al.*, 2013; Hofmann & Goebl, 2014; Chatziioannou & Hofmann, 2015) and so are suitable for studying articulation and timbre control. This paper, which includes the doctoral research of the first author, reviews and extends the literature, including recent papers from the present team (Li *et al*., 2015, Li *et al*., 2016a, b). Sound files are available (Music Acoustics, 2016).

The cartoon in Fig. 1(a) shows several important features. The flexible reed almost closes the aperture to air flow, and is pushed towards closing by the upwards force applied by the lower lip and also by the air pressure in the mouth acting on the lower surface of the reed. The tongue can displace the reed towards or away from the mouthpiece and thus vary the aperture, sometimes suddenly. Downstream from the reed lies the instrument bore, one of whose resonances controls the pitch to first order; upstream lies another duct, the vocal tract, whose resonances also influence the sound.

Fig. 1(b), after Benade (1976), shows how the air flow U depends on the blowing pressure P and the force F applied by the player's lower lip. At low blowing pressure, and assuming that the kinetic energy of the jet into the mouthpiece is lost in turbulence, $U(P)$ is dominated by the 'Bernoulli term': $P \cong \frac{1}{2}\rho v^2$, so $U \cong A(2P/\rho)^{1/2}$, where ρ is the air density and A is the area of the aperture. Sufficiently large P closes the reed against the edge of the mouthpiece aperture, so U goes to zero. This edge is curved [dotted line in Fig. 1(a)], with the consequence that $U(P)$ does not intersect the axis at a finite angle [region 'C' on the curve in Fig. 1(b)]. It also makes the reed a stiffening spring. The lip force F also tends to close the reed, so larger lip forces give smaller U.

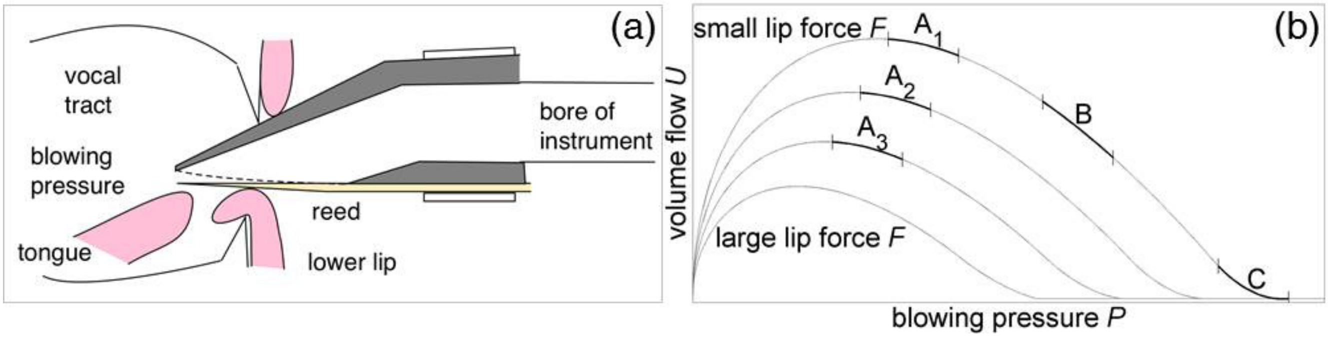

Figure 1: (a) is a cartoon of a clarinet mouthpiece and embouchure. (b) shows a simple model of the flow U past the reed produced by blowing pressure P at different values of the force F applied by the lip.

Note the region of negative slope in $U(P)$. In this region, the small signal AC conductance $\partial U/\partial P$ is negative. The DC conductance U/P is positive, so in this region DC power provided by the lungs can be converted to AC (acoustic) power in the instrument. We return to this simple model below.

2. MATERIALS AND METHODS

In this paper, the initial and final transients of notes played by expert players are studied using a clarinet fitted with a pressure transducer in the mouthpiece to measure the blowing pressure P and the acoustic pressure p_{mouth} in the mouth. Other microphones measure pressure $p_{mouthpiece}$ in the mouthpiece, p_{barrel} in the barrel, at 10 cm from the reed, and p_{sound} just outside the bell [Fig. 2(a)]. A high impedance, electrically-isolated circuit using a fine wire on the reed detects tongue contact. More details are in (Li *et al*., 2016a).

