LIP MOTION, THE PLAYING FREQUENCY OF THE TROMBONE AND THE UPSTREAM AND DOWNSTREAM IMPEDANCES

Henri Boutin
University of New South Wales, Sydney

Neville Fletcher
Australian National University, Canberra

John Smith
University of New South Wales, Sydney

Joe Wolfe
University of New South Wales, Sydney

henri.boutin@unsw.edu.au, neville.fletcher@anu.edu.au
john.smith@unsw.edu.au, j.wolfe@unsw.edu.au

ABSTRACT

We report the motion of trombone players' lips, its phase with respect to the mouthpiece pressure, the impedances of the bore and the player's vocal tract, and the frequency difference between the bore resonance and played note. The bore resonance frequency shifts very little with playing and often decreases somewhat: the effect of CO_2 can exceed that of temperature and humidity. The bore impedance is usually compliant for the note B♭2 and inertive for B♭3. The vocal tract impedance measured at the player's mouth is inertive for both notes. In terms of Fletcher's simple model for regeneration (JASA, 93, 2172), the results are consistent with a $(+1,-1)$ valve for B♭2 and $(-1,+1)$ for B♭3. The pressure in the mouthpiece in both cases rises before the lips separate. For B♭3, where the lip motion is mainly transverse, this is consistent with the inertive load. For B♭2, the substantial motion of the lips in the direction of flow provides a sweeping motion which produces the current into the bore that precedes lip opening.

1. INTRODUCTION

How and why do the lips of a brass player vibrate? This is an interesting question in music acoustics, with potential applications in music pedagogy and performance. Images of the motion as functions of time are an important contribution to answering the question. Various studies, including the present one, have used stroboscopy or high speed video for this purpose: Copley and Strong [1], Yoshikawa and Muto [2], Tarnopolsky et al [3], Campbell and colleagues [4] and others.

In mathematical models of the vibrating lip, the acoustic impedance spectra of the upstream and downstream side of the lip are important [5,6]. Simultaneous measurements of the acoustic pressure in the mouth and that in the mouthpiece during trombone playing [7] have shown that the ratio of the former to the latter increases strongly as the players play higher, but varies among players. This increase is in part due to the way the impedance maxima of the bore decrease with increasing frequency. However, the variation among players strongly suggests that they use their vocal tracts in different ways.

Measuring the upstream impedance Z_{mouth} — the impedance of the player's vocal tract measured near the lips — is non-trivial: the signal produced by the vibrating lip is much more powerful than the probe signal used to measure Z_{mouth}, because the energy of the probe signal has to be divided among hundreds of different frequencies. Nevertheless, this has been reported for the trumpet [8] and the didjeridu [3]. Measuring the downstream impedance Z_{bore} also has challenges because: (*i*) the instrument operates close to an impedance peak, (*ii*) the impedance peaks are quite narrow and (*iii*) the speed of sound and thus the resonant frequency depends subtly on temperature, humidity and the concentration of CO_2 inside the bore. So it is necessary to measure Z_{bore} under conditions close to playing so as to understand the combined effect of temperature, humidity and CO_2. The relative timing of the lip motion and the pressure in the mouthpiece is also important. The timing of lip contact can be measured by the high frequency electrical admittance y_{lip} between upper and lower lips [9,10].

In order to explain how the lip motion is driven at different playing frequencies, the objectives of the present study are: to investigate the effects of temperature, humidity and concentration of CO_2 on the bore resonances, to measure the mouth and bore impedances during playing, and to compare the lip contact with the pressure in the mouthpiece.

2. MATERIAL AND EXPERIMENTAL SETUP

We report the measurements of the impedance of the trombone bore, the impedance of the player's vocal tract, the pressure in the mouthpiece and a variable related to the opening area between the player's lips. These signals were measured using three different experimental setups described in the next paragraphs. Six amateur players were experimental subjects.

