Trombone lip mechanics with inertive and compliant loads ("lipping up and down")

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Running title: Trombone lip mechanics: 'lipping up/down'

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ABSTRACT

Trombonists normally play at a frequency slightly above a bore resonance. However, they can ‘lip up and down’ to frequencies further above the resonance (more compliant load) and below (inertive load). This was studied by determining the pressures, flows and acoustic impedance upstream and downstream and by analyzing high speed video of the lips. The range of lipping up and down is roughly symmetrical about the peak in bore impedance, rather than about the normal playing frequency. The acoustic flow into the instrument bore has two components; the flow through the lip aperture and the sweeping flow caused by the moving lips. Variations in the phases of each of these two components with respect to the mouthpiece pressure allow playing regimes loaded by bore impedances varying from compliant to inertive. In a simple model, this sweeping motion also allows the pressure difference across the lips to do work on the lips around a cycle. Its magnitude is typically about 20 times smaller than the work input to the instrument but of the same order as the maximum kinetic energy of the lips. In some cases, this sweeping work may therefore contribute most or all of the energy required for auto-oscillation. [*200 words, limit 200*]

I. INTRODUCTION

In models of lip oscillation for playing brass (lip-valve) instruments, the phase and magnitude of the acoustic impedance that loads the lips on the downstream side are important, and primarily determine the playing pitch. However, players of brass instruments can 'lip up' and 'lip down': in other words, they can adjust their lips and other playing parameters so as to shift the pitch significantly up or down without changing the configuration of the instrument. An understanding of how this is done requires knowledge of how the motion of the lips, the flow into the instrument and the pressures up- and downstream vary when lipping up and down. Measurements of these parameters form the basis of this paper. They are then used, in conjunction with a simple model, to show how the observed motion can provide the energy for auto-oscillation for both compliant and inertive loads.

The motion of the lips of players of lip-valve instruments has been studied by stroboscopy and high-speed video (*e.g*. Martin, 1942; Copley and Strong, 1996; Yoshikawa and Muto, 2003; Tarnopolsky *et al*., 2006; Newton *et al*., 2008; Bromage *et al*., 2010) and hardware lip models (*e.g*. Gilbert *et al*., 1998; Cullen *et al*., 2000). The steady pressure in the player's mouth (upstream) has been related to the downstream acoustic pressure in the instrument (Bouhuys, 1968; Elliott and Bowsher, 1982; Yoshikawa, 1995; Fletcher and Tarnopolsky, 1999). The acoustic impedance Z_{mouth} in the player's mouth has been measured during playing (Tarnopolsky *et al*., 2005; Chen *et al*., 2012). The acoustic pressures have been measured up- and downstream simultaneously (Fréour and Scavone, 2013). In a previous paper (Boutin *et al*., 2015), we have related lip motion to the up- and downstream impedance spectra, the acoustic and steady pressures and to the flow into the instrument, for playing at normal pitch.

Brass instruments are normally played at frequencies that slightly exceed those of the bore resonances and so the bore impedance Z_{bore} is compliant: the phase of the flow into the instrument leads that of the pressure in the mouthpiece. This phase is an important constraint in models of self-oscillating valves (*e.g*. Elliott and Bowsher, 1982; Fletcher, 1993). It is known, however, that the lipping up and down of brass instruments covers a range above and below the peak of Z_{bore} that lies near the playing pitch (Yoshikawa, 1995; Chen and Weinreich, 1996; Campbell, 1999; Eveno *et al*., 2014). Consequently, it is interesting to investigate the correlations among lip motion, up- and downstream pressure and flow for notes with either compliant or inertive loads. It is also interesting to know how the range of lipping up and down is distributed with respect to the frequency of the resonance that sustains the fundamental of a particular note.

In this paper the acoustic impedance upstream and the pressures up- and downstream are measured during playing and related to the flow into the instrument. Analysis of the motion of the lips then allows two components of the acoustic flow to be identified; the aperture flow through the lip aperture and the sweeping flow produced by the lips as they move into and out from the mouthpiece. This is done for normal playing and for lipping up and lipping down, covering a range in which the phase of the bore impedance changes sign and the magnitude changes considerably. These results are discussed in relation to a simple model for the lip motion that quantifies the energy input to auto-oscillation by the sweeping motion over the range of lipping up and down.

II. MATERIALS AND METHODS

A. The instrument.

The trombone (Yamaha YBL 321) and mouthpiece are those used in an earlier study (Boutin *et al*., 2015) with the B♭-F 'trigger' in the shorter configuration and the main slide all the way in. (This is called first position by trombonists, and used to play notes in a harmonic series, including the note B♭2, nominally 116.5 Hz, but which was 'lipped' to frequencies in the range 100 Hz to 125 Hz in this study). The tuning slide was always 18 mm from its shortest position (a typical position for playing at A440).

The original mouthpiece was replaced by a transparent one having the same volume and a similar rim. A shank with the same shape was inserted on the side, rather than the axis of the mouthpiece, so that the lips were visible from in front and from the side through plane glass plates. The previous study showed the pressure throughout the mouthpiece to be uniform to a good approximation, so a single pressure transducer (8507C-2, Endevco, CA, USA) measured the mouthpiece pressure near the rim.

B. The trombone input impedance

The input impedance of the trombone bore, $\cancel{Z_{\mathrm{bore}}(f),}$ was measured using an impedance head mounted in a plane plate that was sealed to the rim of the modified mouthpiece (Boutin *et al.*, 2015). An acoustic current source (Smith *et al.*, 1997) was located in the plane next to a microphone (4944A, Brüel & Kjær, Denmark) connected to a pre-amplifier and a FireWire audio interface (MOTU 828, Cambridge, MA). The impedance head was calibrated by measuring the impedance of an acoustically infinite duct, 142 m long and 7.8 mm diameter. The broadband signals used for calibration and measurement were sums of sine waves between 50 Hz and 1.0 kHz, with a spacing of 0.67 Hz (44.1 kHz/2^{16}). Measurements were conducted in a lab at temperature of 26.3 ± 0.3 °C and 55 ± 6% relative humidity.

The frequency and magnitudes of the peaks in impedance of the instrument depend on the temperature and composition of the air in the instrument bore. To determine their behavior during playing, the input impedance of the instrument was measured as soon as possible (within 3 s) after the instrument, initially at ambient temperature and flushed with dry air, had played a sustained note for 10 seconds. The impedance head was then connected and impedance measurements started. Each impedance measurement comprised 32 contiguous cycles of the measurement signal, each cycle involving 2^{16} samples at the sampling frequency of 44.1 kHz and consequently lasting 1.49 s. The frequency and magnitude of each impedance peak were then calculated for each cycle. The values at the moment when playing ceased (*i.e.* 3 s before the first cycle of measurement) were determined by linear regression over the following 32 cycles during the measurement period. These were used for the precise determination of the relation between the resonance and playing frequencies and for the determinations of acoustic flow.

The durations of the notes played in the lipping up and down part of this study varied from about 5 to 15 s, with extended pauses in between. For calculations in this study the values of Z_{bore} used are those extrapolated as described above from measurements made after 10 s of playing at normal pitch.