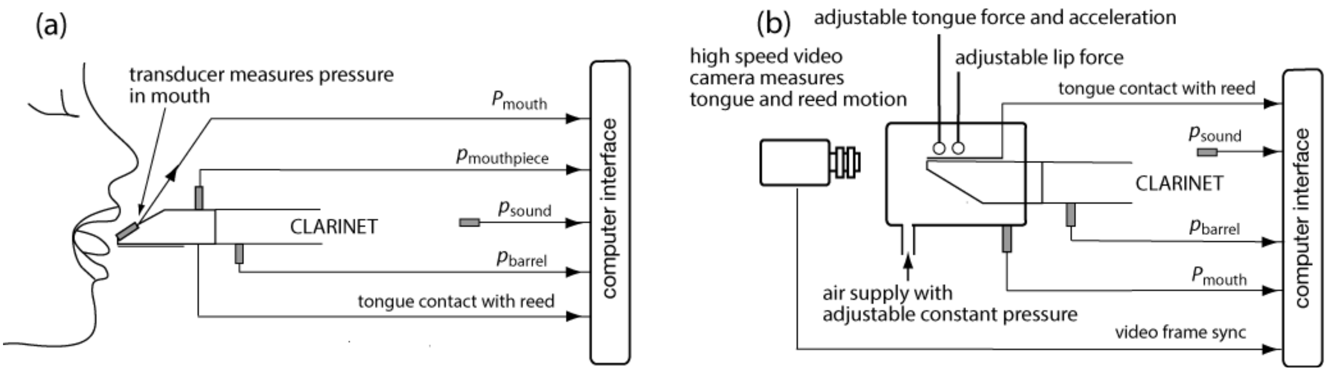

Figure 2: (a) shows the system used to measure the coordination of blowing pressure and tongue-reed contact for human clarinetists. (b) shows the clarinet-playing machine used to vary the control parameters independently.

The effects of blowing pressure P, lip force F and the force and acceleration applied by the tongue are studied using a clarinet-playing machine [Fig. 2(b)], in which each of these control parameters is controlled and varied independently. Again, microphones measure mouth, barrel and bell pressures. More details are in (Li *et al*., 2016b).

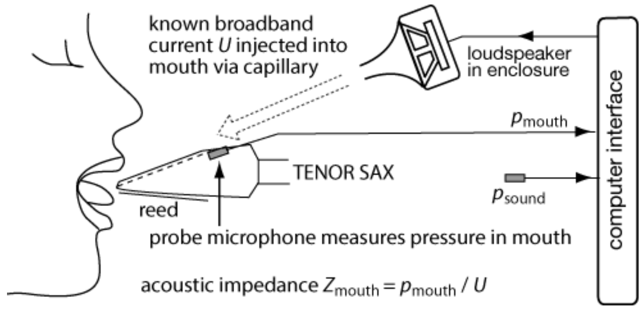

Figure 3: The system used to measure vocal tract impedance during saxophone playing.

The way in which expert players use their vocal tracts to control the spectral envelope of a note is studied using a saxophone fitted with transducers to measure the acoustical impedance acting on the reed in the mouth (Fig. 3). A synthesised broadband acoustic current is injected into the vocal tract and the pressure in the mouth near the reed is measured. More details are in (Li *et al.*, 2015).

3. RESULTS AND DISCUSSION

3.1 Playing range of the clarinet

The left part of Fig. 4 shows the playing region for the written C4 note (but sounding Bb3, nominally 233 Hz; the clarinet is a transposing instrument). The negative sloping line limiting the playing region at high blowing pressure *P* and lip force *F* is the extinction threshold at which *P* and *F* close the reed against the mouthpiece.

