

The effect of blowing pressure, lip force and tonguing on transients: A study using a clarinet-playing machine

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Wind instrument players control the initial and final transients of notes using breath, lips, and tonguing. This paper uses a clarinet-playing machine and high-speed camera to investigate how blowing pressure, lip force, and tonguing parameters affect transients. After tongue release, the reed quickly comes to rest, losing its mechanical energy. However, the changing aperture past the reed rapidly changes the airflow. For pressure above the oscillation threshold, successive interactions between reflections of this pulse of airflow and the reed produce an exponential increase in the sound. The rates r of exponential increase in the fundamental of the sound range from several tens to several hundreds of dB s^{-1} , as functions of blowing pressure and lip force. Because the reed's initial mechanical energy is lost, tongue force and acceleration have little effect on r . However, larger tongue force and acceleration produce more rapid changes in flow, which start notes sooner after tongue release. Further, large tongue force increases the third harmonic during the transient. There is a hysteresis region on the (pressure, lip force) plane where regenerative oscillation is not produced spontaneously by increasing blowing pressure only. Here, tongue action can initiate sustained notes at low pressure. © 2016 Acoustical Society of America.

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I. INTRODUCTION

Players of wind instruments often use the tongue, in combination with varying breath pressure, to begin a note with appropriate initial transient. Musicians consider tonguing and other aspects of articulation to be very important in expressive and tasteful playing. For this reason, the way in which transients are produced and controlled by different tongue actions, in combination with other embouchure parameters, is an important question that interests music students, teachers, and acousticians.

The clarinet is a suitable instrument on which to study transients. Its steady state acoustical behaviour has been well studied experimentally (e.g., Wilson and Beavers, 1974; Bak and Dolmer, 1987; Idogawa *et al.*, 1993; Mayer, 2003; Dalmont *et al.*, 2003; Dalmont and Frappé, 2007; Ganzengel *et al.*, 2007; Almeida *et al.*, 2013) and theoretically (e.g., Gilbert *et al.*, 1989; Grand *et al.*, 1997; Kergomard *et al.*, 2000; Dalmont *et al.*, 2003, 2005; Atig *et al.*, 2004; Facchinetti *et al.*, 2003; Ollivier *et al.*, 2004, 2005; Dalmont and Frappé, 2007; da Silva *et al.*, 2007).

Many clarinet pedagogues discuss the tonguing technique (e.g., Anfinson, 1969; Brymer, 1977; Thurston, 1977; Thurston and Frank, 1979; Sadie, 1984; Gingras, 2004; Sullivan, 2006). Researchers have also studied the initial transients produced by controlled profiles of blowing pressure without tonguing (Bergeot *et al.*, 2014) and found that the growth rate of the initial transient typically does not vary if the blowing pressure is increased linearly at different rates. Tonguing and transients produced by clarinetists and

saxophonists have been studied experimentally and theoretically recently, such as the duration of tongue-reed contact, tongue-finger coordination playing at different tempi (Hofmann and Goebel, 2014; Chatziioannou and Hofmann, 2015), the vocal tract effect on initial transients (Guillemain, 2007), and how players control their vocal tract, lips, and breath during performance (Chen *et al.*, 2009; Guillemain *et al.*, 2010). Tonguing is also considered in several physical models used for woodwind synthesis (Ducasse, 2003; Sterling *et al.*, 2009; Chatziioannou and Hofmann, 2013, 2015). However, the effects of blowing pressure, lip force, and tonguing parameters on transients have not been studied in detail.

A. Initial and final transients in playing

An earlier study (Li *et al.*, 2016) investigated how clarinetists coordinate tonguing with the time variation in blowing pressure to produce the different articulations specifically required by different musical conditions. The initial transient includes a phase during which sound pressure increases exponentially over time before saturation. The rate of this exponential rise (r , in dB s^{-1}) varies for different articulations and varies between players. To achieve different values of r for different articulations, players vary the rate of increase in blowing pressure and also vary the value of blowing pressure at which they release the tongue during the pressure increase. It is also possible that players vary the force F_{tongue} that the tongue applies to the reed before release (Guillemain *et al.*, 2010), and the acceleration a of the tongue as it moves away from the reed. However, it appears that the effects of these parameters on the transients have not been studied quantitatively.

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The production of different articulations by players invites further questions: how does the rate r depend on the control parameters, including the blowing pressure P in the mouth and the force F_{lip} applied by the lip? How important are the force F_{tongue} applied by the tongue to the reed, the initial displacement of the reed Δy_0 , and the acceleration a involved in removing it from the reed, and what are their effects? These questions cannot easily be studied systematically with human players. First, players do not hold P or F_{lip} constant; neither can they vary them independently; second, it is difficult to measure tongue force F_{tongue} and acceleration a precisely during performance. For that reason, the present study investigates the effects of different parameters independently using a playing machine in which these parameters are controlled.

B. Oscillation thresholds and the hysteresis region on the (P, F_{lip}) map

When the blowing pressure P is gradually increased at a fixed lip position and force F_{lip} , the reed will start to oscillate at a particular value of P called the oscillation threshold P_{osc} . Above a considerably higher value of P (the extinction threshold P_{ext}), oscillation does not start. P_{ext} corresponds to the static pressure excess necessary to hold the reed closed against the mouthpiece. These oscillation thresholds at constant blowing pressure have been studied both theoretically and experimentally, together with the regeneration process and the pressure-flow relations (Kergomard *et al.*, 2000; Dalmont *et al.*, 2005; Dalmont and Frappé, 2007). More recently, the dynamic oscillation threshold was investigated using time varying, blowing pressure profiles with different increase rates on an artificially blown clarinet (Bergeot *et al.*, 2014). A playing machine has also been used to measure playing properties and the oscillation thresholds as functions of both the blowing pressure and the force applied by a mechanical lip (Almeida *et al.*, 2010, 2013).

With playing machines, the thresholds are usually measured by increasing the blowing pressure while holding other parameters constant. The measured values of the minimum pressure required for oscillation exhibit hysteresis (Dalmont *et al.*, 2003, 2005; Dalmont and Frappé, 2007; Almeida *et al.*, 2013): they depend on how blowing pressure is varied over time. For example, the pressure required to start oscillation by increasing blowing pressure from lower values will be higher than the pressure required to maintain oscillation when the pressure is decreased. Thus, on the (P, F_{lip}) plane, an oscillation threshold curve measured by small increasing steps in blowing pressure is different from one measured by small decreases in blowing pressure. The areas between each of the two oscillation thresholds and their corresponding two extinction thresholds are hereafter called the hysteresis regions. Notes cannot be started in the low P hysteresis region by increasing blowing pressure alone, but can be sustained in the hysteresis region by decreasing blowing pressure once started.

