THE ACOUSTICS OF THE TROMBONE : HOW DO PLAYERS LIP UP AND DOWN?

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Four advanced trombonists and three beginners played the note B♭2 (the lowest normal note played with the slide retracted), then 'lipped up and down'. The normal playing frequency lies above that of the bore impedance peak, so the bore is a compliant load. However, the range reached while lipping is approximately centered on this peak. To investigate how the lip oscillation is regenerated with inertive or compliant acoustic loads, acoustic pressure and flow waveforms were determined both up- and downstream from the lips, while playing. The lip opening area and the flow component due to the lips' sweeping motion were also estimated using a transparent mouthpiece and high-speed video. The lips move forward before separating, then backward before closing. Consequently, the acoustic flow into the mouthpiece becomes positive before the lips open. Further, the volume V of air swept by the lips in the direction of the flow is positive around one cycle. A model in which the lips execute out-of-phase simple harmonic motions in the forwards and vertical directions is consistent with the results. The pressure difference ΔP across the lips does nett positive $\Delta P dV$ work on the lips, providing sufficient energy for regeneration of the oscillation. As the note is lipped down to inertive load, the phase of the mouthpiece pressure moves ahead of that of the flow, and ΔP moves further ahead of the volume of air swept in the horizontal direction. The latter effect decreases $\Delta P dV$ work, so, for very inertive loads, the oscillation stops. Lipping upwards is limited partly because negative mouthpiece pressure must always overlap largely with the lips being closed, and the limited magnitude of sweeping flow limits the extent to which flow can lead the lip aperture. Consequently, further increases in lip stiffness produce jumps to the next impedance peak.

Keywords: brass instruments, lip motion, pitch

1. Introduction

In brass and other lip-valve instruments, the player's lips usually vibrate at a frequency slightly above a peak in the acoustic impedance spectrum $Z_{\text{bore}}(f)$ of the instrument bore, measured at the mouthpiece. Nevertheless, by changing playing parameters, they are able to 'lip up and down' so as to play over a range of frequencies from above this peak (a compliant load) to below (inertive). To understand lip

vibration and the effect of up- and downstream acoustic loads, it is helpful to know the phase and magnitude of $Z_{bore}(f)$ and $Z_{mouth}(f)$, of the acoustic pressures $p_{bore}(t)$ and $p_{mouth}(t)$, the airflow $U_a(t)$ between the lips and that due to the sweeping motion of the lips $U_{sw}(t)$. The motion of the lips, the total upstream pressure P_{mouth} and the total flow U are also important. Here we report measurements of all of these quantities for lipping up and down. Seven players were observed and their general results are discussed but, in this preliminary study, the results for only one of the players are analysed in details.

Previous studies of lip-valve instruments have focused on lip motion, e.g. [1-7]. We have previously studied lip motion and related it to the up- and downstream AC and DC pressure and flow components [8], but that study considered only normal playing pitch. Here we apply these techniques to notes lipped up (where the load is even more compliant) and down (inertive). The ways in which an auto-oscillating valve adapts to acoustic loads with large phase differences can be expected to give insights into its basic mechanics.

2.   Materials and Methods

The instrument and mouthpiece used in the previous study (a Yamaha trombone YBL 321, [8]) are used with the slide in the contracted position. Players played B♭2, whose nominal frequency at A440 is 117 Hz, but 'lipped' it over the range 100 Hz to 125 Hz, which is approximately four semitones.