2.1 The trombone and the mouthpiece

All the players played same modified trombone (*Yamaha* model *YBL* 321). This instrument has a valve that converts it from the tenor range to the bass range, but the valve was left in the tenor position. In all experiments, the slide was kept in the same position (first position: all the way in) and the tuning slide was extended 18 mm. The instrument was clamped to a lab bench but mechanically isolated from it with foam.

The players involved in these experiments were asked to play up to five of the lowest notes above the pedal note: B♭2 (nominally 117 Hz), F3 (175 Hz), F♭3 (233 Hz), D4 (294 Hz) and F4 (349 Hz). However, in this brief report, only the data for two notes are analysed: B♭2 (nominally 117 Hz) and B♭3 (233 Hz).

The mouthpiece was replaced with an experimental mouthpiece (Figure 1) having the same cup volume (11.6 cm^3), diameter (2.53 cm) and throat geometry as the original mouthpiece. The mouthpiece is transparent with two flat glass windows to allow high-speed video and stroboscopic observation of the motion of the lips. In a hole of diameter 2.3 mm in one side is sealed an *Endevco* piezoresistive pressure transducer (model *8507C-2*). Two brass electrodes are set into the rim of the mouthpiece, so that they contact the face above the upper lip and below the lower. They are connected to the input of an electroglottograph (*EGG*, model *EG2-PCX2*) from *Glottal Enterprises*.

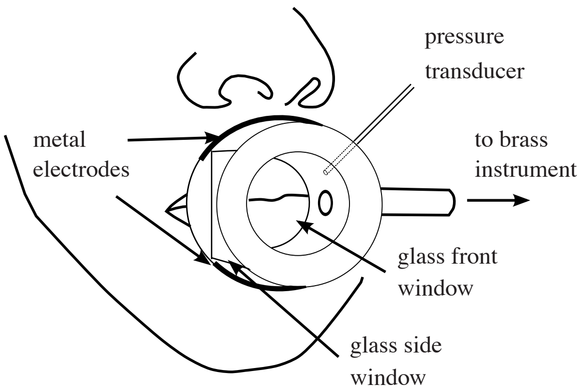

Figure 1. The modified mouthpiece equipped with two brass electrodes connected to an electroglottograph (*EGG*) to measure lip contact after Wolfe and Smith [9], and Freour [10]], a piezoresistive pressure transducer connected to the mouthpiece cup. Its design follows Ayers [13]: the two glass windows provide undistorted front view and side view of the lip motion.

2.2 The bore impedance

For the temperature studies, the capillary method is used to measure the bore impedance Z_{bore} so that it could be sealed to the mouthpiece very quickly. The impedance head comprises an acoustic current source with high impedance and a microphone. The current source is similar to that used by Wolfe et al [11] and comprises a truncated cone concentric with a conical hole, but separated from it by three 100 μm wires placed at 120° angles. The source and a microphone (*B&K* model *4944A*) are located side by side in the plane against which the trombone mouthpiece is clamped. The impedance head is calibrated with a semi-infinite pipe of length 142 m and of diameter 7.8 mm.

For calibration and measurements, a loudspeaker generates a broadband acoustic current at the reference plane. This contains frequency components ranging between 50 Hz and 600 Hz with a resolution of 0.67 Hz ($= 44.1$ kHz$/2^{16}$). During a calibration iteration, the amplitudes of each of the spectral components of this current are equalized [11].

2.3 The vocal tract impedance

The method used to measure the vocal tract impedance of the trombone player is the three microphone technique using non-resonant loads, described by Dickens et al [12]. Its advantage over the capillary method for this application is that a more powerful probe signal is possible, and this is helpful in the presence of the broadband noise measured close to the player's lips.