How do the different control parameters control the transients? The current paper reports measurements of the initial and final transients using a playing machine. Blowing

pressure P , lip force F_{lip} , and the initial tongue force F_{tongue} are controlled and held constant over a range of different values to measure their effects on r , the exponential increase in the fundamental of the sound. The motion of the reed and tongue are recorded on high-speed video to determine the acceleration a of the tongue and to study the growth over time of the amplitude of the reed vibration. The role of tonguing in playing within the hysteresis region was also investigated.¹

II. MATERIALS AND METHODS

A. Experimental setup

Figure 1 is a schematic of the experimental setup. The design and construction of the playing machine has been described previously (Almeida *et al.*, 2010). Briefly, the blowing pressure P is controlled on the long time scale by adjusting the speed of a pump which provides air to the artificial mouth and is kept constant on the short time scale by a proportional-integral-derivative loop controlling a leak, which is opened and closed using an electromechanical shaker. The instrument used in this study is a Yamaha YCL 250 clarinet with a Yamaha CL-4C mouthpiece (Yamaha, Japan) and a Légère synthetic clarinet reed (hardness 3, Légère Reeds, Ontario, Canada) with a tongue sensor, described below. A small slab of polyurethane foam (Sorbothane, Kent, OH) is used as the artificial lip. Over a large range of playing parameters, this lip can avoid squeaks and produce a tolerable sound. A mass hanging on the lip provides a known lip force to the reed. The masses used range from 25 g up to 400 g (the value that closed the reed against the mouthpiece), in steps of 25 g.

The artificial tongue consists of a pad of the same material as the lip. This is pushed vertically against the lip by a 2-beam system located above the artificial mouth so that the vertical force and acceleration of the tongue can be controlled. As shown in Fig. 1, a mass m_1 is located at the right of beam 1. Before the tongue is released from the reed, the weight of this mass provides the force that produces an initial displacement Δy_0 of the reed from its equilibrium position. Beam 2 with a mass m_2 on the right is located above and to the left of beam 1, with a vertical separation d . The tongue is lifted from the reed when the left of beam 2 is released by the experimenter. Different combinations of m_1 , m_2 , and d produce different tongue accelerations. With this system, the tongue force is always in the direction to close the reed aperture, and its acceleration in initial transients is always in the direction to open it. (However, the saliva on a human tongue allows it to pull the reed away from the mouthpiece.)

The reed and tongue motions are captured by a high-speed video camera (X-stream VISION™ XS-4, IDT, Pasadena, CA) at 8000 frames per second, which is a compromise between resolution in time and image size (180×140 pixels) and quality. With a light source located at the opposite side of the artificial mouth, the tongue and the reed can be clearly observed with a large contrast to the background (Fig. 1 inset). Thus, the motion of the tongue and reed over time is extracted by an automated image analysis routine that detected the averaged vertical position of several points along

B. Experimental protocols

Two different methods of controlling the tongue were used. The 2-beam, 2-mass system shown in Fig. 1 produces both a nearly constant tongue force F_{tongue} and a nearly constant acceleration a upon release. Therefore, it was used in the experiments in which these values were held constant and the blowing pressure P and lip force F_{lip} were varied to study their effect on initial transients.

The range of acceleration produced with different combinations of m_1 , m_2 , and d is limited, so beam 2 in Fig. 1 was removed when investigating the effect of tongue acceleration a at constant P and F_{lip} . The tongue force F_{tongue} , which determines the initial displacement of the reed Δy_0 , and the tongue acceleration a were both controlled by pressing the left end of beam 1 with a finger. This can produce a much larger range of tongue acceleration a than the 2-beam system. Learning to use a finger to produce a range of accelerations a was a little like learning tonguing when playing the instrument: the experimenter adjusted the force applied to achieve different tongue accelerations and listened carefully, using the sound as a guide to make the initial transients and therefore the accelerations as repeatable as possible. The initial displacement of the reed Δy_0 and tongue acceleration a were then calculated *post hoc* from the high-speed video images, and the series of measurements were continued until the desired range of values of a and Δy_0 had been recorded. In this series of experiments, several combinations of blowing pressure P , lip force F_{lip} , and mass m_1 were chosen and kept constant. After each tongue release, the tongue and reed motion were recorded by the high-speed video camera and the tongue-reed contact, blowing pressure P , the sound in the barrel p_{barrel} , and the radiated sound p_{rad} were recorded simultaneously.

The saturation at the end of the initial transient is not abrupt. So the exponential increase rate r was measured from the moment when the mouthpiece pressure first exceeded the background noise until it was 6 dB below saturation. (More details are given in Li *et al.*, 2016.)

To investigate the effect of blowing pressure P and lip force F_{lip} on the exponential increase rate r , tonguing parameters (i.e., a and F_{tongue}) were kept constant using the 2-beam system. The lip force F_{lip} was first set at a low, constant value and blowing pressure P was set to a constant value above P_{osc} . The tongue was released and tongue action, P , p_{barrel} , and p_{rad} were recorded. Then P was increased to the next sampling point for data acquisition and a similar procedure was repeated until P was above the extinction threshold P_{ext} . The lip force F_{lip} was then increased to a new constant value and similar procedures were repeated.

For the study on tonguing in the hysteresis region, P was initially set at the maximum value the pump can provide (about 7 kPa) and P , p_{barrel} , and p_{rad} were recorded. Then P was decreased to the next sampling value and kept constant for data acquisition. This procedure was continued until P was well below P_{osc} . In the next stage, P was increased in small steps until the blowing pressure reached its maximum value. In this pair of experiments, the artificial tongue never contacted the reed. Then, similar experiments with tonguing

while increasing P were carried out using the 2-beam system to activate the tongue. With a constant tongue force F_{tongue} , P was first set below the threshold P_{osc} and the tongue was released. Then the procedure was repeated with successive slight increases in P until P_{osc} was exceeded. Similar experiments were repeated, but with a different F_{tongue} . The lip force F_{lip} was then increased to a new constant value for the next set of measurements where data for decreasing P and for increasing P with and without tonguing were again recorded. Except during experiments, the mass hanging on the lip was removed to minimize changes in the reed properties due to any plastic deformation of the reed under load.

III. RESULTS AND DISCUSSION

A. The effects of tongue force and acceleration on initial transients

In this part of the study, the tongue force F_{tongue} was determined by the mass m_1 on beam 1 and the acceleration was controlled manually to produce a large range of accelerations. Figure 2 shows the reed and tongue motions, p_{barrel} and p_{rad} , for three typical examples of initial transients of the written C4 note played with the same P (4.6 kPa) and F_{lip} (1.5 N), but different tongue force F_{tongue} and accelerations a . $t = 0$ is the instant when the tongue ceased contact with the reed, detected by the tongue sensor. The tongue force F_{tongue} is 0.05 N for Figs. 2(a) and 2(b) and 0.15 N for Fig. 2(c).