Z_{mouth} was measured during playing as reported previously [6]. The impedance head comprised two small cylindrical ducts glued together. One duct connected to a pressure transducer (8507C-2, Endevco, CA) and preamplifier connected to a FireWire audio interface (MOTU 828, Cambridge, MA) (see Fig. 1). The second delivered a sound current source comprising a sum of sine waves from 50 to 1000 Hz with spacing 0.67 Hz. The impedance head was calibrated with an acoustically infinite duct [9]. The pressure transducer signal was modulated to preserve its DC component and later demodulated. With no injected sound signal, this transducer measured the mouth pressure. Mouthpiece pressure was measured with a similar transducer.
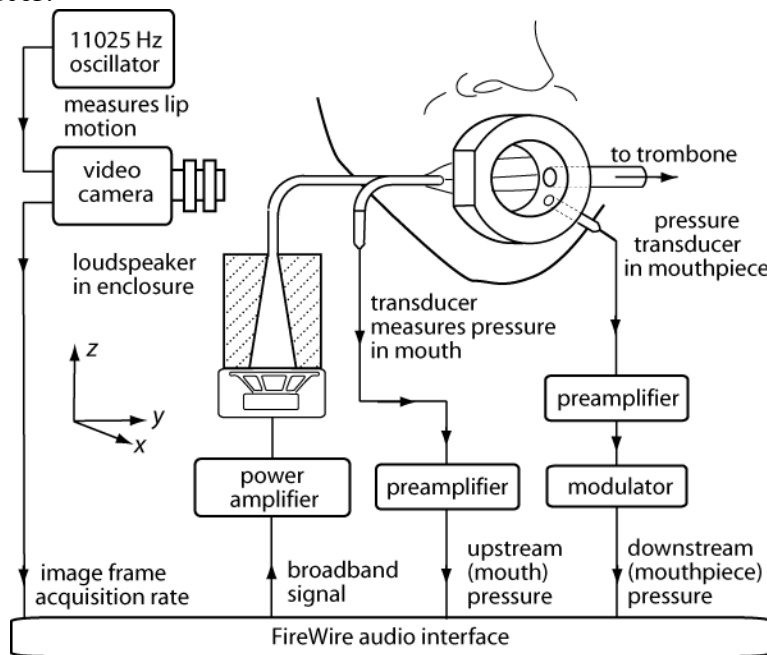

Figure 1: Schematic of the experiment (not to scale).

In separate experiments, measurements of Z_{bore} were made as a function of time 3 s after players had been playing a cool dry instrument for 10 s (to simulate conditions in the experiment) and extrapolated by linear regression back to the time at which playing stopped.

A high-speed camera (X-stream VISION™ XS-4), synchronized with the interface, recorded (x, z) images directly through the window from the side of the lips and (y, z) images opposite the lips via a mirror parallel to z and at $-45\,°$ to x (Figs 1 & 2).
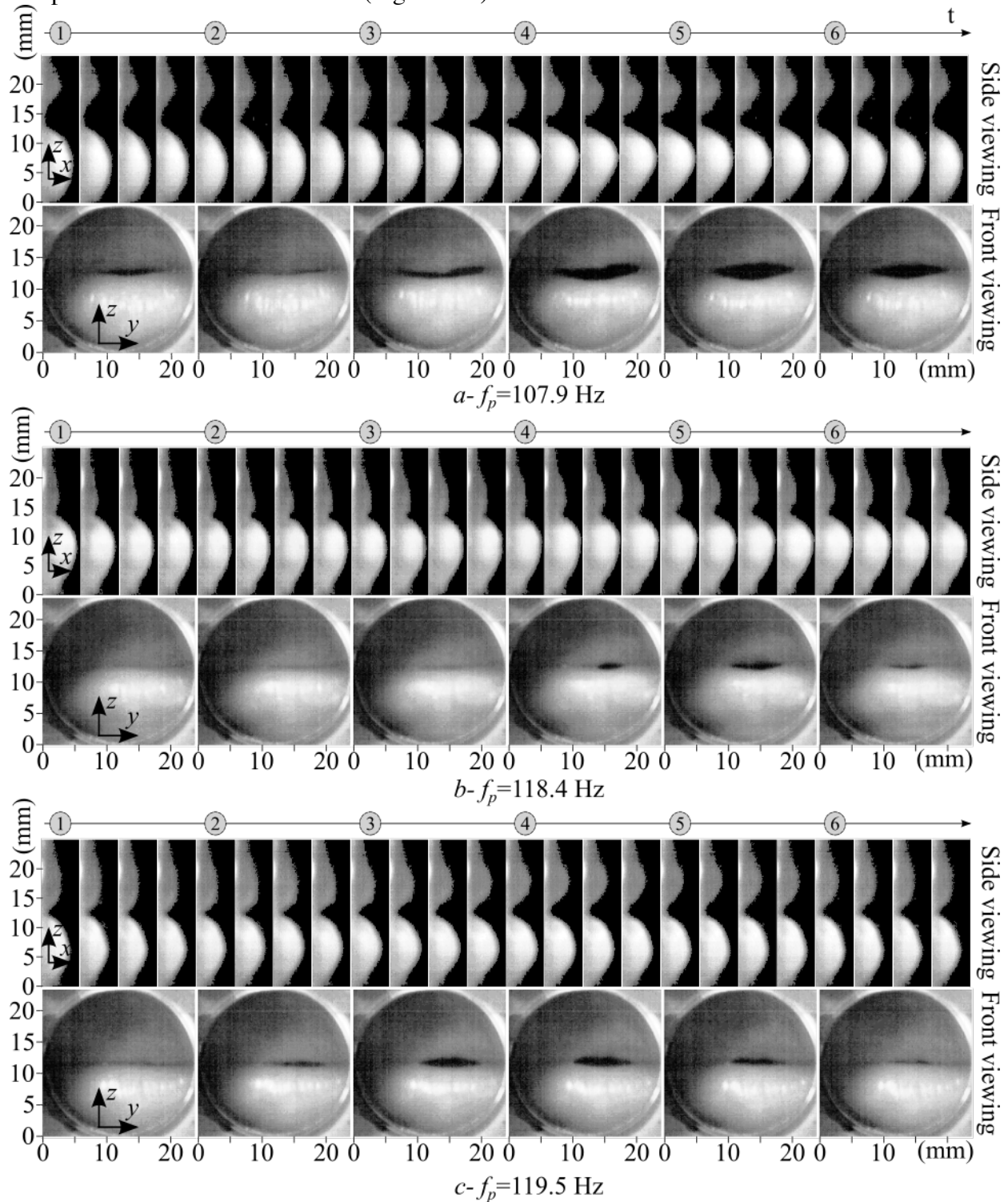