We use our smallest impedance head (of outer diameter 4.8 mm) to minimise the perturbation of the player, who is asked to hold this pipe between the lips at the corner of the mouth during playing, while orienting it so that the measurement plane is between the upper and lower teeth and behind the central portion of the lips. A flange on the head at 25 mm from the measurement plane limits the maximum insertion into the mouth. The probe signal contains 34 cycles of length 2^{16} points (about 1.49 s), so that the measurements can last up to 50 s. 820 frequencies spaced at 0.67 Hz cover the range 50 Hz to 600 Hz.

2.4 The pressure in the mouthpiece, the lip motion and their relative phase

The pressure transducer in the mouthpiece, flush with the wall of the cup, is connected to a bridge amplifier and then to a sound card (*MOTU*, model *Firewire* 828). The sound card gain was calibrated using a known voltage source (*Topward* model 8120) of variable frequency. Then we replaced the transparent back plate of the mouthpiece by a plug in epoxy resin, equipped with a reference microphone (*B&K* 4944*A*). The mouthpiece was then driven with a broadband signal over the range [50 Hz, 1 kHz] and the ratio between the spectrum of signals from the pressure transducer and the reference microphone recorded. In the following experiments, with the transparent window replaced, this ratio determines the pressure in the mouthpiece cup from the transducer signal.

The *EGG* connected to the brass electrodes provides a signal negatively correlated with the electrical admittance between the two lips. It has no DC component, is maximum when the lips are open and minimum when they are closed. Thus it is correlated with and approximately in phase with the opening area between the lips, so we call it $OV(t)$ (for *open variable*). In order to evaluate the delay introduced by the *EGG* we connected a voltage-controlled resistance at its input. The delay (0.1 ms between 100 Hz and 1 kHz) is not negligible compared to the period of the notes played ($\approx$ 10 ms), but this difference can be added when comparing the phase difference between the pressure in the mouthpiece and the lip opening area as given by the outputs of the piezotransducer and the *EGG*.

3. TEMPERATURE AND GAS EFFECTS ON THE RESONANCES OF THE BORE

As the trombonist starts to play, the temperature, the humidity and the concentration of CO_2 all increase in the bore. How do the impedance peaks vary with playing? We measured the input impedance of the trombone before the instrumentalist plays, and after he has played for 3 s, 10 s, 30 s and 4 min. Between measurements, the air inside the bore was flushed, and the bore impedance was measured again. During the 3 s and 10 s experiments, the player was asked to take a breath and to play a single sustained note. These experiments reproduce the playing conditions met by the player when his instrument is initially dry and at ambient temperature (26.8°C and relative humidity 57% in this instance). In the longer experiments (30 s and 4 min) the performer was asked to play several long notes and to inhale at will. The impedance head, coated with a thin layer of petroleum jelly, was sealed to the mouthpiece rim, within 3 s of the end of the playing and the impedance measured for successive cycles over the following 50 s. This protocol was followed once or twice with every player. The impedance spectra were sampled at 0.67 Hz. Around the peaks, these data were interpolated with a fitted cubic function, giving an estimated frequency resolution of 0.1 Hz. The mean curves corresponding to each playing duration are shown in Figure 2.

For all playing conditions, the second, third and fourth impedance peaks fall within the ranges $113.0 - 113.9$ Hz, $170.9 - 172.1$ Hz, and $227.7 - 229.4$Hz. These are the peaks used to play B♭2, $F3$ and B♭3 respectively. For each, we note that the peak frequencies and amplitudes decrease after playing for 3 s. After 10 s and 30 s of playing, the frequencies are slightly greater than after 3 s and the amplitudes almost unchanged. After 4 min, the peak frequencies return approximately to their initial values, while the amplitudes decrease further. The same trend was observed on the 9 peaks between 50 Hz and 600 Hz. The changes in their amplitudes and frequencies are plotted on Figure 3.