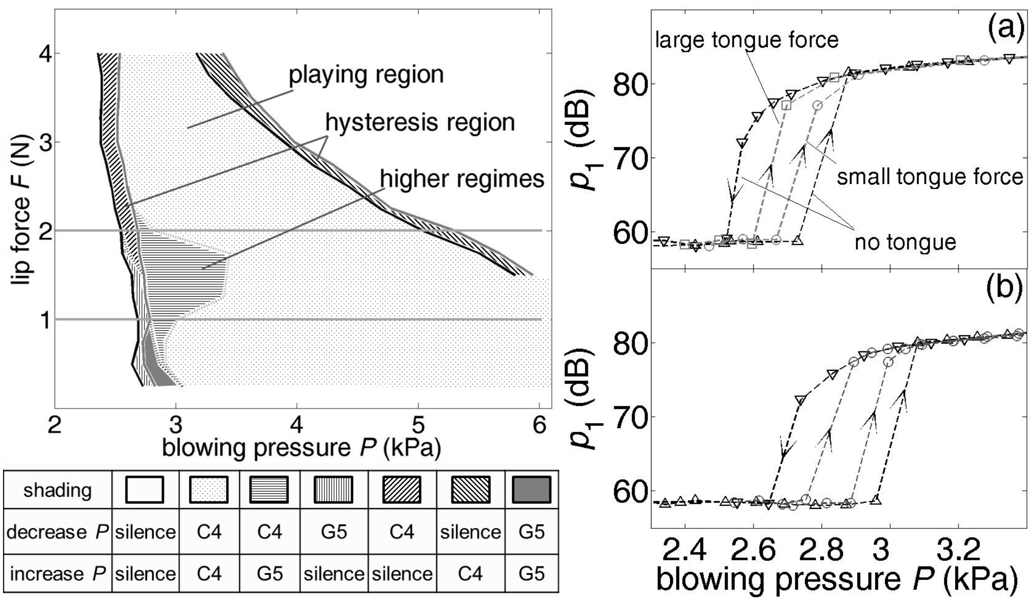

Figure 4: At left, the various playing regions are identified on the (*P*, *F*) plane. At right, the threshold hysteresis region is investigated by plotting sound level (of the fundamental) p_1 as a function of *P* at constant lip force of 2.0 N (a) and 1.0 N (b). The arrows indicate increasing or decreasing *P*.

On both sides of the playing region lie hysteresis regions. For increasing *P*, oscillation starts and stops at higher values of *P* than those at which it stops or starts when *P* is decreased. Hysteresis with varying *P* at constant *F* is shown explicitly in the figures at right. With increasing *P*, oscillation begins at a high value of *P* when there is no tongue action. At lower *P*, within the hysteresis region, oscillation can be initiated by tongue action. When *P* is decreased, oscillation continues to lower values of *P*. The hysteresis region around (3 kPa, 1.5 N) is interesting in that here the instrument can play the wrong note: it can play at the second resonance of the bore rather than the first. This possibility is well known to clarinetists, as is the difficulty of slurring from G5 to C4: once the instrument plays at a higher resonance, it tends to continue playing at that pitch.

Players can vary (P, F) but are constrained by the dependence of playing frequency on P and F. Thus a *crescendo* at constant pitch requires compensation of these (and/or other) control parameters (Almeida *et al.*, 2013).

3.2 Initial transients controlled by human players

Figure 5 compares the C5 note played (a) with minimal attack without using the tongue and (b) with an accent. Starting a note very softly is idiomatic for the clarinet and, in the case shown at left, the tongue is released well below threshold and blowing pressure P is gradually increased until threshold is reached, then held nearly constant before being gradually increased once the note starts. For the accented note, the blowing pressure P already exceeds the oscillation threshold when the tongue is released, and a rapid increase in the amplitude of the sound begins almost immediately. The blowing pressure is then reduced for the sustained part of the note, before decreasing below threshold to finish it. The acoustic current into the bore equals that out of the mouth. However, the acoustic pressure in the bore is much higher. This is because the oscillation frequency lies at a resonance of the bore, where the acoustic impedance (ratio of pressure to flow) is much higher than that of the mouth. A range of other accents, pitches and 'dynamics' (*i.e.* sound levels) is presented elsewhere (Li *et al.*, 2016a).