Figure 2. Twenty four equally spaced stills of side views (x,z) and six equally spaced front views (y,z) from one cycle of the videos of lipping down (top), normal playing (middle) and lipping up (bottom). The numbers above indicate the side views that are simultaneous with each of the front views.

Seven players were measured: four advanced and three beginners. The advanced player analysed in this study initially spent several minutes becoming familiar with playing the instrument, positioning the impedance head and triggering measurements. For measurements, he began by playing a note sharp and then lipping it up as far as he could without 'jumping' to the next resonance. After a few seconds and when satisfied with the stability of the new pitch, the player pushed a switch, which started recording of images by the camera. Later, the player started with a note played flat and lipped down as far as possible. The instrument was dried with compressed air between each measurement.

Following [8], the total acoustic flow is calculated by dividing the acoustic pressure measured up- and downstream by the mouth and bore impedances respectively (all quantities complex, of course). The total flow swept by the motion of the lips is calculated from the shapes of the lips in each camera frame; this is discussed further below. The difference between the total flow and the sweeping flow is the flow through the lip aperture. When the lips are closed, the aperture flow is zero, so the total flow is equal to the sweeping flow. This identifies the DC flow; a constant value to add to the total acoustic flow, to minimize its difference from the sweeping flow while the lip aperture is closed.

3. Results and discussion

Figure 2 shows still images for one cycle for each of lipping down, normal and lipping up of B♭2. In the side view (x, z), x is the longitudinal displacement and z the vertical; the lower series shows the front (y, z) view through the main mouthpiece lens, including the aperture between the lips.

The images show that the x motion leads the z motion in phase: the first few (x, z) images show that the lips move forward into the mouthpiece while closed; later images show that most of the opening of the lip aperture occurs while they are displaced forward and the last several in the series show that most of the closing occurs either during the end of the lips' retraction or while retracted against the teeth. Similarly, the volume V_{lip} of lip tissue in the mouthpiece is ahead in phase of the aperture between the lips. Qualitatively, this is similar to reports of brass players' lips made (for normal playing) by Copley and Strong [2] and Yoshikawa and Muto [3].

Fig. 3 plots x_u, x_l and z_u over the cycle, where the x are the maximum longitudinal displacements of the upper and lower lips and z_u the maximum value of the aperture below the top lip. The phasor diagrams of Fig. 4 show magnitudes and phases of the fundamental component of eight waveforms: mouthpiece pressure P_{bore}, ΔP across the lips, total acoustic flow U_{ac}, longitudinal sweeping flow U_x, opening area, and the x- and z-displacements of the lips. The length of each line corresponds to the magnitude of the fundamental; its angle relative to the horizontal axis shows the phase difference with the mouthpiece pressure, chosen as a reference. (For lipping down, $U_x > U_{\text{ac}}$ at the fundamental frequency, but the positive average flow means that aperture flow is unidirectional.)