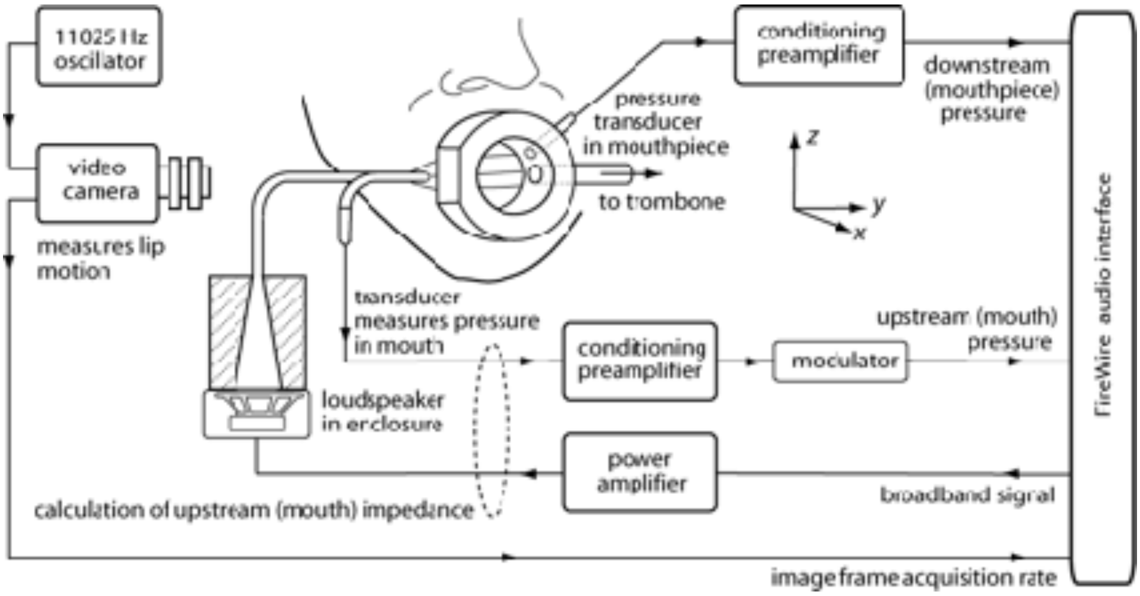

FIG. 1. Schematic diagram (not to scale) showing how the mouth and mouthpiece pressure, the upstream impedance and the lip motion were measured. For clarity, the trombone and the mirror at $-45\,^{\circ}$ are not shown.

C. Measurement of lip motion

The axis of the mouthpiece is horizontal, perpendicular to the face, and defined as the x direction; the y direction is also horizontal along the bore of the trombone and at right angles to x. The z direction is vertical, as shown in Fig. 1. A high-speed video camera (X-stream VISION™ XS-4 with Nikon Nikkor 35 mm f1.4 lens) is used to record (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 $-45\,^{\circ}$ to x. Image acquisition is triggered by input from a pulse generator at 11025 frames per second. The exposure time is 62 μs and the maximum length of each movie is 0.2 s.

For experiments, the player started playing a note at normal pitch and then either lipped up, lipped down or maintained the pitch. When satisfied with the stability of the playing frequency, typically after a few seconds, the player pushed a switch to start recording of images. The camera generated a square pulse corresponding to the acquisition of each frame; this signal was digitally recorded along with the pressure transducer outputs, which allowed the synchronization of images with the measurements of up- and down-stream pressures.

D. The impedance in the mouth and the up and downstream pressures

Z_{mouth}, the impedance in the player's mouth, was measured during playing as described previously (Tarnopolsky *et al.,* 2005; Chen *et al*., 2012). Two small parallel cylindrical ducts were glued together to make an impedance head with an oval cross section 4.8 mm $\times$ 7.8 mm. This was positioned to pass between the lips at the corner of the mouth (see Fig. 1). Players were asked to position the measurement end of the impedance head at the center of the mouth, between their upper and lower teeth. Players reported no difficulty in playing B♭2, lipping up and down while doing this. This arrangement locates the impedance measurement close behind the lips. One of the ducts was used to inject the current source and the other led to a pressure transducer (8507C-2, Endevco, CA). The current source is the sum of sine waves from 50 to 1000 Hz with spacing 0.67 Hz. This impedance head is calibrated using an acoustically infinite duct, having diameter 26 mm and length 194 m (Dickens *et al*., 2007). The acoustic pressure in the mouthpiece and that in the mouth measured by the pressure transducers in those locations were also recorded digitally. The mouth pressure signal was electronically modulated so that information on its slowly varying or DC component was not removed by the high-pass filtering in the audio interface. This signal was later demodulated during signal processing.

E. The players

Seven players participated in the experiment: four (called advanced players) had more than six years of experience in bands and orchestra. Of the other three (called beginners): two had orchestral and band experience on brass but had not played for several years. The last is the first author, who started playing the trombone for the purposes of this research project, 3 years before the measurements presented in this paper.

They were asked to play for as long as was necessary to become comfortable and to familiarise themselves with the apparatus. Then they were asked to play at normal pitch, for several repetitions. They were then asked to play a sharp, stable note (lipping up), raising the pitch as far as they could while sustaining a stable note, without 'jumping' to the next resonance. Then they played flat (lipping down) at different pitches. Between each set, the instrument was dried with compressed air at laboratory temperature.

F. Acoustic and steady flows and components

The flow U_{bore} into the bore of the instrument is the sum of two components; one is the flow through the lip aperture U_{ap}, the other is the sweeping flow U_{sw} produced by the motion of the lips, *i.e.* $U_{\mathrm{bore}} = U_{\mathrm{ap}} + U_{\mathrm{sw}}$. The aperture flow has a DC component ($\bar{U}_{\mathrm{ap}}$) and an acoustic component (u_{ap}). (Henceforth the DC components will be indicated by a capital letter with an overhead bar or macron, and the acoustic component by lower case). The sweeping flow U_{sw} is equal to the time derivative of the volume V of the lips inside the mouthpiece cup; this means that $\bar{U}_{\mathrm{sw}} = 0$. Thus

$$U_{\mathrm{bore}} = \bar{U}_{\mathrm{bore}} + u_{\mathrm{bore}} = \bar{U}_{\mathrm{ap}} + u_{\mathrm{ap}} + u_{\mathrm{sw}} \qquad (1)$$

The acoustic flow into the bore, u_{bore}, is calculated by dividing the spectrum of the mouthpiece pressure p_{bore} by the bore impedance spectrum Z_{bore} measured in the mouthpiece under playing conditions (both quantities complex), a technique described previously by Boutin *et al.*, 2015.

To calculate the sweeping flow u_{sw}, the vertical cross-sectional area A of the lips inside the mouthpiece cup is calculated from the side view of each video image. The volume V is then given by $V = A\,L$, where L is the effective width of the lips (assumed constant) in the horizontal (y) direction. (There are some similarities to the sweeping flow due to the motion of a reed (Dalmont *et al.*, 1995).)

During the phase when the lips are closed, there can be no aperture flow ($U_{ap} = 0$) and then $U_{\text{bore}} = u_{\text{sw}}$ - see eqn 1. Consequently, it is possible to determine the effective lip width L and the value of $\bar{U}_{\text{bore}}$, neither of which were measured directly. This involved a linear least-squares fit between the waveforms of u_{sw} ($= L dA/dt$) and U_{bore} $\left(= \bar{U}_{\text{bore}} + u_{\text{bore}} \right)$ during the period when the lips are closed. (The average value of L was 13 mm which is 0.56 times the inner width of the mouthpiece). The acoustic aperture flow u_{ap} (the component of the acoustic flow passing between the lips) is simply the difference between u_{bore} and u_{sw}.

G. Longitudinal sweeping flow

According to a simple model discussed later, the PV work done on the lips by ΔP, the pressure difference across the lips, depends on the longitudinal sweeping flow, *i.e.* the component of sweeping flow in the x direction. The displacement of the inner surface of the lips is not available, so the calculations of longitudinal sweeping flow must be regarded only as estimates. The upper and lower edges of the aperture $z_{\text{upper}}(y,t)$ and $z_{\text{lower}}(y,t)$ are used in a definition of the effective upper and lower heights of the aperture with respect to the position $z = 0$ of the aperture at the first frame of lip opening: these are given by $z_{\text{top}}(t) = \int z_{\text{upper}}(y,t)\,dy/L$ and $z_{\text{bottom}}(t) = \int z_{\text{lower}}(y,t)\,dy/L$. The component of volume displaced by the lips in the x or longitudinal direction during dt is then

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

(2)

where the upper and lower limits are the top and bottom of the image. Then, the longitudinal sweeping flow is defined as $U_x = dV_x/\mathrm{d}t$.