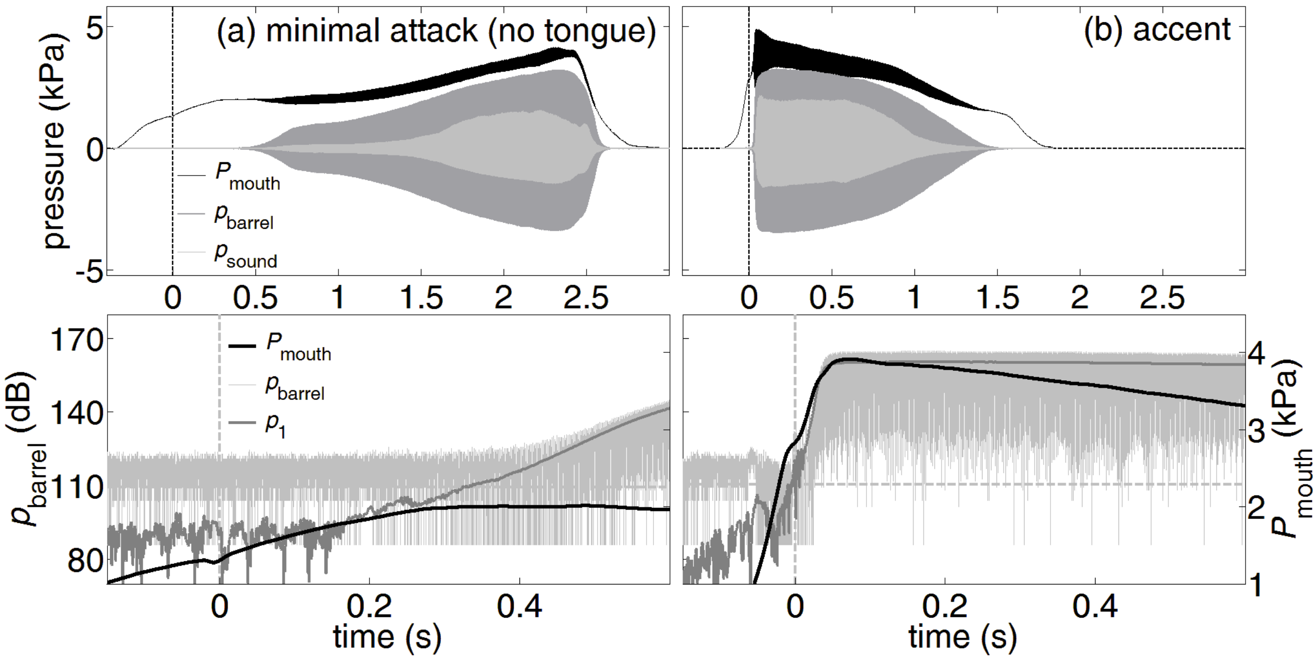

Figure 5: The note C5 played with minimal attack (left) and accent (right). The black line shows the mouth pressure, dark grey the pressure in the barrel and pale grey that outside the bell (the last is uncalibrated). The vertical dashed line at t = 0 is the moment of tongue release. The close-ups below show the exponential increase, on a dB scale. The horizontal dashed line shows the noise level in the barrel in dB over the 0.1 seconds before tongue release.

For all articulations, the initial transient shows a region of exponential growth in the fundamental, over a range of tens of dB, with the rate r varying for different articulations (Fig. 6). It also varies for notes of different pitch, and with the experience of the players, which is shown in Fig. 6. by comparing student players with experts.

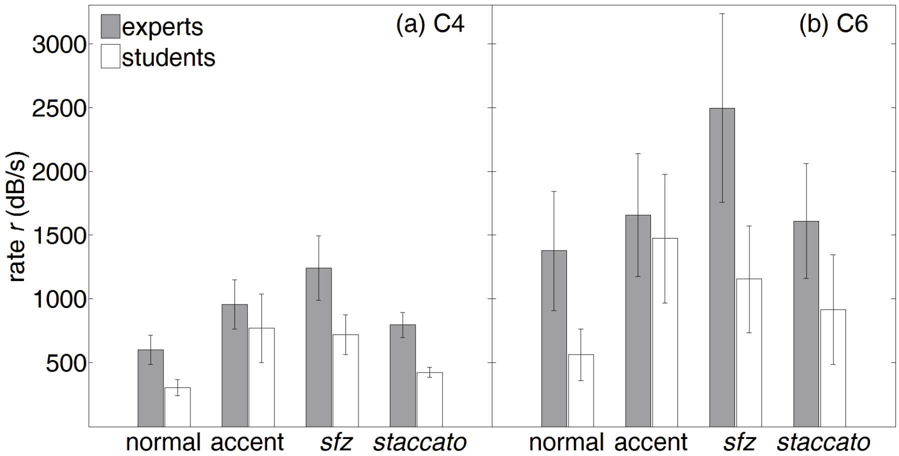

Figure 6: The rate of exponential increase in the fundamental for different articulations at different pitches.