ΔP is almost exactly at π with respect to P_{bore}; this is because mouth impedance is small, so the acoustic pressure in the mouth is much smaller than that in the bore. The total acoustic flow is 58° behind P_{bore} for the inertive load when lipping down, but ahead for the compliant load; 62° when lipping up and 59° for normal playing. The aperture is approximately in phase with P_{bore} for lipping up (0.2° ahead) and normal pitch (5° ahead) and 45° behind for down. The forwards position x of the leading lip is ahead of the aperture for lipping up and normal pitch, respectively 42° and 33°, and further ahead, 55°, for lipping down: as remarked above, the lips move forward before opening.
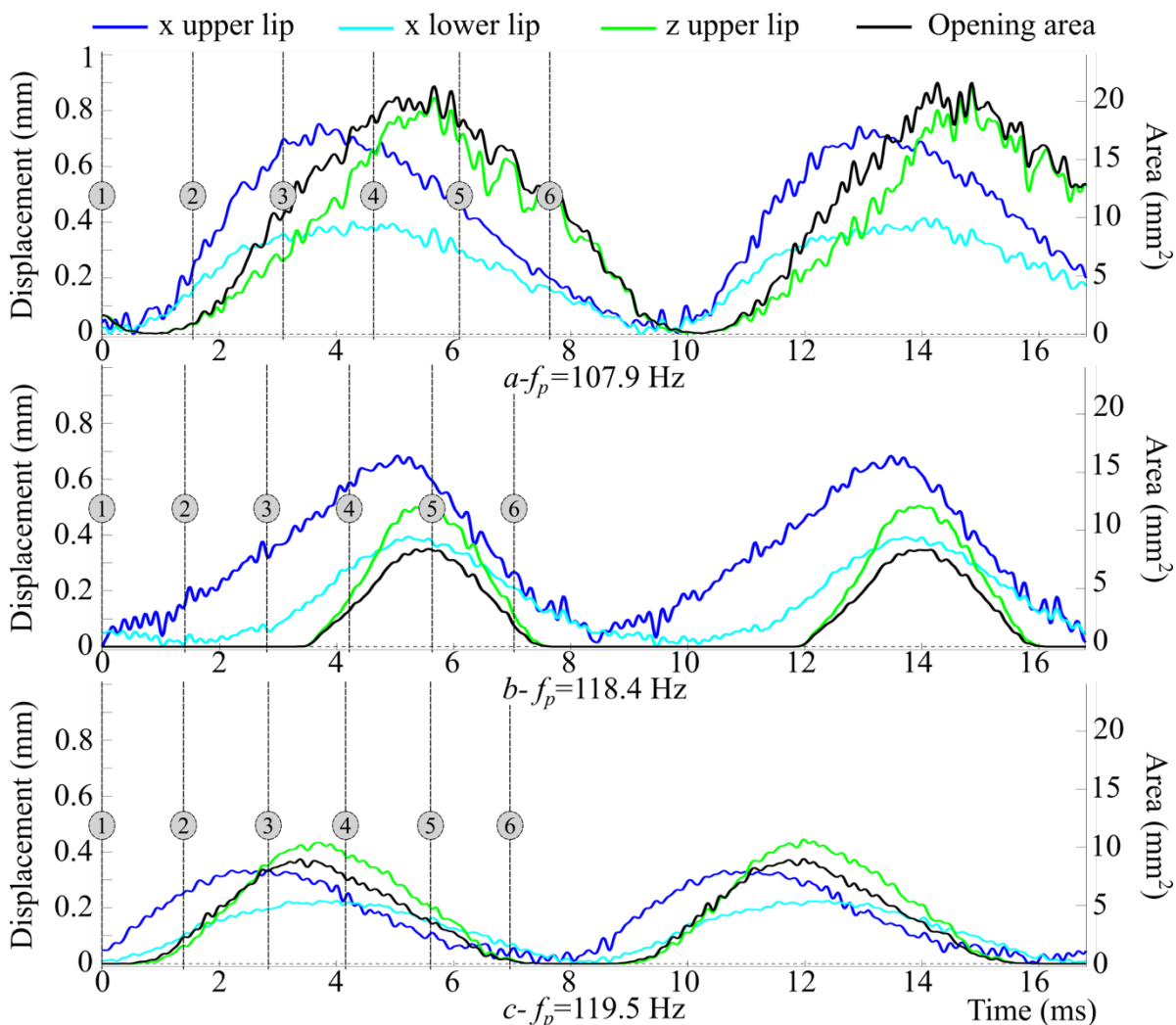
Figure 3. Plots of x (the maximum longitudinal displacement of the lips) and z_u (the maximum vertical displacement of the top lip relative to the aperture reference, where the lips separate) around two cycles for lipping down (a), normal playing (b) and lipping up (c). The circled numbers correspond to the front views of Fig.2.
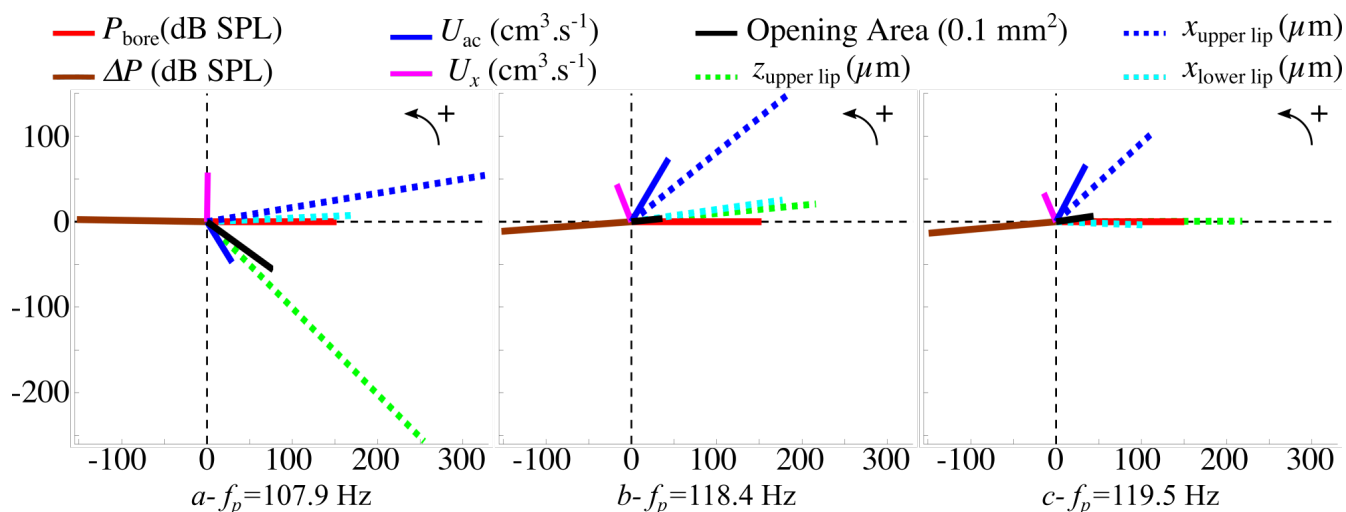