The tongue force displaces the reed Δy_0 from its equilibrium position ($y = 0$) before oscillation begins. Δy_0 is approximately 40 μm for Figs. 2(a) and 2(b) and 80 μm for Fig. 2(c). The motion of the tongue near $t = 0$ shows an approximately parabolic shape. Thus, the tongue acceleration a during release was obtained by fitting a parabola over a distance range of 0.2 mm. Here, the acceleration a of these fitted curves for Figs. 2(a)–2(c) has values 0.27, 1.94, and 1.91 m s^{-2} , respectively, called small, large, and large in Fig. 2. The sound files and videos for this and other figures are available online (Music Acoustics, 2016) and also included as supplementary materials.²

Figure 2 shows that the trajectory of the reed and the tongue agree within one pixel before the tongue breaks contact with the reed, indicating that the reed's stiffness can accelerate it rapidly enough to maintain contact, at least for accelerations less than 1.9 m s^{-2} .

After tongue release, the time course of growth in reed vibration and sound are different for the different values of the initial displacement of the reed (produced by different F_{tongue}) and the tongue acceleration. Here $t_{200\text{Pa}}$ is defined as the time taken for p_{barrel} to reach 200 Pa (140 dB with respect to 20 μPa) after tongue release. The $t_{200\text{Pa}}$ values for Figs. 2(a)–2(c) are 77, 41, and 32 ms, indicating that vibration and sound start to increase earlier and reach higher values sooner after a larger initial tongue displacement Δy_0 and/or a larger tongue acceleration a .

The earlier start of the exponential rise with larger tongue acceleration and tongue force does not appear to be caused by the reed having a greater initial potential energy (due to larger Δy_0) or a larger kinetic energy when the reed reaches its equilibrium position after release (due to larger

a). In each case, the reed stops at its equilibrium position for several milliseconds after tongue release, thereby losing the potential energy associated with its initial elastic displacement and the kinetic energy associated with its motion as it follows the moving tongue. Instead, the effect of Δy_0 and a on the initial transient appears to be due to the rapid change in the air flowing into the mouthpiece: in Fig. 2(c), the initially closed reed channel opens and the reed returns to its equilibrium position in about 8 ms, producing a large change in the airflow. In Figs. 2(a) and 2(b), the reed channel is not completely closed before the tongue release; it opens and the reed returns in about 17 and 6 ms. p_1 , the amplitude of the first harmonic in p_{barrel} , shows a very rapid increase above noise levels that coincides with the action of tongue release, as shown in the insets of Figs. 2(b) and 2(c). This shows that large tongue acceleration a and/or large initial displacement Δy_0 of the reed can produce the immediate large change in p_1 of p_{barrel} . Similar sudden rises above noise in the p_1 in the barrel were also observed when human players performed accents (Li *et al.*, 2016). In both cases, however, it should be noted that, p_1 , the amplitude of the first harmonic in p_{rad} outside the bell, does not rise suddenly above the noise (bottom row of Fig. 2).

It is not surprising that the reed loses its initial mechanical energy: in the steady playing condition, the vibration of the reed is driven by the standing wave in the bore, which stores much more energy than does the reed. The playing frequency lies well below the natural frequency of the reed, which is close to that of the squeak that is feared by clarinetists. It is important to have enough loss in the lip (and perhaps the reed) to prevent oscillations at or near the natural frequency of the reed—playing a clarinet using teeth instead of a reed produces a squeak. None of the sound samples in this study show a brief oscillation near the reed frequency, and neither do those in the study of human players (Li *et al.*, 2016). The reed’s initial motion is not wasted, of course: the sudden change in airflow past the reed travels down the bore to the open tone-hole array, where it is reflected. It returns and interacts with the reed to start the exponential increase. We return to discuss regenerations and losses below using a simple model of auto-oscillation.

As the vibration of the reed grows, it quickly becomes asymmetrical as the reed approaches the mouthpiece. For the same tongue force F_{tongue} and initial displacement Δy_0 of the reed [Figs. 2(a) and 2(b)], the main difference in reed motion is that, for large a , the vibration starts sooner after tongue release. When there is both a large initial displacement Δy_0 and a large acceleration a [Fig. 2(c)], there is a further difference: the third harmonic rises abruptly above background and remains proportionally stronger during the rise in both reed motion and radiated sound. In the barrel pressure, the third harmonic is below the first by about 14 dB in Figs. 2(a) and 2(b) and 12 dB in Fig. 2(c). In the sustained part of the notes, however, the levels of the third harmonic are approximately equal at 86 dB. In the radiated sound, the sound level of the third harmonic is closer to that of the first because the bell radiates high frequencies better than low, so the effect is noticeable in the radiated sound. For the three cases shown in Fig. 2, the amplitudes of the fundamentals p_1 and the third

harmonics p_3 in the barrel all increase exponentially. The rate r of exponential increase of the fundamental is $475 \pm 20 \text{ dB s}^{-1}$ for all cases, indicating that (with constant P and F_{lip}), the tongue force and acceleration have little effect on r .

B. The effects of P and F_{lip} on initial transients

The study (Li *et al.*, 2016) using human players (who vary the blowing pressure P during transients) showed that the exponential increase rate r increased with increasing average P soon after the tongue release. That study did not measure lip force F_{lip} , which is also probably varied by human players. To investigate how r varied with P and F_{lip} under controlled conditions, tonguing was conducted using the 2-beam, 2-mass system, in which tongue force F_{tongue} and acceleration a were kept constant. For the experiments reported below, the tongue force F_{tongue} was 0.15 N and the acceleration a was $2.51 \pm 0.12 \text{ m s}^{-2}$.

After the tongue release, r can be negative as well as positive. When the blowing pressure is slightly below the oscillation threshold, the initial change in flow at tongue release and its reflections produce a sound with an exponential decay—a negative value of r . In this condition, although the reed provides some positive feedback, the power it injects is insufficient to overcome losses in the bore and lip (discussed below in Sec. III C). The barrel sound is a brief “pop,” giving the sensation of the pitch of the note corresponding to that fingering. A graph and sound file are included in the supplementary materials² and on the web site accompanying this paper.