III. RESULTS AND DISCUSSION

A. Up- and downstream impedance, pressure and flow

The acoustic pressure difference across the lips $\Delta p = p_{\mathrm{mouth}} - p_{\mathrm{bore}}$ is given by $-(Z_{\mathrm{mouth}} + Z_{\mathrm{bore}})u_{\mathrm{bore}}$, where u_{bore} is the acoustic flow out of the mouth and into the bore and where p and Z are the acoustic pressures and impedances measured in the mouth and mouthpiece (subscripts mouth and bore) (Elliot and Bowsher, 1982; Benade, 1985). The magnitudes of the impedance peaks measured in the mouths of brass players are typically ~10 times smaller than those of the bore of the instrument, and the players do not tune these to the playing pitch (Chen *et al.*, 2012; Boutin *et al.*, 2015). Fréour and Scavone (2013) find that $|p_{\mathrm{mouth}}|/|p_{\mathrm{bore}}|$ can exceed one at the playing frequency, but mainly for high notes, where Z_{bore} becomes small. Consequently, in normal playing for the notes studied here, Z_{mouth} contributes little to the series impedance ($Z_{\mathrm{mouth}} + Z_{\mathrm{bore}}$) and thus little to Δp. For lipping up and lipping down by more than 10% in frequency, however, players are well away from the bore resonance so Z_{mouth} is a somewhat larger fraction of the series impedance at the playing frequency. Figures 2*a* and *b* show that Z_{mouth} is still several times smaller than Z_{bore} for playing frequencies around B♭2.

Z_{mouth} has a larger contribution for the next higher notes of the harmonic series: F3 and B♭3 (with nominal frequencies 174.6 Hz and 233.1 Hz for A440 tuning in equal temperament). Indeed, while the ratio $\left|Z_{\text{mouth}}\right| / \left|Z_{\text{mouth}} + Z_{\text{bore}}\right|$ remains below 20% around the peaks of Z_{bore} at F3 and B♭3, it reaches 41% while lipping up from F3 to 175.6 Hz, and 40% while lipping down from B♭3 to 216 Hz.

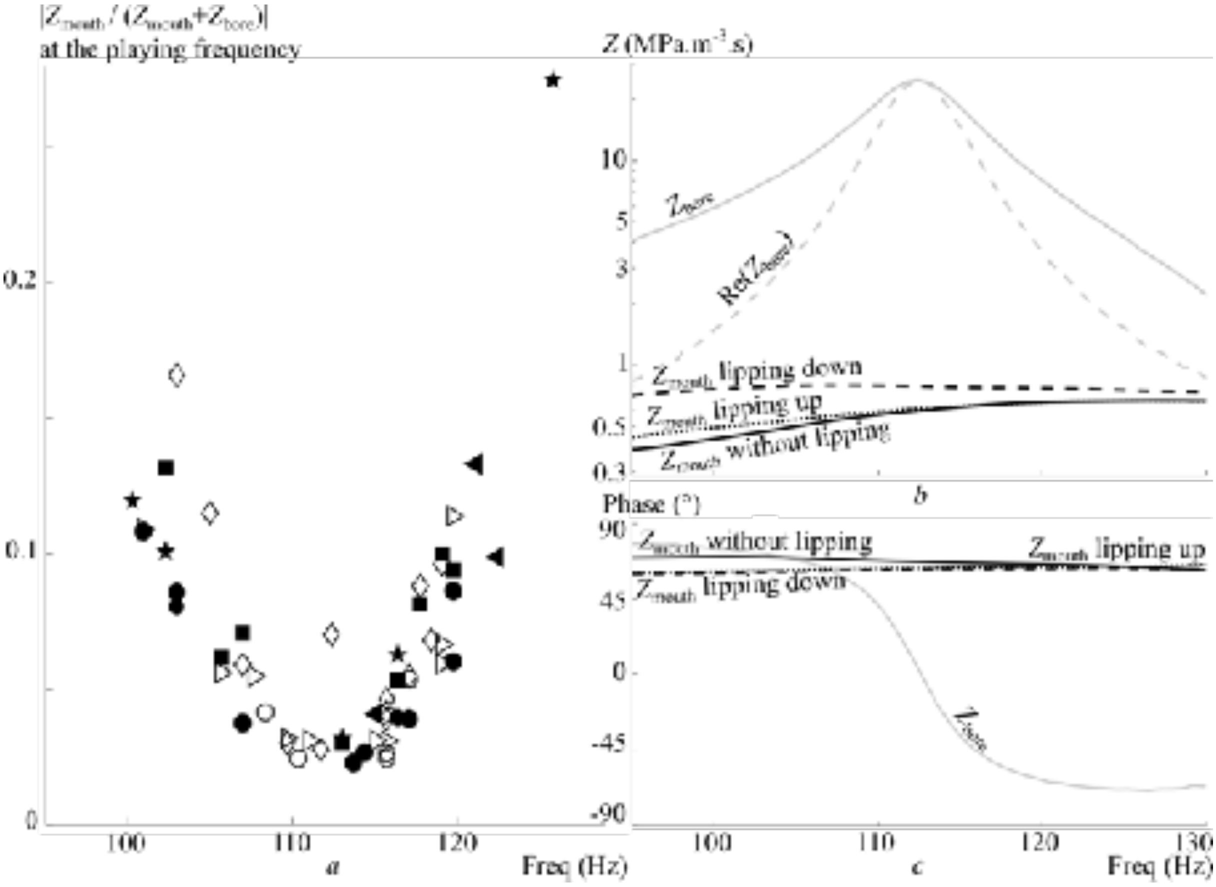

FIG. 2. *a*: (*left*) Impedance ratios $\left|(Z_{\text{mouth}}/(Z_{\text{mouth}} + Z_{\text{bore}})\right|$ at the playing frequencies near B♭2 (nominally 116.5 Hz) for the seven players. Each symbol shows one measurement. The open symbols correspond to beginners. (*right*) – Measured bore impedance (magnitude and real part (*b*), and phase (*c*) (gray curves) and mouth impedances (black curves) averaged for all players while playing at normal pitch (solid), while lipping down (dashed) and while lipping up (dotted).

The normal playing range is always on the upper (compliant) side of the impedance peak. However, players can lip up a little way from the normal range and can lip down over a rather larger pitch range. Thus, the range of lipping up and down is not symmetrical with respect to the normal playing frequency. Rather, Fig. 2 indicates that the lipping range is roughly symmetrical with respect to the frequency of the (nearly symmetrical) impedance peak.