Figure 4. Phasor diagrams of the fundamental components for lipping down (a), normal pitch (b) and lipping up (c): mouthpiece pressure, acoustic pressure difference across the lips, total acoustic flow and longitudinal sweeping flow in the mouthpiece, longitudinal and vertical components of the lips' motion.

The aperture flow is a large fraction of total acoustic flow, so this limits how far its phase can differ from that of the lip aperture A (Figs 2-4). Because of the small upstream impedance, the pressure difference across the lips ΔP is almost in antiphase with P_{bore}. ΔP can easily be large when the lips are closed (and it accelerates them forwards). When the lips are open, ΔP can include a Bernoulli term, $i.e.$ a pressure difference $\sim \frac{1}{2}\rho v^2$ required to accelerate the air, plus small viscous losses. (At the low pitch considered here, the inertance of the air between the lips has little effect.) However, a large v with even a modest lip aperture requires a very large flow. So the fundamental of ΔP is roughly in antiphase with A. These two effects limit how far the phase of P_{bore} can be from that of U, Nevertheless, U is not sinusoidal and its maximum may occur early during the lip-open period, especially if the sweeping flow is large, or it may occur late. The large, short, negative pulse in P_{bore} must occur while the lips are closed, as observed in [8], but can occur early in that period (for lipping down) or late (for lipping up). These effects might constrain the range of lipping up or down. So might energy effects, which we now discuss.