The repeated measurements made before playing on different days are always located at less than 0.26% from their average frequency, with a standard deviation of 0.09%. Figure 3 shows that, after playing for 3 s and 10 s, the peak frequencies decrease in average by 0.48% and 0.62% respectively. Because humidity and temperature both increase the speed of sound, we conclude that, in these experiments, increased concentration in CO_2 in the bore more than compensates for the increases in temperature and humidity. This is not surprising: 3 s is easily enough time for the player to replace the air in the bore, but probably not enough time for the air to warm the instrument. Rises in water concentration are limited by the temperature.

In the 30 s-experiment, the players inhaled at least once between notes. So the CO_2 ceased increasing. This would explain why the peak frequencies stopped decreasing. In the 4 minute experiment, the players breathed several times as well, and there was time for temperature and thus water concentration to rise. Here, resonant frequencies differed little from the dry, ambient conditions: an average increase of 0.02%.

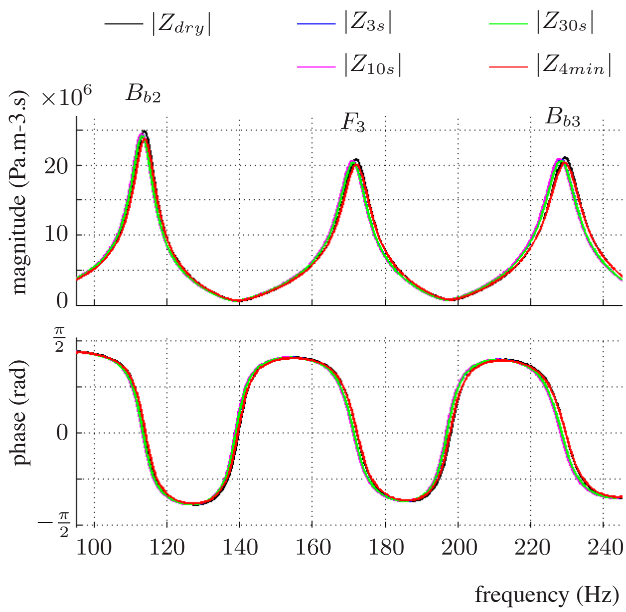

Figure 2. This graph shows several measurements of the impedance of the bore of the trombone equipped with the experimental mouthpiece when the slide is in 1^{st} position and the trigger valve is not depressed. The three peaks in magnitude are the 2^{nd}, 3^{rd} and 4^{th} resonances of the bore. The corresponding notes are labelled on the graph. Z_{dry} is the average curve obtained before playing; Z_{3s}, Z_{10s}, Z_{30s} and Z_{4min} are the average curves obtained after the musicians played the notes they wished for these durations. All measurements were carried out the same day. The temperature and the relative humidity at the time were respectively 26.8°C and 57%.

The decrease in the amplitude of the impedance peaks can possibly be attributed to humidity. We expect that gas composition would have very little effect on the characteristic impedance $\rho c/A$. However, as suggested by Coltman [14], air near 100% humidity could, in a standing wave, evaporate and condense during each cycle, which would increase losses. This could explain why after playing 4 min, the minima in Z_{bore} increase in magnitude (by 3.3% in average) while the maxima decrease (by 3.8% in average).

4. THE VOCAL TRACT IMPEDANCE

Among the previous studies focusing on the brass players' lips, two different lip motions in different ranges are reported [1, 2]. In the lower register, components of motion parallel and perpendicular to the flow have similar amplitudes, while in the high register the parallel component is much smaller. A simple model by Fletcher [6] associates qualitatively different kinds of auto-oscillatory lip valve motion with different values of reactive components of the upstream and downstream impedances.