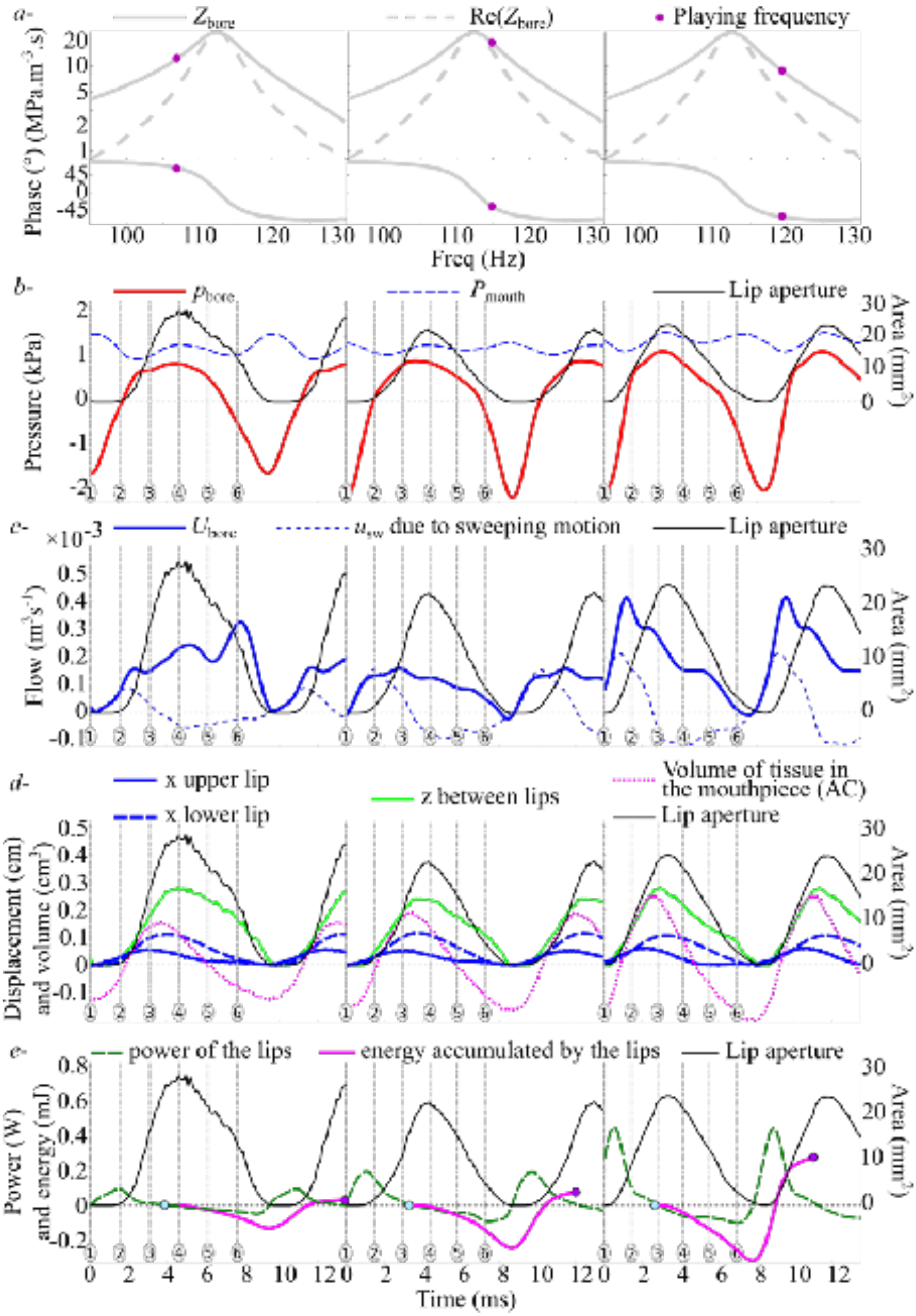

FIG. 3. <color online> Pressures, flow and lip motion for an expert player lipping down (left

column, 107.0 Hz), normal playing (center, 114.8 Hz) and lipping up (right, 119.3 Hz) for the note B♭2. The top row (*a*) shows the bore impedance, as well as the playing frequency (pink dots), the second row (*b*) shows the pressures up- and downstream, the third row (*c*) shows the total flow into the bore and the sweeping flow and the fourth row (*d*) shows the forward displacement of the upper and lower lips, the height of the aperture between them and the AC component of the volume of lip tissue in the mouthpiece. Using a simple model described below, the fifth row (*e*) shows the instantaneous sweeping power applied to the lips by the pressure difference and the integral of this quantity (the energy accumulated) during one complete cycle, starting from the pale blue circle on the left and ending at the purple circle on the right; both indicate instants when the power is equal to zero. This integral is the PV work supplied to the lip by the pressure difference and the sweeping action. For reference, the lip aperture is shown in all figures. Still images at the indicated points along this time axis are shown in Fig. 4.

Figures 3 and 4 show measurements on an expert player playing the note B♭2 normally and for lipping it up and down. (One column and three rows of Fig. 3 and two rows of Fig. 4 resemble Fig. 6 of Boutin *et al*. (2015), which only considered playing at normal pitch.) This confirms in detail some previous observations for normal playing and compares them with lipping up and down. First, u_{bore} (the acoustic flow into the mouthpiece and then into the bore) leads the mouthpiece pressure p_{bore} for normal and lipping up and lags it for lipping down: Z_{bore} is inertive for lipping down and compliant for the others. The actual playing frequency is related to the relative phase between p_{bore} and u_{bore} according to the complex spectrum of Z_{bore}. To achieve these phase relationships, players vary their lip properties and mouth pressure; the question is: how do they do it?

Figure 3 also shows that both the acoustic and the average flow are considerably smaller for normal playing, the latter observation being consistent with players' ability to sustain notes longer for normal playing.