The images, displacement curves and phasors in Figs 2-4 show that the x motion of the lips leads the z motion: the lips come forwards while closed and return towards the teeth while open. This phase difference is exaggerated a little in the simple diagram in Fig.5, which follows a model of Strong and Dudley [10] and Adachi and Sato [11], a model that treats the lips as swinging elastic plates.
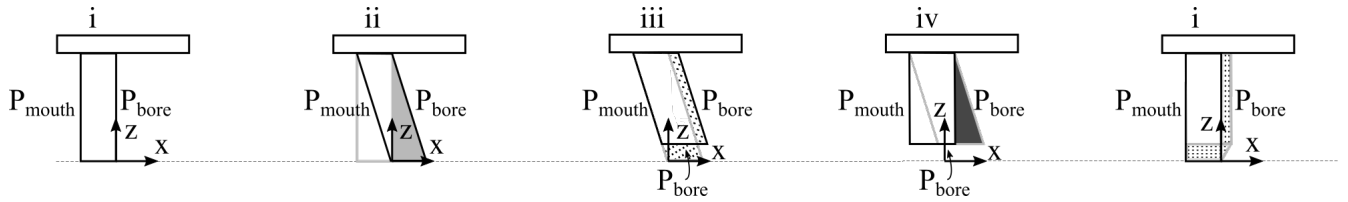

Figure 5. A simple model of the motion of the upper lip: the lower lip would be roughly symmetric below the dashed line. From (i) to (ii) the lip moves forwards (x direction) while closed. From (ii) to (iii), it contracts in the z direction. From (iii) to (iv) it retracts while open. From (iv) to (i) it closes while against the teeth.

For an approximate calculation, we assume that the pressures P_{mouth} and P_{bore} acting on the inside and outside lip surfaces respectively are uniform. The flow is assumed to be laminar in the channel between the lips but turbulent when it leaves the channel, so the pressure in the channel is P_{bore}, which is lower than P_{mouth}. Because the channel pressure is P_{bore}, there is no pressure-volume work associated with the changes represented by the dotted areas in Fig. 5.

As we argued previously [12], the pressure-volume work produced around a cycle by $P_{\text{mouth}} - P_{\text{bore}} = \Delta P$ can be positive. First, the DC component of ΔP does positive work around a cycle because the flow swept in the x direction $U_x = dV_x/dt$ is positive around a cycle, as shown by the difference between the light gray and the dark gray areas in Fig.5 ii and iv. Second, in cases where the phase difference between the AC components of ΔP and U_x lies between $-\pi/2$ and $+\pi/2$, this also gives positive work. Thus, it is necessary to distinguish the flow swept by the lips in the x and z directions.

The outside outline of the lips ($x(z)$) and opening aperture (in the (y, z) plane) are available from the video. For each measurement, the effective sweeping width L is estimated as the value which minimizes the difference between total flow and total sweeping flow, when the lips are closed. (This gives values between 13 and 16 mm, in a mouthpiece width of 23 mm, which is about what one would calculate if the lip x motion had an envelope with shape between sine and $\sin^2(\pi y/23 \text{ mm})$ across the mouthpiece). From the upper and lower limits of the aperture, effective upper and lower aperture limits, $z_{\text{top}}(t)$ and $z_{\text{bottom}}(t)$, were determined. The volume component $dV_x(t)$ swept by the lips in the x direction is:

$$dV_x(t) = L \left\{ \int_{z_{\text{top}}(t)}^{z_{\text{upper limit}}} \left(x(z,t) - x(z,t-dt) \right)dz + \int_{z_{\text{lower limit}}}^{z_{\text{bottom}}(t)} \left(x(z,t) - x(z,t-dt) \right)dz \right\} \qquad (1)$$

From this, the longitudinal sweeping flow $U_x = dV_x/dt$ is calculated, and the longitudinal sweeping work is $dW = \Delta P dV_x(t)$. As shown in Figs 2 to 5, the lips are closed when they move forwards and open when they retract. Hence the quantity $\oint dV_x$ round a cycle is positive: +37 mm^3 while lipping down, +7 mm^3 at normal pitch and +9 mm^3 while lipping up. In addition, the lips sweep air in the x direction before opening. Consequently, the longitudinal sweeping flow leads the total acoustic flow: by 147°, 52° and 51° for the three pitches. Therefore, this component of flow contributes to increase the phase of the total acoustic flow, relative to the mouthpiece pressure. We also note that U_x is about 90° ahead of the average x displacement of the upper and lower lips: 83° for lipping down, 96° for normal pitch and 93° for lipping up. This is because $U_x = dV_x/dt$ is proportional to the time derivative of x, as defined in (1).

Table 1: algebraic sweeping power and work done on the sweeping motion in one cycle, compared with an estimate of the lips' kinetic energy, for lipping down, normal pitch and lipping up.