Measurements of the upstream impedance spectrum used a small impedance head inserted in the corner of the mouth with its end lying between upper and lower teeth and close behind the lips. None of the players reported any difficulty to play the notes in this study (B♭2 and B♭3) with the

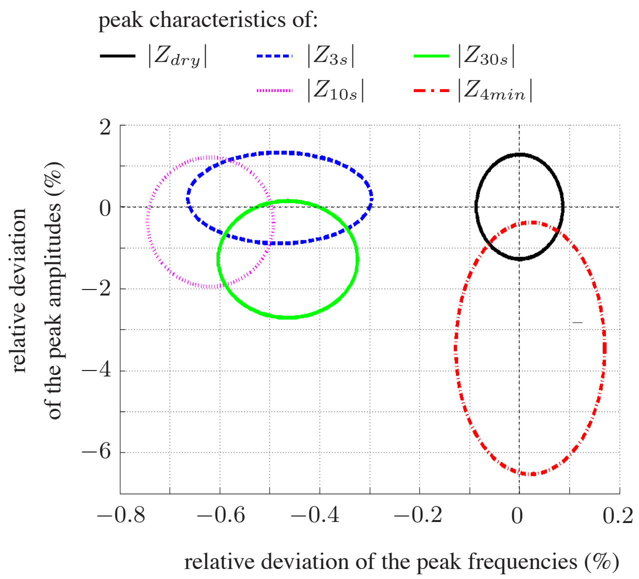

Figure 3. This plot displays the relative deviations (in %) of the impedance peak amplitudes and frequencies, after the musician played for 3s, 10s, 30s and 4min. The center of each ellipse is the mean of all measurements in each condition and the semi-axes show the standard deviations.

impedance head between the teeth and some could comfortably play several notes above these. We asked the players to play long notes, then to take another breath when they were out of air, and to start again. Each measurement lasted 30 s and allowed the subjects to play usually between 2 and 3 notes of 10 s. The experiment was carried out several times with each performer playing the lower pitch note B♭2 and then the higher pitch note B♭3. For each vocal tract configuration, the impedance curves obtained were fairly similar; two of them are displayed on Figure 4.

The players reported that they raised their tongue while playing a high pitch note. This would be expected to raise the characteristic impedance, could explain why Z_{mouth} is typically higher when the player is playing B♭3. (An analogous result was observed by Wolfe et al [15], using a mechanical trombone-playing machine with an outwards opening valve.)

Finally, we removed the impedance probe from the player's mouth and asked each player to play notes (B♭2 and B♭3) for about 10 s. We recorded the sound pressure in the mouthpiece, p_{mp}, and calculated its spectrum over a 1 s interval, in the sustained period, after the attack. We compare it with the bore resonances measured after 10 s, since it is approximately the duration of the notes played. Henceforth, Z_{bore} refers to Z_{10s}. f_p varies somewhat for different performers and samples. However, for all six players, f_p is always located above the bore resonance when the note played is B♭2 and below when it is B♭3. (These inequalities are true for all of the Z_{bore} spectra measured in this study under the various conditions described above.)

From Fletcher's simple model [6], a required condition

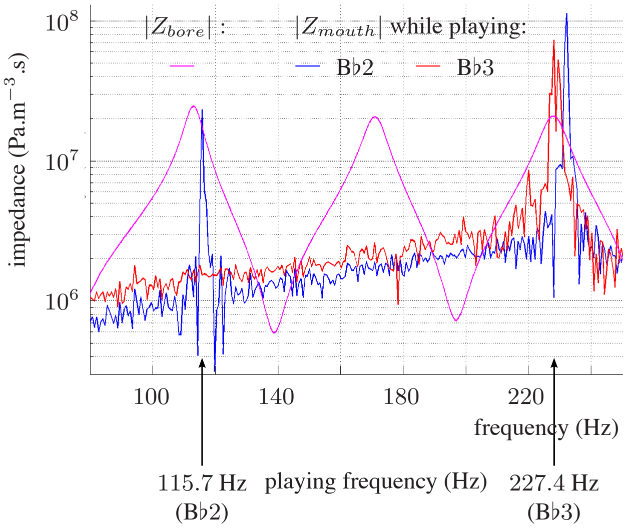

Figure 4. This plot shows the magnitude of the trombone impedance (after playing 10 s) and that of the vocal tract impedance of the musician while playing a B♭2, tongue in low position, and while playing a B♭3, tongue in high position. Both measurements used an impedance head (4.8mm-diameter) introduced in the mouth of the player. The narrow peaks on the curves of vocal tract impedance are artefacts due to the sound of the fundamental playing frequency and, for B♭2, its second harmonic.