B. Motion of the lips

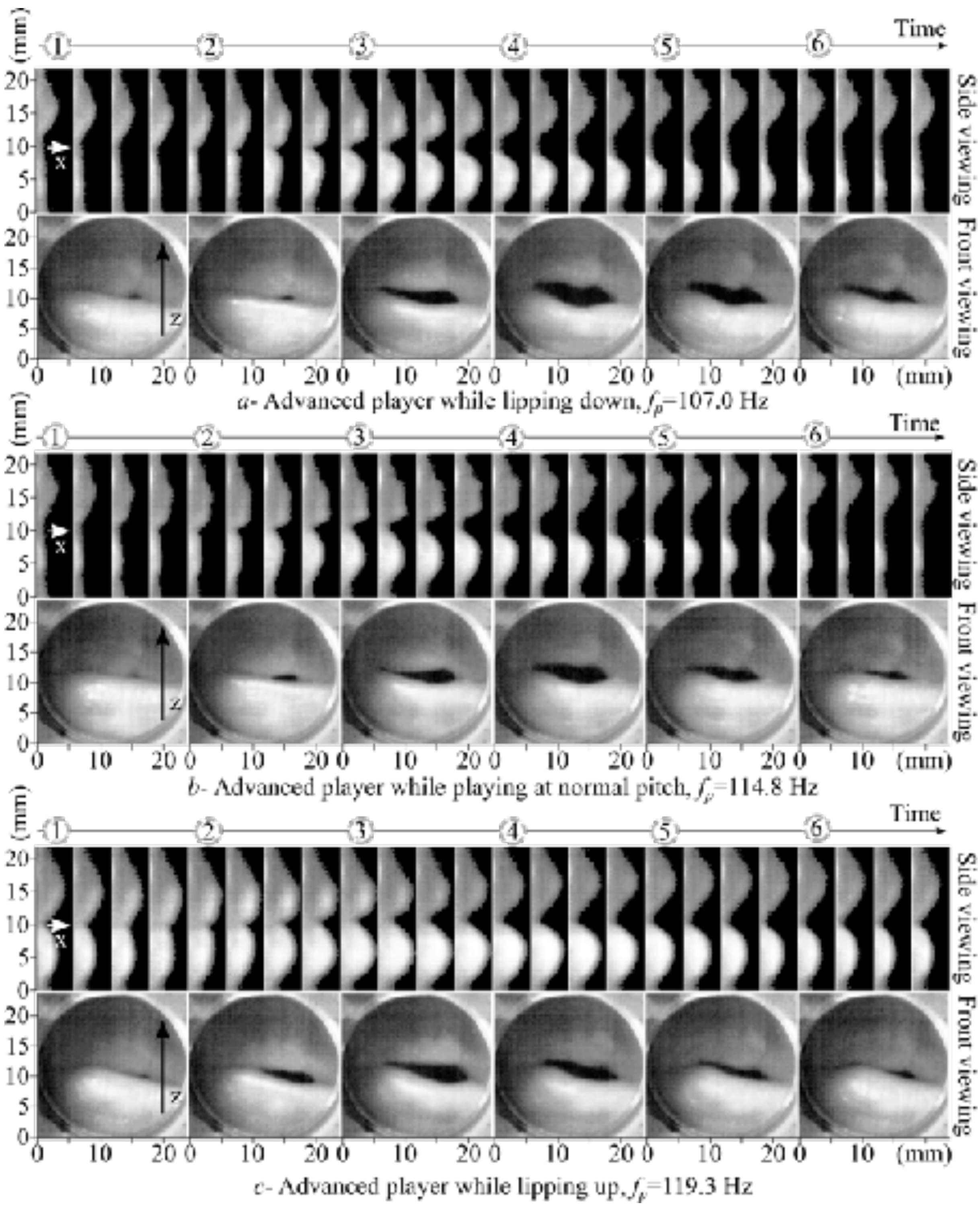

FIG. 4. Still images of the side (x, z) and front (y, z) views of the lips from the videos used for the data showed in Fig. 3: lipping down (top), normal playing (middle) and lipping up (bottom).

In Fig. 3*d*, $x_{\text{upper lip}}$ and $x_{\text{lower lip}}$ show the effective *x*-components of the displacement of the lips on the sagittal plane (the vertical plane of symmetry), estimated from the area of the lips in the side view, divided by their heights; $z_{\text{between lips}}$ is the distance between the highest and the lowest points of the aperture. The plots of $x_{\text{upper lip}}$ and $z_{\text{between lips}}$ in Fig. 3*d* and the images in Fig. 4 show that the longitudinal (*x*) motion leads the transverse (*z*) motion in phase, so that the lips begin to move forward into the mouthpiece while still closed, open while displaced forward, retract from the mouthpiece while open, and close when the lips are substantially retracted towards the teeth. For the same reason, the volume *V* of lip tissue in the mouthpiece leads the area of the aperture between the lips. Similar observations about the motion of brass players' lips for normal playing were made by Copley and Strong (1996) and Yoshikawa and Muto (2003). A quantitative analysis of this behavior and its contribution to maintaining auto-oscillation is given below.

In the present study, players produce auto-oscillation with loads varying from compliant (flow leads pressure) to inertive (pressure leads flow), and the phase difference by which flow leads pressure in the bore varies from about +69° to -75°. How is this range of phase difference between flow and pressure related to the motion and the mechanics of the lips? We begin with qualitative explanations of the data presented in Figs. 3 and 4 for one player; later in Fig. 5 the average data for the fundamental frequency is shown as a phasor diagram for all measurements and players.

For the notes studied here, the impedance magnitude of the vocal tract is small compared with that of the bore, so $p_{\text{mouth}} \ll p_{\text{bore}}$ (especially for normal playing, which is close to a bore impedance peak). So, because p_{mouth} is small, the acoustic component of the pressure difference acting across the lips in the longitudinal direction, $\Delta p = p_{\text{mouth}} - p_{\text{bore}}$, is proportionally little different from $-p_{\text{bore}}$ (this is quantified below). Figure 3*b* shows that the relatively short minimum in the mouthpiece (bore) pressure (corresponding to a maximum in Δp) coincides roughly with the period when the lips are closed, *i.e.* p_{bore} is roughly in phase with the lip aperture, which means that the pressure difference across the lips is large only while the lips are closed. (This is not as trivial as it might seem: the Bernoulli effect and the inertance and viscosity of the air between the lips could contribute to a pressure difference but, for this frequency and an aperture this large, these effects are small.)

Comparing Figs 3b and 3c shows that the interval between extrema in U_{bore} and p_{bore} varies considerably between lipping up and down. (Later we show that the average phase varies from +59° (up) to -55° (down) at the fundamental frequency of the note.) Equation (1) shows that U_{bore} is the sum of two different flows; the sweeping flow u_{sw} which alternates between positive and negative, and the (always) positive aperture flow U_{ap}. The phase difference between U_{ap} and p_{bore} will depend upon the detailed behaviour of Δp and the lip aperture.

The contribution of u_{sw} to U_{bore} makes a significant difference. In general, once the lips start to move forward into the mouthpiece, u_{sw} will start to make a positive contribution to U_{bore}, but U_{ap} remains zero until the lip aperture opens; at that moment U_{ap} starts to make a positive contribution. Eventually the lips will start to retract and u_{sw} then becomes negative. The relative timing of the events, lip advancing, lip opening, lip retraction and lip closing, can shift the relative phase of U_{bore} with respect to p_{bore}.

Thus, if the lips open whilst u_{sw} is increasing or near its maximum, u_{sw} will add to U_{ap} and bring the maximum in U_{bore} forward. If the lips open whilst u_{sw} is decreasing, the maximum in U_{bore} can be delayed; this effect will be much greater when u_{sw} is negative. The relative magnitudes of u_{sw} and U_{ap} will also be important in determining how their sum behaves.

For the lipping up example in Fig. 3, and with respect to the minimum in p_{bore}, the lips open slightly earlier than normal, which allows the flow through the aperture to increase earlier. The lips also start moving forward slightly earlier and faster than for normal. The larger magnitude of u_{sw} adds to U_{ap} during their increasing phases. Furthermore, the larger, subsequent negative value of u_{sw} as the lips retract opposes the contribution of aperture flow U_{ap} to the total flow U_{bore} while the lips are closing. In consequence, u_{bore} lags u_{sw} by a smaller angle than normal and continues to lead p_{bore}.

When lipping down, the aperture is larger, and begins to open later. The sweeping flow has smaller magnitude. In consequence, the positive increasing section of u_{sw} makes a smaller contribution towards u_{bore} while the lips are opening, and its subsequent negative section has less cancelling effect on u_{bore} while the lips are closing. Consequently, u_{bore} lags much further behind u_{sw}, and this contributes to p_{bore} leading u_{bore}.

C. Phases and amplitudes of the fundamental components

Comparison between the acoustic waveforms and the constraints imposed by the impedance of the bore can be improved by considering only their fundamental components. Figure 5 shows the amplitudes of the fundamental components of measured acoustic waveforms and the lip motion and their phase differences for 40 measurements on the seven players. They are gathered into three categories depending on whether players were asked to “lip down” (flat), to play at “normal pitch” (normal) or to “lip up” (sharp). The upper diagrams correspond to the averaged measurements for playing frequencies between 100 Hz and 112 Hz (Fig. 5a), between 112 Hz and 118.0 Hz (Fig. 5b), and between 116 Hz and 126 Hz (Fig. 5c). For each magnitude, the angle of the line corresponds to the phase difference relative to the mouthpiece pressure P_{bore}, chosen as the reference.