The rate *r* of exponential increase is strongly correlated with the average blowing pressure during the transient, and it probably depends also on the lip force *F*, though this was not measured on the human players. To analyse the effects of tongue action, *P* and *F* on *r* and other aspects of the transients, a study was conducted in which these were controlled independently.

3.3 Measuring transients and regeneration with a clarinet-playing machine

A clarinet-playing machine (Almeida *et al*., 2013) allows *P* and *F* to be controlled independently, and was previously used to show the dependence of playing frequency and spectral envelope on *P* and *F*. This machine was modified so that tongue force on the reed and its acceleration away from the reed could be controlled and measured independently. Again, pressure was measured in the (artificial) mouth, in the mouthpiece and outside the bell. These results are reported in detail elsewhere (Li *et al*., submitted). The dependence of the rate *r* of exponential increase on *P* and *F* is shown in Fig. 7. This includes negative values of *r* because, if *P* is below threshold, tonguing produces an impulsive excitation of the bore that decays exponentially (*i.e.* grows with a negative rate).

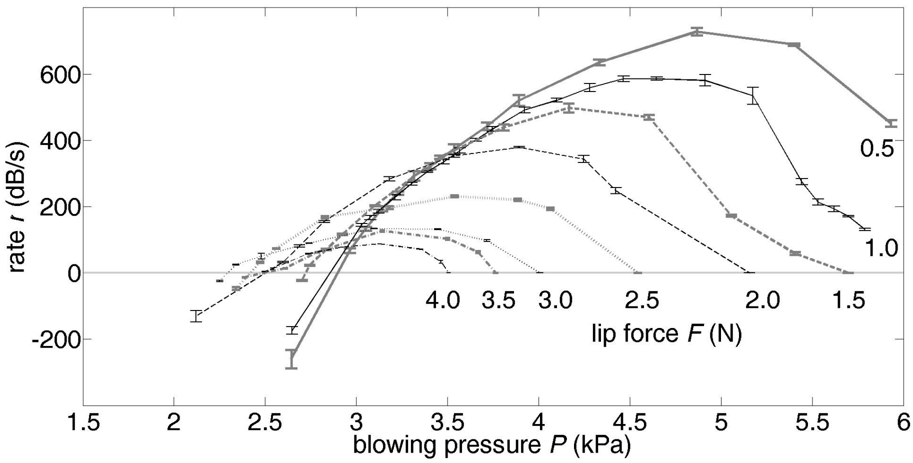

Figure 7: Results from the clarinet-playing machine showing the dependence of the rate *r* of exponential increase in the amplitude of the fundamental on the blowing pressure *P* and lip force *F.* (Negative values of *r* are the rates of exponential decay that follow a perturbation of air flow by the motion of the tongue.)

The rate *r* of exponential increase depends strongly on *P* and *F*. It does not, however, depend on the initiating tongue force and acceleration. High-speed video of the reed shows that, after tongue release, the reed quickly reaches mechanical equilibrium within a few milliseconds. Thus the potential energy of the reed due to its initial displacement and its initial kinetic energy both go to zero: the mechanical energy supplied by the tongue is lost. This is good news for the clarinetist: The reed's natural frequency lies above the playing range so, if the reed motion were not damped by the lip, the reed would have time to oscillate at that frequency before standing waves were set up in the bore. In both the human player and the clarinet-playing machine study, oscillations at or near the reed frequency (approximately that of the squeaks feared by clarinetists) were not observed. What does depend on the tongue action is the time at which the exponential increase begins.