Figure 3 shows the rate r versus P for different sets of lip force F_{lip} for the written C4 note. The $r(P)$ behavior is qualitatively similar for all F_{lip} : at low and moderate P , r increases with increasing P ; at higher P , r decreases and reaches zero at the extinction threshold. At the lowest F_{lip} measured (0.5 N), r has a maximum rate of 730 dB s^{-1} at a blowing pressure of about 5 kPa and the extinction pressure was beyond the range of the experiment. Because both blowing pressure P and F_{lip} act to close the reed against the mouthpiece, the extinction pressure decreases with increasing F_{lip} . The maximum value of the exponential increase

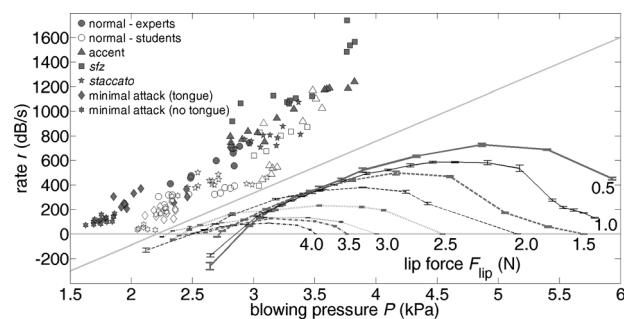


FIG. 3. Below the faint diagonal line are data showing the rate r of exponential increase in barrel fundamental frequency p_1 upon the blowing pressure P for different values of the lip force F_{lip} . For comparison, the data above the diagonal line were measured on human players (Li *et al.*, 2016) when using the different articulations indicated by the symbols. For the human data, the x axis is the average of the (varying) blowing pressure and the lip force is unknown and probably varying.

rate r is also lower for larger F_{lip} , and occurs at lower P : r is always less than 240 dB s^{-1} when F_{lip} is more than 2.5 N , producing a much slower increase in the amplitude of the fundamental during the initial transient.

For comparison, the data of r versus average blowing pressure P_{av} from the study using human players (Li *et al.*, 2016) are added above the diagonal line in Fig. 3. For the human data, the pressures shown are the average blowing pressure, because human players increase P during the initial transient. For any given P , the averages of these human data all lie above those of the present playing machine study: student players achieve higher values of r than the machine, and experts achieve higher rates still. As shown in Fig. 2 and above, r does not depend on the force or acceleration of the tongue. The most likely explanation for the low r using the machine is that the losses in the artificial lip are greater than those in human lips. A possible reason for this is that, as explained above, the material and geometry of the artificial lip were chosen to produce a tolerable sound without squeaks over a substantial range of P and F_{lip} . The lips of human players presumably have lower losses but clarinetists, especially experts, have sophisticated feedback mechanisms to avoid squeaks and have learned to play in restricted small areas of the (P, F_{lip}) plane. Finally, the human data do not show a negative $r(P)$ slope region, probably because there is no incentive for players to raise both P and F_{lip} into a region where $r(P)$ decreases.

Figure 4 shows the reed and tongue motions extracted from the high-speed videos using the method described in Sec. II A, as well as p_{barrel} and p_{rad} for four typical examples of initial transients of the written C4 note. These examples all have similar tongue acceleration a ($2.56 \pm 0.04 \text{ m s}^{-2}$) and initial

displacement Δy_0 (0.08 mm). The first three have constant lip force $F_{\text{lip}} = 2.0 \text{ N}$: they illustrate the effect of varying blowing pressure P , with values 2.91 , 3.65 , and 4.19 kPa in Figs. 4(a), 4(b), and 4(c), respectively. The effect of varying F_{lip} is illustrated by comparing Figs. 4(b) and 4(d), for which F_{lip} is 2.0 N and 1.0 N , respectively; P is 3.65 kPa for both. Again, the sound files and videos are available online and also included as supplementary materials.² From the sound files, differences in loudness and timbre are evident; there are also slight differences in playing frequency. [A previous study using the same playing machine (Almeida *et al.*, 2013) investigated in detail how the sound level, playing frequency, and spectral centroid of a steady note vary with different combinations of blowing pressure P , lip force F_{lip} , and other parameters.]

The rate r of the exponential increase in the fundamental of the barrel pressure p_{barrel} for the four examples shown in Fig. 4 is 210 , 365 , 345 , and 390 dB s^{-1} , respectively. This illustrates the dependence shown in Fig. 3: r increases then decreases with increasing P and also increases with decreasing lip force F_{lip} .

The growth of the third harmonic p_3 in p_{barrel} and p_{rad} during the initial transient is interesting. In all the examples in Fig. 4, the rate of increase for p_3 is larger than that for p_1 in p_{barrel} ; this difference is particularly noticeable for small F_{lip} . In Figs. 4(c) and 4(d), the amplitude of p_3 in the p_{rad} is several dB higher than that of p_1 for tens of milliseconds. This contributes to Figs. 4(c) and 4(d) having brighter, harsher sounding attacks than Fig. 4(b). Further, one can differentiate the transients more clearly when varying F_{lip} and P (Fig. 4) than when varying Δy_0 and a (Fig. 2) over the range studied here. The main difference among the sound files for Fig. 2 is the time taken for the sound to increase to a