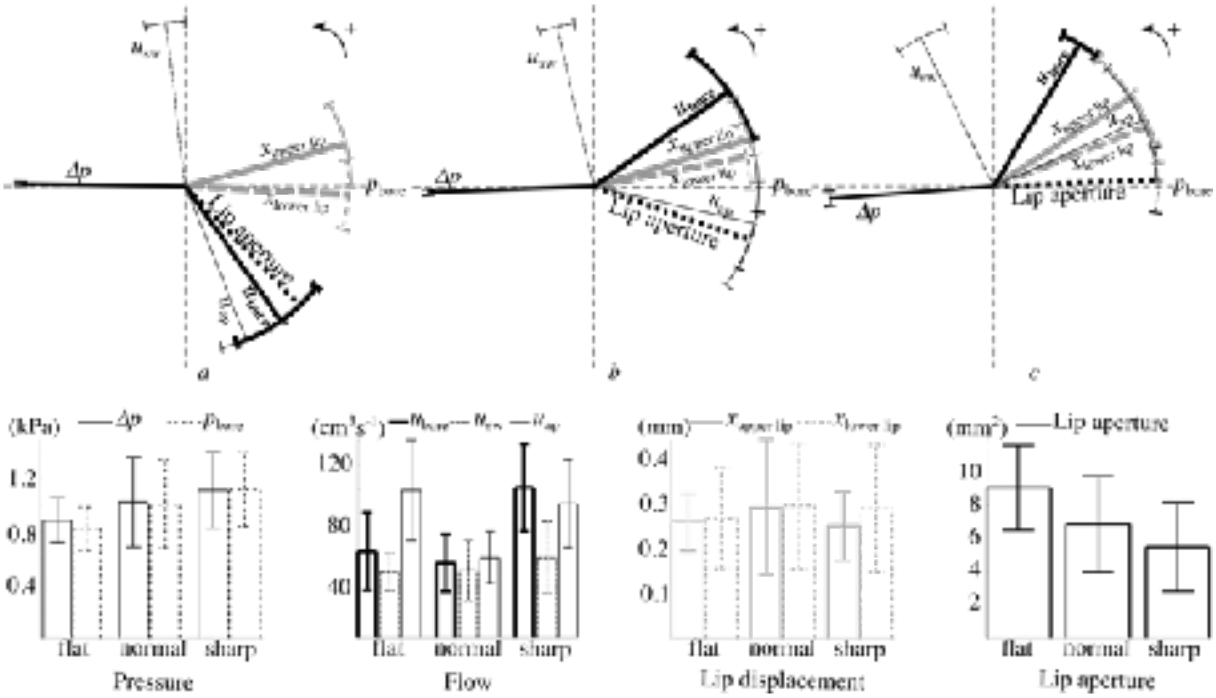

FIG. 5 Top: the phases of the AC components: u_{bore}, the acoustic pressure difference $\Delta p = p_{\mathrm{mouth}} - p_{\mathrm{bore}}$ across the lips, the sweeping flow u_{sw}, the aperture flow u_{ap}, the lip aperture and the x-component of the upper and lower lip motion. The angle between each line and the positive horizontal axis corresponds to the phase difference with respect to p_{bore}, which is chosen as the reference. Data are for all players while lipping down (a), while playing at normal pitch (b), and while lipping up (c). Bottom: average amplitude and standard deviation of each waveform while lipping down (left), playing at normal pitch (middle), and lipping up (right).

The phase difference between the mouthpiece pressure and the flow into the bore has large variations over all players and frequencies: averaged over all data, the mouthpiece pressure leads the flow by 55° while lipping down (inertive load), it lags the flow by 35° at normal pitch and 59° while lipping up (compliant loads). Some of this wide range of phase angles can be explained by altered timing of the lip aperture with respect to the lips moving forward. Here we will take the upper lip as the reference because the upper lip leads the lower lip in 68% of the notes played. In all cases the sweeping flow will necessarily lead the lip motion by around 90°.

When lipping up into compliant loads, the lips open relatively early after they start moving forward; the aperture lags 31° behind x_{upper} compared with 36° in normal playing. Consequently, the aperture flow u_{ap} occurs earlier (a lag of 9° behind x_{upper} compared with 30° in normal playing) and is now approximately in quadrature (92°) with u_{sw}. The vector sum $u_{\mathrm{bore}} = u_{\mathrm{ap}} + u_{\mathrm{sw}}$ is now larger than the individual values of u_{ap} and u_{sw} and leads the lip motion (x_{upper}) by 26°.

When lipping down (inertive load), the lips only open towards the end of their forward motion and the aperture lags x_{upper} by 61° compared with 36° in normal playing. The aperture flow u_{ap} thus occurs later (a lag of 74° behind x_{upper} compared with 30° in normal playing) when u_{sw} is already negative. u_{ap} and u_{sw} are now approximately in phase opposition (165°), but because $u_{\mathrm{ap}} > u_{\mathrm{sw}}$, u_{bore} will have a similar phase to u_{ap} (leads by 5°) and lag x_{upper} by 70°.

Changes in the timing of the lip aperture can thus significantly vary the phase of u_{bore} with respect to the start of lip motion. Lip motion leads p_{bore} by a similar amount for lipping down, normal playing and lipping up (15°, 17° and 33° respectively; Fig 5). Consequently, the timing of the lip aperture similarly affects the relationship between u_{bore} and p_{bore}.

D. Work done on the lips

In order to investigate how ΔP, the lip motion and their phase difference contribute to the lip oscillation, one component of the work done on the lips is estimated using a simple model to explain aspects of the auto-oscillation (Boutin *et al.*, 2014). It has been argued (Cullen *et al.*, 2000) that models with a single degree of freedom ('one mass one spring') cannot reproduce important features of the observed behavior of the lip-bore interaction.

Although the lip-bore-airflow interaction has strongly non-linear elements, some insights may be gained using a linear model for the lip, with two degrees of freedom (as demonstrated by Velut *et al*., 2017).

Following Strong and Dudley (1993) and Adachi and Sato (1996), the lips are treated here as plates that swing in the (x, z) plane and contract and expand along their vertical length. The motion of the top lip in that model is sketched in Fig. 6 for four instants in a cycle in which the bottom right corner executes sinusoidal oscillations in the x and z directions. Note that, as in Figs 3 and 4, the longitudinal (x) motion leads the transverse (z) motion, so that the lips move forward into the mouthpiece while still closed, open while displaced forward, retract from the mouthpiece while open, and close while retracted.

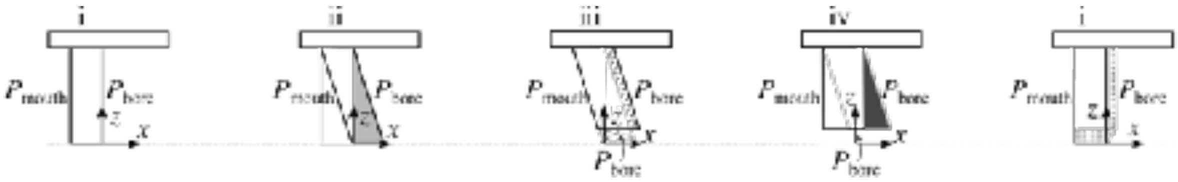

FIG. 6. Black lines show four instants during a cycle of a simplistic model for the motion of the upper lip; grey lines show the previous positions. P_{mouth} and P_{bore} are the pressures in the mouth and bore respectively. x and z are the longitudinal and vertical displacement of the bottom right hand corner of the plate. The phase difference between x and z has been exaggerated in the sketch.

Approximately uniform pressures P_{mouth} and P_{bore} are assumed to act on the up- and downstream sides of the lips respectively. Making the approximation that the kinetic energy of the jet is completely lost in turbulence, there is no pressure recovery: the pressure is the same between the lips as downstream (Elliot and Bowsher, 1982; Cullen *et al*., 2000). (Giordano (2019) calculates the pressure distribution for a partly similar model, though for much higher pressure and frequency.) With this approximation, P_{bore} is also the pressure in the channel, as indicated. (The pressure falls from P_{mouth} to P_{bore} as the air is accelerated to its highest speed between the lips; it then loses all its kinetic energy in turbulence.) Hence, negligible work is done on the lips by ΔP during the lip contraction (ii to iii) and extension (iv to i). Further, these two small contributions tend to cancel each other out around a cycle. (In other words, because the channel pressure equals the downstream pressure, negligible work is required for the ΔV represented by the dotted areas in Fig. 6.) It is therefore important to distinguish between the volume of air displaced by motions in the x and z directions.

This model does not include surface waves or independent motion of multiple masses in the z direction, mechanisms that allow ΔP to do work on the lips due to their z motion. Omitting it here does not imply that such work is negligible. Rather, this work is something that cannot be easily estimated from the measurements reported here, because they do not reveal such motion.