		Lipping down (107.9 Hz)	Normal pitch (118.4 Hz)	Lipping up (119.5 Hz)
Longitudinal sweeping power	DC component	+42 μJ/cycle (+4.6 mW)	+12 μJ/cycle (+1.4 mW)	+9 μJ/cycle (+1.0 mW)
	AC component	-3 μJ/cycle (-0.3 mW)	+67 μJ/cycle (+7.9 mW)	+31 μJ/cycle (+3.7 mW)
Estimate of maximum kinetic energy of the lips		37 μJ	25 μJ	14 μJ

Table 1 gives the sweeping power for lipping down, normal and up, expressed in energy per cycle for comparison with rough upper estimates of the maximum kinetic energy of the lips: $K_m = mv_{xeff}^2 \cos^2(\alpha/2)$, where $m = \rho \pi R^2 T_{\text{lip}} = 2$ g is the mass of the lips, taking $\rho \approx 1000$ kg.m^{-3}, $\pi R^2 = 4.2$ cm^2 the area inside the mouthpiece rim, T_{lip} the lip thickness ~ 5 mm, and α, respectively equal to 55°, 34° and 42° for lipping down, normal playing and lipping up, is the phase difference between x and z. The peak effective x-velocity of the lip motion, is taken as the peak in the derivative of V_{lip}, divided by πR^2.

These rough estimates of maximum kinetic energy of the lips during a cycle (Table 1) are lower than or comparable with the sweeping energy gained by the lips during each cycle. Thus, even if the lip-teeth and lip-lip collisions were completely or largely inelastic, $i.e.$ all or nearly all the lips' kinetic energy were lost in that collision, the sweeping power delivered by ΔP would be large enough to replace it for the next cycle. (The collisions are expected to lose more energy than internal losses.)

Dividing ΔP into its steady and oscillatory components, $\Delta P = \overline{\Delta P} + \widetilde{\Delta P}$, we write the sweeping work, $W = \oint \Delta P U_x dt = \overline{\Delta P} \oint U_x dt + \oint \widetilde{\Delta P} U_x dt$. The first term (first line of Table 1) is positive because the steady component of ΔP and the sweeping flow $\oint U_x dt$ are both positive. The second term (second line of Table 1) depends on the phase difference between U_x and the acoustic pressure difference across the lips, $\widetilde{\Delta P}$. This phase difference increases as f decreases: 72° at 119.5 Hz, 73° at 118.4 Hz and 90° at 107.9 Hz; in the last case, it thus contributes negligible sweeping work (as in Table 1). At the limit of lipping down, this player increases the x motion and increases the phase difference between x and z motion. Thus, even with the mouth pressure at a similar value, the steady component of W increases. This keeps the total W comparable with the maximum kinetic energy of the lips, and hence maintains their oscillation.

4.   Conclusions and perspectives

Players normally played a little above the impedance peak, and so the bore is a slightly compliant load. However, the player in this study could lip down to have an inertive load, with P_{bore} leading U by up to 58° and with Z_{bore} at 57% of maximum, or lip up to have U lead P_{bore} by up to 62° and Z_{bore} at 35% of maximum.

For this player lipping up and at normal pitch, the steady and oscillatory components of ΔP provide positive work W on the non-zero sweeping flow $\oint U_x dt$. While lipping down, $\widetilde{\Delta P}$ is $\pi/2$ out of phase with the sweeping flow U_x, and only $\overline{\Delta P}$ contributes work. In all cases, the sweeping work exceeds or is comparable with estimates for the maximum kinetic energy of the lips. Thus, the simple model in Fig 5 explains the source of energy for regeneration. Let us model it as a simple one degree-of-freedom harmonic oscillator, whose x motion is driven by ΔP. To lip up, players increase the lip stiffness and hence the lip resonance frequency f_{lip}. This helps reduce the phase lag of x and hence U_x behind ΔP, and the oscillatory component of W rises. As players relax their lips, the resulting decrease of oscillatory sweeping work is compensated by the increase of its steady component, because ΔP is maximum around the peak of Z_{bore}. This allows players to lip down. As the lip stiffness further decrease, W eventually falls below the collision and internal losses, so the oscillation stops, or (for higher bore resonances) the playing frequency jumps to the next resonance below. Analysis of the results for all of the subjects, figures for the time variation of all variables and a further discussion of lip mechanics will be included in a paper with longer page limit.

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