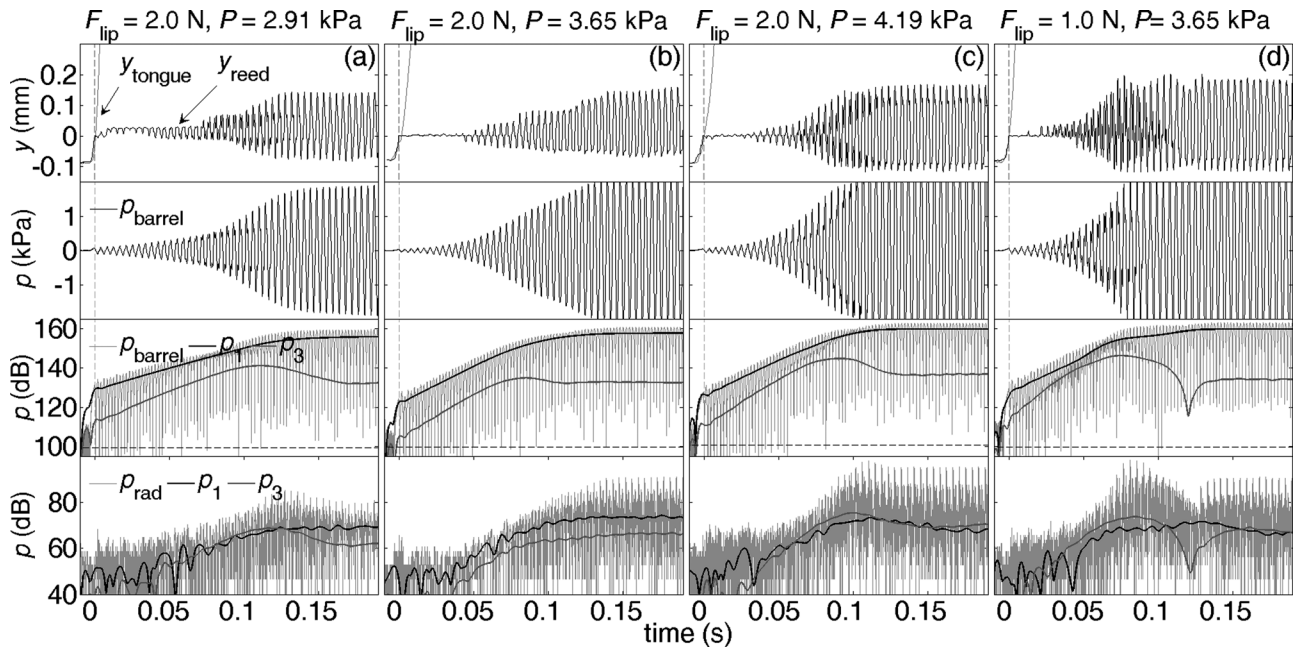


FIG. 4. As in Fig. 2, the top row shows the tongue and reed motion; the second row shows the barrel pressure p_{barrel} on a linear scale. The third and fourth rows show, respectively, on a log scale, p_{barrel} and p_{rad} , the pressure radiated by the bell, and the amplitudes of their first and third harmonics. Tongue acceleration and initial reed displacement are the same for all figures. (a), (b), and (c) illustrate the effect of varying blowing pressure P at constant lip force F_{lip} . Comparing (b) and (d) shows the effect of varying F_{lip} at constant P . The horizontal dashed line indicates the noise level in the barrel over the 0.1 s before tongue release at $t=0$.

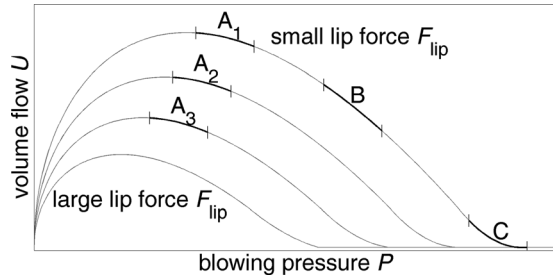


FIG. 5. A schematic plot of volume flow U versus blowing pressure P for different lip forces; after [Dalmont and Frappé \(2007\)](#).

given level from the instant of tongue release. However, this variation is not clearly audible in the sound files.

Some of the effects of P and F_{lip} on the rate of increase r could be qualitatively explained in terms of the dependence of volume flow U on P in the absence of a resonant bore downstream. Figure 5 is an idealised representation of such measurements made by [Dalmont and Frappé \(2007\)](#), following [Benade \(1976\)](#). At low P and for constant F_{lip} , U is approximately proportional to $P^{1/2}$ because the kinetic energy of the air flowing through the narrow aperture between the reed and mouthpiece is produced by the blowing pressure (then largely lost in turbulence downstream). At high P , however, increasing P tends to close this aperture and so $U(P)$ has a negative slope. A sufficiently high P or F_{lip} or a combination of these closes the reed permanently against the mouthpiece at an extinction point ($U=0$). Similarly, in the present study, high P , F_{lip} , or a combination of the two closes the reed and the $r(P)$ lines in Fig. 3 also reach the $r=0$ axis. [In a simple model in which the reed is treated as a one-dimensional spring with effective stiffness independent of F_{lip} and P , the descending $U(P)$ curve intercepts the $U=0$ axis with a finite angle. In reality, the curvature of the mouthpiece (Fig. 1) means that the length of the vibrating part of the reed decreases with increasing F_{lip} and P , making it stiffer and reducing the slope in $U(P)$, as was shown by [Dalmont and Frappé \(2007\)](#).]

Consider small oscillations in P and U at constant lip force F_{lip} , and neglect the inertia of the reed and losses associated with its motion. At low P , the slope of $U(P)$, which is the acoustic conductance of the reed excitation system, is positive and energy associated with the oscillation is dissipated. At higher P , the small-signal acoustic conductance $\partial U/\partial P$ is negative (while the static conductance U/P is always positive). In this regime, auto-oscillation with a resonant load is possible as steady power from the source of U and P is converted into acoustic power. The bore of the clarinet, the reed, and the lip all have finite losses, so one would expect auto-oscillation to commence when the average slope of the $U(P)$ curve is sufficiently negative (suggested by A_1 , A_2 , and A_3 in Fig. 5). With increasing F_{lip} (which tends to close the reed), the maximum in $U(P)$ falls at lower values of P . This helps explain the behaviour of $r(P)$ in Fig. 3 at low P : the value of P at which the experimental lines cross the $r=0$ axis decreases with increasing F_{lip} over most of the range of F_{lip} . (This model is quantified below.)

On the high P side of the curves, where $\partial U/\partial P$ is negative, the average slope becomes more negative with increasing P (B in Fig. 5). This helps explain the region of increasing $r(P)$ in Fig. 3. However, when the average P approaches the extinction threshold, the slope of $U(P)$ becomes less negative (C in Fig. 5). These observations help explain why $r(P)$ first increases with increasing P in Fig. 3 and then decreases as the extinction point is approached.

A similar series of experiments was also conducted on the written G5 note. The fingering for this note is like that of C4, except for the addition of the register key for G5. For this note, the curves for rate r versus P for different sets of lip force are qualitatively similar to those for C4, but with a smaller range of P and F_{lip} : 2.3 to 4.9 kPa and 0.5 to 1.75 N, respectively. For this note, the P values when r becomes positive (i.e., where $\partial U/\partial P$ becomes negative according to the simple model) vary only a little with varying lip force, a difference which is not readily explained by the simple model discussed above. This might be due to the fact that the inertia of the reed, which is not included in this simple model, is not negligible at high frequencies.

Players rarely begin notes without using the tongue. One likely reason is that the tongue gives greater control over the timing of the initial transient, and timing is a very important variable in music. The pulse in airflow produced by the tongue-induced reed motion initiates the exponential rise at a controlled time. The rate of the exponential rise is controlled independently by blowing pressure and lip force. The current study used constant blowing pressures and sustained notes were initiated at pressures above the threshold (sustained notes are not produced below the threshold). It is also possible to initiate a note by raising the pressure through the threshold value, which has been done in a playing machine study ([Bergeot et al., 2014](#)). In that case, the initial transient usually begins soon after the threshold pressure is passed, so that the initial exponential rise rate is not independently controlled. In one part of the study with human players ([Li et al., 2016](#)), players were asked to begin notes as softly as possible, with and without using the tongue. Without the tongue, expert players can approach the threshold smoothly, but there is greater variability in the time for the acoustic pressure to reach a given value. For notes played normally and with several different types of accents, players sometimes release the tongue slightly before reaching the threshold pressure, especially for higher notes. The human tongue can of course move in three dimensions. Further, it can pull the reed away from the mouthpiece using the adhesive properties of saliva, allowing the reed's stiffness to accelerate it toward the mouthpiece. However, as explained above, tongue action mainly determines the timing of the initial transients, and the size of the initial pulse in airflow, rather than the rate r of exponential increase.