In the model used here, with pressure between the lips equal to P_{bore}, the nett sweeping work done around a cycle can be positive for two reasons. First, if Δp (the acoustic component of ΔP) and the forward velocity had roughly the same phase, then Δp would do positive work on the lips in both directions. The second reason comes from the observation that the lip aperture is smaller when moving forward in the x direction than when returning. For this behavior, even if ΔP were constant ($\Delta p = 0$) around a complete cycle, then the work done on the lips would be positive, because the closed lips sweep more volume in the x direction during the forward motion than the open lips do in returning. Thus $\Delta\bar{P}$ always does PV work on the lips for the motion observed here, while the sign of the PV work done by Δp changes, depending on the relative phase of Δp and the longitudinal lip motion $x(t)$.

U_x is the longitudinal component of the flow due to the sweeping action of the lips, calculated as described in section IIG. The work dW_x done on the lips by the pressure difference over each time step, according to the simple model, is then calculated as

$dW_x = \Delta PU_x dt$. Note that the longitudinal sweeping flow U_x has a non-zero average, because the lips are taller as they move forwards and shorter when they retreat. This contributes in the positive sense to dW_x. The integral of dW_x round a whole cycle is hereafter called the sweeping work W_x.

Around one cycle of the note B♭2, the PV work done by ΔP on the lips' longitudinal sweeping flow (the sweeping work) for normal playing by advanced players has an average value equal to 38 ± 28 μJ. The relatively large variation of the values includes noise due to the image analysis but also suggests the possibility of different playing styles among subjects. Its value depends on the pressure difference ΔP across the lips, the longitudinal sweeping flow U_x and the phase difference between their acoustic components Δp and u_x.

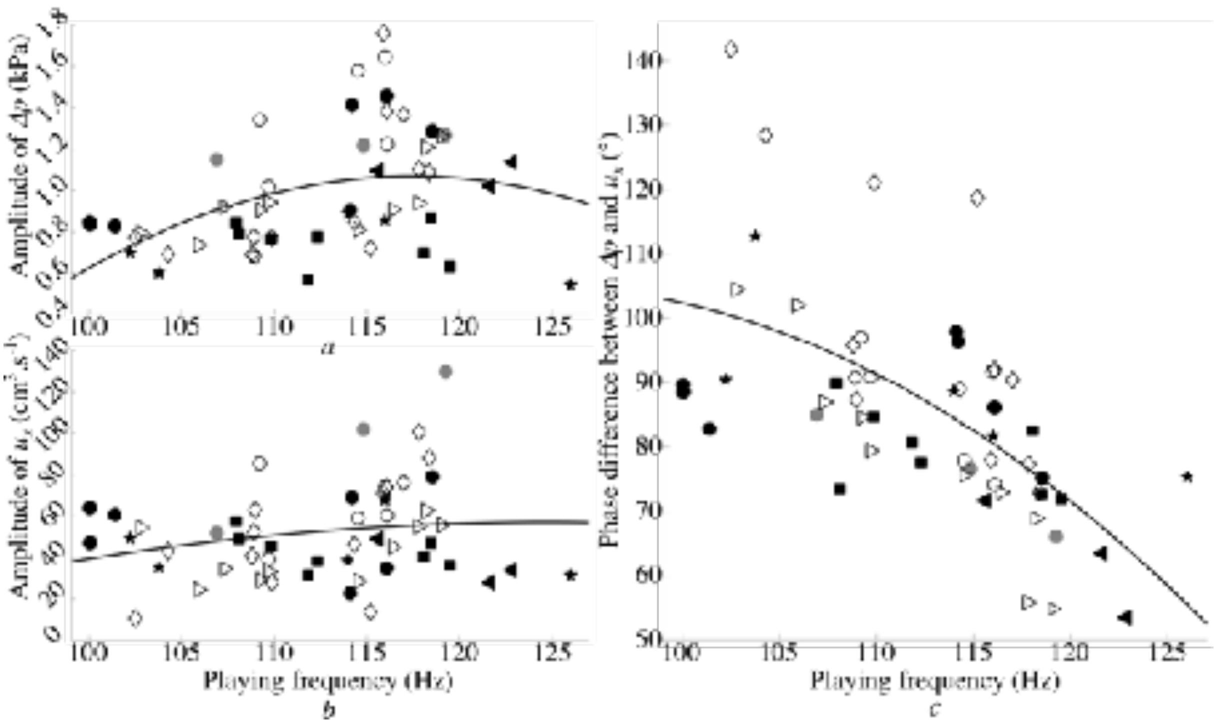

FIG. 7. Amplitude of the acoustic pressure difference Δp across the lips (a), of the acoustic component of the longitudinal sweeping flow u_x (b) and phase difference between Δp and u_x (c), versus playing frequency for advanced players (closed symbols) and beginners (open symbols). The solid black lines show quadratic regressions. The grey symbols are for the

examples in Figs 3 and 4.

The amplitude of u_x does not have a strong systematic dependence on the playing frequency, see Fig. 7*b*. The amplitude of Δp reaches a maximum value around the normal playing frequency (about 116 Hz), see Fig. 7*a*. This variation of pressure amplitude contributes more work done on the lips when playing at normal pitch. In contrast, the increasing phase difference between Δp and u_x while the playing frequency decreases, see Fig. 7*c*, implies less sweeping work when players lip down.

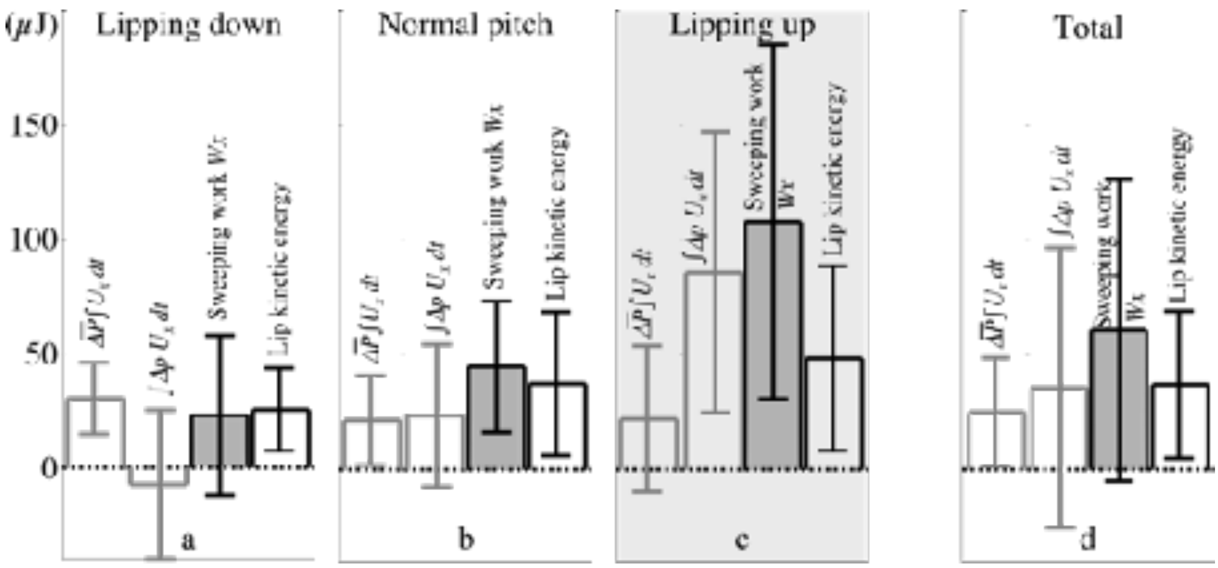

FIG. 8. Averages and standard deviations of the energies associated with the lips during one cycle for lipping down (a), normal pitch (b), lipping up (c), and all measurements (d). The longitudinal sweeping work W_x is shown in black with gray shading and its two components are shown in gray on its left. The lip kinetic energy is in black without shading.