The likely mechanism for how the tongue initiates oscillation is its aero-acoustic effect. By either displacing the reed or by sealing the aperture directly, the tongue can change the aperture. When the tongue releases the reed, the sudden change in aperture produces a similarly sudden change in flow into the bore. This pulse travels down the bore, reflects at the open tone hole array (or, for the lowest note, the bell) and returns to the mouthpiece. At P above threshold, each interaction of the pulse with the reed adds energy to the acoustic wave. The increase is proportional, leading to an exponential rise.

3.4 A simple model for regeneration and the exponential phases of initial and final transients

The results in Fig. 7 can be explained in terms of a simple model based on the $U(P)$ curve in Fig. 1(b) and the assumption that, because the playing frequency is well below the natural frequency of the reed, the inertia of the reed may be neglected. In the simplest model, losses associated with the motion of the reed and lip are also neglected. The small signal conductance of the reed is then $G_{reed} = \partial U/\partial P$, which is negative over a finite range of P. Once G_{reed} is sufficiently negative to provide a power equal to the rate of loss of energy by viscothermal losses in the bore and radiation, oscillation is possible. If these losses and the reed generator are treated as linear for small signals (*i.e*. pressure proportional to flow), then the system can be represented by a simple circuit (Fig. 8).

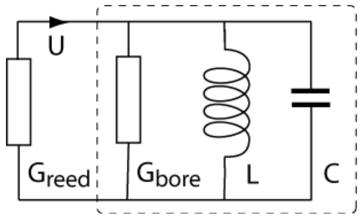

Figure 8: The conductance G_{bore}, inertance (*cf.* electrical inductance) L and compliance (capacitance) C inside the dashed line are an empirical, linear representation whose parallel resonance is the peak of the impedance spectrum of the bore at which the note plays. The conductance $G_{reed} = \partial U/\partial P$ may be negative (in which case regenerated AC power exceeds losses in the reed) or positive (in which case the net AC power generation by the reed is negative).

A clarinet plays at a fundamental frequency very close to that of a maximum of impedance of the bore. At resonance, the impedance is real and $Z_{max} = 1/G_{bore}$. At this resonance, the impedance of the reed must therefore be approximately real, and consequently can be represented by the conductance G_{reed}, whether negative or positive.

At resonance, the total power stored in L and C together is Cp^2, where p is the RMS acoustic pressure. Over a whole number of cycles, the rate of storage of energy is $2CP \cdot dp/dt$. Conservation of energy requires that power output from the reed equals power lost in the bore and radiation plus the rate of increase in stored energy, which is written:

$$-G_{reed}p^2 = G_{bore}p^2 + 2Cp\frac{dp}{dt} \tag{1}$$

so $\frac{dp}{dt} = -\frac{p(G_{bore}+G_{reed})}{2C}$ which has the solution

$$p = p_0 e^{-t/\tau} \tag{2}$$

where $\tau = \frac{2C}{G_{//}} = \frac{2C}{G_{bore}+G_{reed}}$ is the time constant.

In terms of that circuit, if the reed is closed so that it neither provides nor loses energy, then G_{reed} is zero and the sound wave decays exponentially with $\tau = 2C/G_{bore}$, where $G_{bore} \cong 1/Z_{max}$ and C are in agreement with values measured for the input impedance of the clarinet (Dickens *et al.*, 2007, Li *et al.*, 2016a). On the other hand, when $\partial U/\partial P$ in Fig. 1(b) is sufficiently negative that $G_{reed} + G_{bore} < 0$, the signal grows exponentially, with a time constant τ

= $2C/G_{//}$, which is equivalent to a rate r of exponential growth given (in dB·s^{-1}) by

$$r = -\frac{G_{reed}+G_{bore}}{C} \cdot 10log_{10}e \tag{3}$$

Figure 1(b) shows $U(P)$, from which $\partial U/\partial P = G_{bore}$ is seen to be a function of blowing pressure P and lip force F. Considering regions 'C', and because both P and F act to close the reed, the value of P at which the reed closes and r must go to zero decreases with increasing F, in agreement with the results in Fig. 7. The regions marked 'A' in Fig. 1(b) indicate the lowest value of P at which $G_{reed} = -G_{bore}$. These indicate that the value of P where r first becomes positive increases with increasing F, also in agreement with Fig. 7. Integrating measured $r(P, F)$ with respect to P also gives curves qualitatively similar to the relevant sections of Fig. 1(b).