C. A simple model for exponential increase

In this section, a simple model is proposed for the auto-oscillation of the reed and to explain the dependence of the exponential increase rate r on P and F_{lip} . For the early part of the transient, well before saturation, only the fundamental

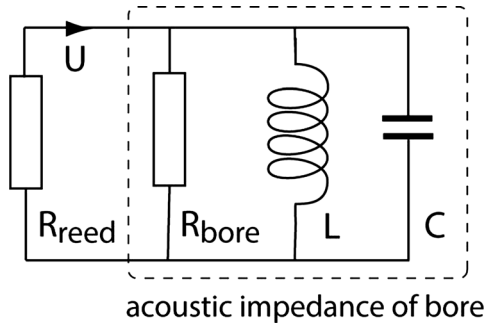


FIG. 6. A simple equivalent AC circuit model. The parallel elements inside the dashed border (L , C , and R_{bore}) are an empirical representation of the acoustic impedance Z_{bore} of the bore at frequencies near the peak at which the instrument plays. R_{reed} represents the small-signal acoustic resistance $\partial P/\partial U$ of the reed, which may be positive or negative, as shown in Fig. 5.

is considered. The instrument is assumed to play at a frequency near a peak of the acoustic impedance Z_{bore} of the bore. That peak is represented by the parallel resonance of a compliance C , inertance L , and resistance R_{bore} , as depicted by the elements inside the dotted border in Fig. 6. In this empirical model, R_{bore} is the (large) resistive impedance of the bore at resonance; R_{bore} , C , and L appear in parallel with the reed source. If the clarinet plays near a maximum in impedance of the bore, then the bore impedance at the playing frequency is almost completely resistive ($Z_{\text{bore}} = R_{\text{bore}}$) and the pressure and flow are in phase. This means that the reed can be represented as a resistance, R_{reed} . R_{reed} may be either positive, and thus dissipative, or negative, in which case it can produce positive feedback and auto-oscillation.

Taking p as the root-mean-square (RMS) acoustic pressure across all the elements in Fig. 6, the total energy stored in the compliance and inertance together is Cp^2 at any time. Averaged over an integral number of cycles, the rate of increase in the stored energy is therefore $2Cp \, dp/dt$. So conservation of energy may be written as power produced by reed source = power dissipated in bore + rate of increase in energy storage

$$-\frac{p^2}{R_{\text{reed}}} = \frac{p^2}{R_{\text{bore}}} + 2Cp \frac{dp}{dt}. \quad (1)$$

Writing the parallel resistance

$$R_{//} = 1/(1/R_{\text{reed}} + 1/R_{\text{bore}}).$$

Equation (1) becomes

$$\frac{dp}{dt} = -\frac{p}{2R_{//}C}, \quad (2)$$

which has the solution

$$p = p_0 e^{-t/\tau} \text{ where } \tau = 2R_{//}C = \frac{2R_{\text{bore}}R_{\text{reed}}C}{R_{\text{bore}} + R_{\text{reed}}}, \quad (3)$$

where $\tau = 2R_{//}C$ is the time constant.

If the reed aperture is shut (no flow), then the reed resistance is very large, so $\tau = 2R_{\text{bore}}C$ and the oscillation

amplitude decays exponentially with properties determined by the bore, as expected. However, when R_{reed} is negative and if also $|R_{\text{reed}}| < R_{\text{bore}}$, then τ is negative and the amplitude of the oscillation increases exponentially with rate (in dB s^{-1})

$$r = -10 \log_{10} e \cdot \frac{(R_{\text{reed}} + R_{\text{bore}})}{R_{\text{reed}}R_{\text{bore}}C}. \quad (4)$$

The threshold is predicted for the pressure P that gives $R_{\text{reed}} + R_{\text{bore}} = 0$.

If the clarinet plays at a frequency near that of its first impedance peak, then (for the parallel resonance circuit in Fig. 6) $R_{\text{bore}} \sim Z_{\text{peak}} \sim 80 \text{ MPa s m}^{-3}$ for C4 (Dickens *et al.*, 2007). The quality factor Q and the resonant frequency ω_0 of the R_{bore} , L , and C parallel resonance are related by $Q = \omega_0 R_{\text{bore}} C$. So $C = Q/R_{\text{bore}}\omega_0$. Using the values from Dickens *et al.* (2007), C is $0.21 \text{ mm}^3 \text{ Pa}^{-1}$. From Eq. (4), R_{reed} is a function of r which is in turn a function P and F_{lip} . So the data in Fig. 3 can be presented as $R_{\text{reed}}(P, F_{\text{lip}})$ in Fig. 7.

For sufficiently small oscillations, and in the absence of any losses associated with the vibrating reed and the lip in contact with it, R_{reed} , which is the AC value of $\partial P/\partial U$, would equal the reciprocal of the slope of the $U(P)$ sketched in Fig. 5, representing the quasi-static behaviour of the reed. The reciprocals of the curves in Fig. 7 can be integrated to give curves qualitatively similar to the corresponding regions of those in Fig. 5. The integration is not complete, however, because the measurements do not include pressures far below threshold or pressures that exceeded the range of the pump used. Qualitative similarities are also seen with the model of Dalmont *et al.* (2005), which uses a massless and lossless reed and lip, and a reed represented as a linear spring. The data in Figs. 3 or 7 can be used to estimate parameters in that model, but the present system differs from that simple model in several ways. Apart from the forces and losses associated with motion of the reed and lip, the curve in the mouthpiece on which the reed bends means that the spring constant varies as a function of P and F_{lip} . Further, the reed and the lip that moves with it have inertia. Finally, there are losses of energy associated with the motion of the reed and lip.

D. Tonguing in the hysteresis region

The effect of tonguing on hysteresis was studied for the written notes C4, G4, and G5. With all other conditions

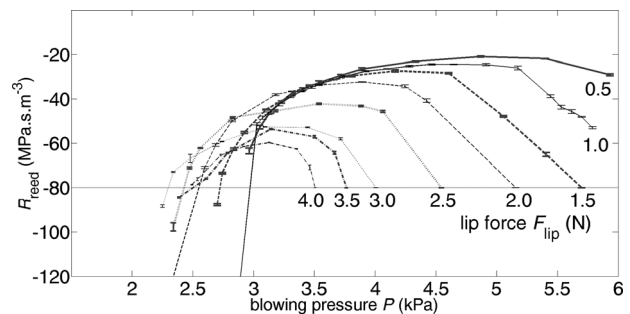


FIG. 7. The AC resistance R_{reed} as a function of blowing pressure P and lip force F_{lip} . The horizontal line indicates the threshold at $R_{\text{reed}} = -R_{\text{bore}} = -80 \text{ MPa s m}^{-3}$.

constant, the clarinet plays in a finite region on the (P, F_{lip}) plane. Here, Fig. 8 shows the measured plane for the written C4 note. Different shadings show whether the intended note or another note plays. For each lip force, the oscillation threshold (at low blowing pressure P) and the extinction threshold (at high P) are the values of P at which the radiated sound level drops to background noise level. (For both thresholds, P increases as the lip force decreases, thus showing negative slopes in the lines on the P, F_{lip} plane.) Both observations are consistent with Fig. 5 using an argument like that in Secs. III B and III C. Adjacent to these lines are hysteresis regions: areas in which the boundaries of the playing region are history dependent. At constant F_{lip} , and without tonguing, both the oscillation threshold and the extinction threshold are greater for increasing P than decreasing P . In practice, the hysteresis region on the low P side is more interesting to players and is related to initial transients, and so is further discussed here.