Figure 8 shows the sweeping work $W_x = \int \Delta P \,.\, U_x dt$ done on the lips during one cycle. Overall, W_x increases from lipping down to normal to lipping up (frequency ranging from 100 to 126 Hz). There is considerable scatter. For 39 of the 51 measurements and for 20 of the 23 notes played by advanced players, W_x is positive and its average value is 39 μJ overall, and 46 μJ for advanced players. For 12 of the measurements, it is negative (median value equal to –22 μJ).

The negative values in W_x are interesting. How is auto-oscillation possible when ΔP does negative sweeping work? Note that nearly all of the negative cases are for two particular players (beginners) when lipping down. It is possible that another effect, such as the surface wave effect mentioned above, provides the positive work in such situations. The experiments conducted here do not allow estimates of work from these other effects, so the following discussion quantifies only the longitudinal sweeping work.

In the simple model discussed above, two different effects provide driving force on the lips. First, the oscillatory pressure difference Δp acts to accelerate them in the x direction. If the phase of this pressure term is within about $\pi/2$ of that of v_x (and thus if Δp is between about zero and π ahead of x), Δp does positive work on the lips round each cycle. In lipping down, the phase of Δp leads x by nearly π, but the angle decreases for normal and lipping up. Thus this term delivers little power for regeneration when lipping down, but successively more regenerative power for normal and for lipping up and contributes to the positive correlation evident in Fig. 8.

A second effect is that $\overline{\Delta P}$ does work on the lips around a whole cycle because of the non-zero longitudinal sweeping flow; this term delivers power $\overline{\Delta P}U_x$, in phase with u_x, as explained above. The longitudinal u_x term arises because the lips are longer coming forward than going backwards, so $\overline{\Delta P}U_x$ is expected to be in phase with v_x or $\pi/2$ ahead of x. This provides a regenerative work term that is largely independent of the phase of other variables.

E. Energy considerations

Figure 8 includes estimations of energies made using the average values for each of the three gestures. The sweeping work done on the lips is estimated using $\int \Delta P U_x \mathrm{d}t$ for one cycle using the simple model. The sweeping work is divided in two terms: $\Delta \bar{P} \int U_x \mathrm{d}t$ and $\int \Delta p U_x \mathrm{d}t$. The first term (first bar) is positive on average, since $\Delta \bar{P}$ and $\int U_x dt$ are positive, while the second term (second bar) can be positive or negative, depending on the phase difference between Δp and u_x. Any work done in the transverse direction according to vertical motion and to other effects and models is not included.

To obtain a rough estimate of the kinetic energy of the lips, the maximum of the effective x-velocity, $v_{x\mathrm{eff}}$, is given by the peak of the time derivative of lip volume inside the mouthpiece cup, divided by 4.2 cm^2, the area inside the mouthpiece rim. The x and z-components of the lip motion have comparable amplitude, so they are arbitrarily set equal. If the measured phase difference between the two is α, then the maximum kinetic energy is $m v_{x\mathrm{eff}}^2 \cos^2(\alpha/2)$. The values in Fig. 8 assume an effective thickness of 5 mm (so a mass m of 2 g bounded by the mouthpiece rim). Consequently, even if the lip-lip or lip-teeth collision is wholly or substantially inelastic, the sweeping work done by ΔP can usually replace it. Note that these energy terms are all much smaller than the energy input by the player's breath, $\int P_{\mathrm{mouth}} U_{\mathrm{bore}} \mathrm{d}t$, which is typically ~1 mJ for one cycle (an input power of about 100 mW).

As discussed earlier, the lip regeneration via the sweeping motion in normal playing involves one or both of two effects: a positive $\Delta \bar{P}$ and an x motion that leads the z motion, or a similar phase of Δp and v_x. In the absence of the downstream resonator, and well away from resonances of the vocal tract, only the first effect is available. If a player could buzz the lips using the lip motion measured for normal playing but with a constant value of $\Delta \bar{P}$ ~1.3 kPa, equal to that for normal playing, then the sweeping work would be ~20 μJ, (as in Fig. 8).

F. **The range of lipping up and down**

To the question of what limits the range of lipping, many brass players would give a simple pragmatic answer: in practice, players who try to lip up a long way end up ‘jumping’ to the instrument’s next register. In many cases, this is what happened in this study when players tried to extend the range of lipping up. In the other direction (lipping down from B♭2), the only bore resonance with a lower frequency (at about 38 Hz) is difficult to play because its harmonics do not coincide with resonances. Instead, experienced players can play what is called a pedal note, B♭1, for which the second and higher harmonics fall close to the second and higher resonances, but the first does not fall near a resonance. In this study, the lower limit did not involve ‘jumping’ to a lower register, but instead, players ceased to make a periodic sound. (It should be remembered that the limits discussed here only apply to stable notes: many good players can, without using the slide, perform a ‘lip *glissando*’ (strictly a lip *portamento*): they can smoothly vary the pitch over a large range, crossing several resonances.)

This raises the question: is the limitation to lipping up and down determined by the inability of the lips to match Z_{bore}, and/or does pitch bending in one direction or another continue until there is insufficient energy to maintain auto-oscillation?

Figure 2 indicates that the lipping range is roughly symmetrical around the nearly symmetrical impedance peak in Z_{bore}. The range of phase angle is roughly symmetric around zero. When lipping up, the lip aperture opens soon after the lips enter the mouthpiece. If u_{bore} is to lead p_{bore} by a larger amount, then the lips must open even earlier and /or the relative magnitude of u_{ap} with respect to u_{sw} reduced (see Fig. 5). When lipping down, the lips open later; if u_{bore} is to lag p_{bore} even further, then the lips must open even later and/or the relative magnitude of u_{ap} with respect to u_{sw} increased.

The negative value of $\int \Delta p\, U_x dt$ for lipping down contributes to the low value of sweeping work in Fig. 8. This may contribute to the lower limit of lipping down, but not to the upper limit.

IV. CONCLUSIONS

Players normally play a little above the frequency of the bore impedance peak; they are capable of 'lipping up' roughly half a semitone and 'lipping down' roughly a tone. The upper and lower limits of the range have similar values of the impedance magnitude, being about 15% of the magnitude at resonance, and relative phases ranging from about –69° to +75°.

In order to lip up and down, players must alter the phase between p_{bore} and u_{bore} so it matches the requirements of Z_{bore} at the desired frequency. This adjustment is possible in part because U_{bore} has two distinct components. One is the flow through the lip aperture, U_{ap}, which is always positive and starts when the lip aperture opens. The other is the sweeping flow, u_{sw}, that is a consequence of the changing volume of the lips inside the mouthpiece; this flow is initially positive when the lip volume increases and becomes negative as the lips begin to contract. The relative timing of these four events, lip forward motion, lip aperture opening, lip retraction and lip closing, can shift the relative phase of U_{bore} with respect to p_{bore}. (Other subtleties are discussed above.)

Because the lips move forward before they open, non-zero work would be done on them by the pressure difference across the lips even if that pressure difference were constant. If it varies and has phase overlap with the longitudinal velocity of the lips, the work done per cycle is greater. The work from these two terms is available to compensate for internal mechanical and other losses associated with vibration. This sweeping work is about 20 times smaller than the work it modulates, *i.e.* the work input to the instrument by pressure and air flow from the mouth. The sweeping work is, however, of the same order as the maximum kinetic energy of the lips. It is thus capable of replacing the energy lost per cycle in lip-lip and lip-teeth collisions. This makes sweeping work a likely source of much or perhaps all of the energy required for auto-oscillation.

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