It should be noted that, unlike Fig. 7, the study on human players (Li *et al.*, 2016a) showed monotonically increasing $r(P)$. The reason is simply that there is usually no incentive for human players to raise P into the region at which it produces less rapid transients and less regeneration.

3.5 Players' control of the spectral envelope of the sustained part of a note

The spectral envelope of the sustained part of a note is an important part of the timbre of an instrument. To complete this story of how players control the beginning, middle and end of notes, it is worthwhile including a brief review on how players use their vocal tracts to control the spectral envelope at constant frequency and amplitude.

This study was conducted on a saxophone with an impedance head in the mouthpiece (Fig. 3) and is reported in detail elsewhere (Li *et al.*, 2015). Using subscripts bore and mouth for the acoustic pressure p and acoustic impedance Z of each, definition of Z and continuity require that the flow U into the instrument satisfy

$$-\frac{p_{mouth}(f)}{Z_{mouth}(f)} = U(f) = \frac{p_{bore}(f)}{Z_{bore}(f)} \qquad \text{whence}$$

$$\frac{Z_{mouth}(f)}{Z_{bore}(f)} = -\frac{p_{mouth}(f)}{p_{bore}(f)} \tag{4}$$

Equation (4) looks simple, but does not immediately tell us how Z_{mouth} controls p_{bore} and thus the radiated sound. Two possibilities can be considered. First, if high Z_{mouth} inhibits flow through the mouthpiece at some frequency, then both p_{mouth} and p_{bore} can be reduced, though not by the same factor. This case is how the spectral envelope is controlled in the didjeridu: peaks in Z_{mouth} produce antiformants (minima in the spectral envelopes of p_{bore} and p_{sound}) in the output sound (Tarnopolsky *et al.*, 2005). Alternatively, it is possible that a large value of Z_{mouth} at a particular frequency might modify the oscillation of the reed so as to produce more acoustic current at that frequency. In this case, peaks in Z_{mouth} produce formants (maxima in the spectral envelopes p_{bore} and p_{sound}) in the output sound.

Six expert players took part. Their measurements showed that, when the peaks of mouth impedance Z_{mouth} exceeded about 1–3 MPa·s·m^{-3}, maxima in Z_{mouth} correlated with maxima in the radiated sound: impedance peaks in the mouths of saxophonists produced formants in the sound at nearby frequencies. The formants in the bore and radiated sound were, however, much smaller than the formants in p_{mouth}, so that the effect seemed considerably stronger to the performer (whose percept included the pressure transmitted from mouth to ear) than to listeners.

4. CONCLUSIONS

To play a note, players of single reed instruments control their blowing pressure, their lip force, their tongue action, the acoustical properties of their vocal tracts and the coordination of these.

- The initial and final transients of notes have phases of exponential increase and decrease respectively. The range of rates r of exponential increase is lower for larger lip forces. With increasing blowing pressure, r first increases then decreases. However, the human players in this study did not raise pressure high enough to show r decreasing with increasing P.
- The tongue force and acceleration have little effect on r. However, the timing of tongue release during the player's increase in blowing pressure determines the timing of the exponential rise.

- The mechanical energy initially given to the reed by the tongue is lost, and the reed's own motion is sufficiently damped to ensure that oscillations at the reed resonance are rare. The sudden motion of the tongue and reed produce a pressure pulse whose reflection at the remote end of the bore and regenerative interactions with the reed give rise to an exponential increase in the sound.
- A simple model of energy budget in the bore explains the above.
- The spectral envelope of the sustained part of a note can be controlled by the player's vocal tract. Peaks in the impedance spectrum Z_{mouth} produce broad peaks in the spectral envelope (formants) at nearby frequencies.
- Players use their tongues to end *staccato* notes, in which case the exponential decrease rate in the final transient is determined by the storage of energy in the standing waves and losses of energy in the bore and by radiation. If the reed is not stopped by the tongue, the decay rate can be slower.

  Further details, including sound files are provided (Music Acoustics, 2016).

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