In Figs. 9(a) and 9(b), the amplitude of the fundamental p_1 obtained from p_{rad} is plotted against the blowing pressure P at two values of constant lip force: 2.0 and 1.0 N, respectively. The lines linking data shown with downward pointing triangles show measurements made as P was decreased; in this range, the sound level fell to the level of noise at $P = 2.52$ kPa for $F_{\text{lip}} = 2.0$ N. Three separate data sets show the results for increasing P . With no tonguing (upward pointing triangles), auto-oscillation is detected above the background noise when P rises above 2.87 kPa. For the smaller tongue force ($F_{\text{tongue}} = 0.1$ N), the sound level rises suddenly at P above 2.78 kPa and for the larger tongue force ($F_{\text{tongue}} = 0.15$ N), above 2.69 kPa. In Fig. 9(b), qualitatively similar behavior is shown for a different lip force, $F_{\text{lip}} = 1.0$ N.

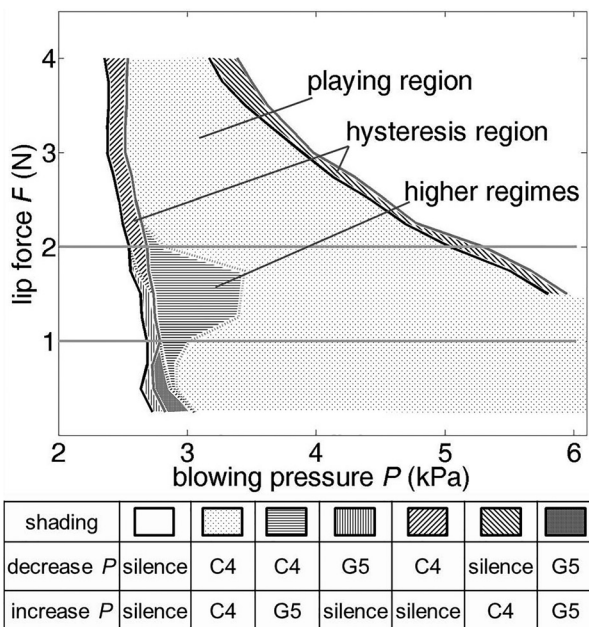


FIG. 8. Measured playing regions on the (P, F_{lip}) plane for the written C4 note. Solid dark and pale gray lines show the oscillation (left) and extinction (right) threshold for decreasing and increasing P , respectively. Different shadings indicate the different regimes.

The area around $F_{\text{lip}} = 1.5$ N and $P = 3$ kPa in Fig. 8 is interesting because, in the absence of tonguing, the wrong note can be initiated: G5 instead of C4, i.e., the instrument plays at the second peak in the impedance spectrum of the bore, rather than the first. Musicians could either avoid this region of (P, F_{lip}) , or else use appropriate tonguing. The difficulty of descending a 12th from the *clarino* register (e.g., from G5 to C4) without tonguing is well known to clarinetists. [The parameters used in Figs. 2 and 4 lie in the stable range of (P, F_{lip}) .]

The area of hysteresis leading to a wrong note varies among notes. For instance, it appears to be absent for the written G4 note in the throat register (Li *et al.*, 2014). For this note, the instrument plays at the first peak of the input impedance of the instrument bore (Dickens *et al.*, 2007), while the second peak is at about 1046 Hz (the written D6). For notes in the *clarino* register (whose fundamental lies near the second peak of the input impedance of the instrument bore), one could ask whether wrong notes whose fundamental corresponds to the first peak of the input impedance might be initiated. However, opening the register key to favor production of the *clarino* register not only detunes the first impedance peak, but also reduces its magnitude (Dickens *et al.*, 2007). For the written G5 note studied here, only a weak component near this detuned peak at about 280 Hz (close to the written Eb4) was observed in the sound with some combinations of P and F_{lip} , and it was not audible in the sound files. The (P, F_{lip}) plane for the written G5 note shows features similar to those shown for C4 and G4 above, but with a smaller and narrower range of lip force, from 0.5 to 1.75 N. In the hysteresis region at low P side

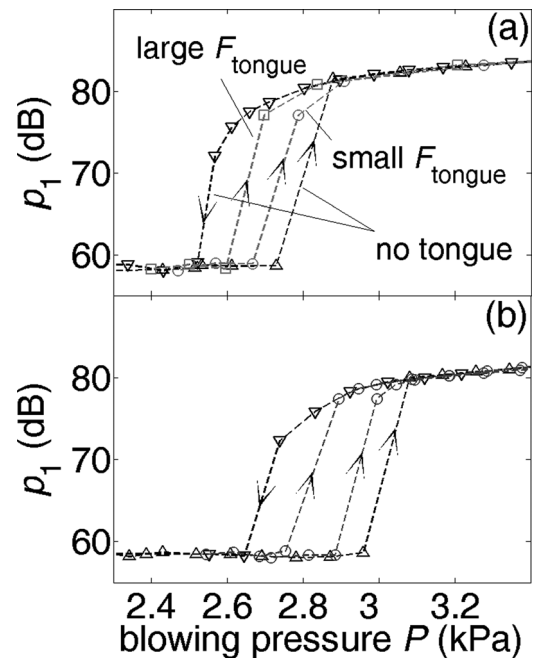


FIG. 9. (a) and (b) show the amplitude p_1 of the fundamental in the radiated sound p_{rad} versus P for two values of the lip force ($F_{\text{lip}} = 2.0$ and 1.0 N, respectively). P was gradually increased without tonguing (rightmost upward arrow) and decreased (downward arrow). Between these two lines lie data for increasing P , but with tonguing using two values of tongue force.

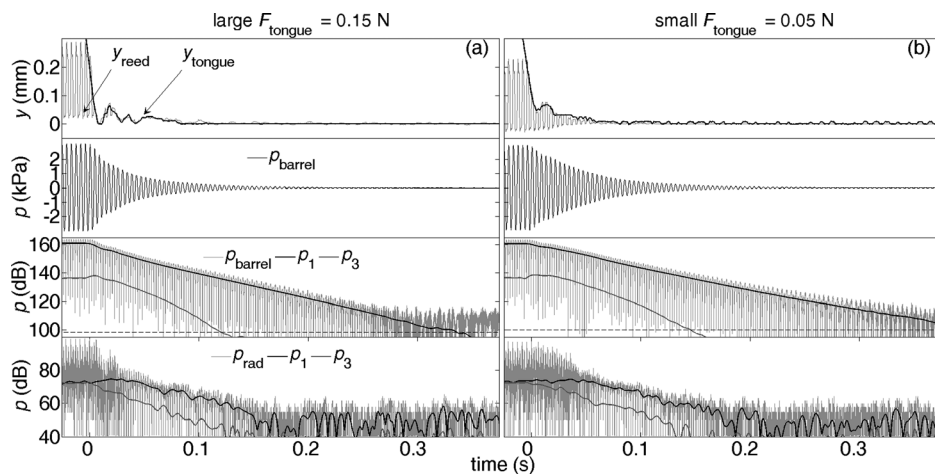


FIG. 10. The effect of tongue force on the final transient. Graphs displayed on the left and right correspond to large (0.15 N) and small (0.05 N) final tongue forces, respectively. The same blowing pressure P (4.6 kPa) and lip force F_{lip} (1.5 N) were used for all measurements. Figures at the top are for averaged tongue and reed motion, the amplitude (RMS) of the fundamental p_1 , and the third harmonic p_3 extracted from the barrel pressure p_{barrel} and the radiated sound p_{rad} , respectively, as functions of time.

(2.14–2.36 kPa), notes can be started with tonguing while increasing P .

These data show that tonguing can initiate auto-oscillation in the hysteresis region, and that larger F_{tongue} accesses a larger region of it. A likely explanation is that the abrupt movement of tongue and reed produces a sudden increase in the airflow U through the aperture into the instrument. In the region where auto-oscillation is possible, the resultant pulse travels down and up the bore and, being amplified on reflection at the reed, is the beginning of regeneration of the sound.

One implication of this figure for players is that they can end a note by playing *decrescendo* from a moderate value of P all the way down to the lower oscillation threshold. Further, the player can adjust the lip force as the threshold is approached. A second is that quiet notes can be started within the hysteresis region by using the tongue; increasing the tongue force, and therefore making a larger sudden change in the airflow, allows notes to be started at lower P .

E. Final transients using the tongue

In the previous study (Li *et al.*, 2016), student and expert clarinetists were found to use the tongue to stop notes in just one of the six types of articulations studied: *staccato*. This makes a qualitative difference: for a tongue-stopped note, the fundamental amplitude p_1 in the p_{barrel} shows a nearly exponential decrease in amplitude in the final transient immediately after tongue touch, whereas the final transient without tonguing includes the relatively slow reduction in amplitude while the blowing pressure falls to threshold level, followed by an exponential decay. In that study, the quality factors calculated using the exponential decay rates for each tongue-stopped note are similar to those calculated from the bandwidth of the peak in the impedance spectrum near which the instrument plays that note. This indicates that, for the notes stopped by human tongues, the decay rate is controlled chiefly by the passive acoustical properties of the bore, rather than by the players. In terms of the simple model, $1/R_{reed}$ is approximately zero in Eqs. (1) to (4), r is negative and $\tau = 2R_{bore}C$.

In the present study, final transients were studied for notes finished by letting the tongue fall with two different

known masses dropping 40 mm. This system generated known final resting tongue forces, but had the disadvantage that the tongue bounced on the reed before coming to rest.

Figure 10 shows the variations y in the reed and tongue positions, as well as p_{barrel} and p_{rad} for two examples of final transients with same blowing pressure P (4.6 kPa) and lip force F_{lip} (1.5 N), but different final tongue forces F_{tongue} of 0.15 and 0.05 N. After the bounces, nearly exponential decreases in the barrel pressure can be observed in both cases: the decay rate r is -185 dB s^{-1} and -135 dB s^{-1} for Figs. 10(a) and 10(b), respectively: the smaller tongue force provides the smaller decay rate (less negative r). For different blowing pressure P and lip force F_{lip} but constant tongue force F_{tongue} that is large enough to close the reed, r has similar negative values (order of -200 dB s^{-1}).

For this written C4 note, the rate r derived from the bandwidth of the measured acoustic impedance spectrum of the clarinet (Dickens *et al.*, 2007) is $-250 \pm 40 \text{ dB s}^{-1}$. The r values obtained in this study are smaller (less negative) than these values. One possible explanation is that the artificial tongue touching the reed with a small tongue force leaves a gap in the reed channel and does not completely prevent reed vibration, so that a small positive feedback partly compensates for the losses in the bore. Consequently, the parallel resistance of R_{reed} and R_{bore} is somewhat larger than R_{bore} because of the negative R_{reed} , which gives a larger time constant and a less negative r .

IV. CONCLUSIONS

Under the conditions studied here, the mechanical energy of the reed that is produced by tonguing is quickly lost. However, the sudden change in the aperture for airflow past the reed produces an acoustic current pulse in the bore. Over a limited area in the plane of blowing pressure P and lip force F_{lip} , successive reflections of this pulse interact with the reed to cause the amplitude of the fundamental in both reed vibration and bore pressure to grow at an exponential rate r . Different combinations of constant P and F_{lip} produce r values ranging from negative to $\sim 800 \text{ dB s}^{-1}$, which overlap with the lower range produced by human players. When the blowing pressure is above threshold, the

tongue action largely determines the timing of the initial transient, whose rate of exponential rise is determined independently by the blowing pressure and tongue force. For constant P and F_{lip} , varying tongue force F_{tongue} and tongue acceleration a have little effect on r values. However, a larger F_{tongue} and a (and the changes in the reed aperture and air flow that accompany them) cause the exponential rise to begin earlier. A larger F_{tongue} can produce a quicker growth of the third harmonic in the radiated sound during the initial transient, which affects the sound heard in the initial transient.

Tonguing can initiate notes within the hysteresis region on the (P , F_{lip}) plane where notes cannot be initiated by increasing P only. Notes can be started at lower P values if a larger tonguing force F_{tongue} is used.

Notes stopped by touching the reed with the mechanical tongue decay exponentially at a rate somewhat smaller than that calculated from the bandwidth of the corresponding impedance peaks. The rate of decay decreases as the tongue force decreases. A simple model for the small signal AC resistance of the reed source explains semi-quantitatively how P and F_{lip} control the exponential growth rate r .

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¹A report of a pilot study on tonguing in the hysteresis regime was presented at ICSV 21 (Li *et al.*, 2014).

²See supplementary material at <http://dx.doi.org/10.1121/1.4960594> for the sound files, high-speed videos of the examples in Figs. 2 and 4, and a graph and sound file showing an exponential decay in the sound after tongue release.

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