for a valve to auto-oscillate is:

$$Im\left(\frac{W\bar{p}_1\mu(\sigma_2 Z_2 - \sigma_1 Z_1)}{\sqrt{2\rho\bar{p}_1} + W\bar{x}(Z_1 + Z_2)}\right) > 2\pi f_p \times k, \quad (1)$$

where W is the valve width perpendicular to the flow, $\bar{x}$ the static component of the valve opening and $\bar{p}_1$ the static pressure upstream of the valve. ρ is the air density, k the attenuation coefficient of the valve and f_p its playing frequency. μ is proportional to the valve flap area divided by the effective mass involved in the oscillation. The pair $(\sigma_1, \sigma_2) = (\pm 1, \pm 1)$ describes how the valve operates: $\sigma_1 = +1$ if a positive pressure upstream of the valve tends to open it further, and -1 if it tends to close it. σ_2 is similarly defined with respect to the pressure downstream of the valve. Finally Z_1 is the impedance 'looking into' the upstream side of the valve in the direction of the load, and Z_2 'looking into' the downstream side of the valve. Here they correspond to Z_{mouth} and Z_{bore} respectively. This simplified model assumes that the valve channel is negligible length, the static pressure downstream is zero and that the valve flaps never collide with each other and undergo simple harmonic motion. In addition it neglects the inertance of air inside the channel and the flow generated by the flap motion. Even though these simplifying assumptions are not satisfied by the lip valve, the model is still qualitatively helpful in discussing whether a vibration mode can auto-oscillate or whether it is driven by an other mode.

Our measurements show that the imaginary parts of the impedances (X_{mouth} and X_{bore}) have magnitudes comparable with the real parts (R_{mouth} and R_{bore}) at the playing frequencies, cf. Figure 5. This means that the losses in the vocal tract and the bore and its radiation impedance cannot be neglected. Thus (1) leads to the following conditions:

$$\sigma_2 X_{bore} - \sigma_1 X_{mouth} > \alpha(X_{mouth} + X_{bore}) \times .. \quad ..(\sigma_2 R_{bore} - \sigma_1 R_{mouth}), \quad (2)$$

$$\text{with } \alpha = \frac{W\bar{x}}{\sqrt{2\rho\bar{p}_{mouth}} + W\bar{x}(R_{mouth}+R_{bore})} \quad (3)$$

Typical values of X and R at both playing frequencies studied are obtained from the measurements of Figure 5. This involves removing the very narrow peaks at the harmonics of the note being played and interpolating and smoothing the real and imaginary parts of the vocal tract impedance with a Savitsky-Golay filter:

	Z_{bore} $(MPa.m^{-3}s)$		Z_{mouth} $(MPa.m^{-3}s)$	
f_p	R_{bore}	X_{bore}	R_{mouth}	X_{mouth}
115.7 Hz (B♭2)	13.8	−11.1	0.95	0.76
227.4 Hz (B♭3)	20.4	3.5	2.6	0.98

Table 1. Typical values of the real and imaginary parts of Z_{bore} and Z_{mouth} at both playing frequencies 115.7 Hz (B♭2) and 227.4 Hz (B♭3)

Since R_{mouth}, R_{bore} and $\bar{x}$ are positive, $\alpha > 0$ in (2). In the case of B♭2, $-X_{bore} > X_{mouth} > 0$. Then the only condition for (2) to be satisfied with any positive values of R_{mouth} is (σ_1, σ_2)=(+1, −1). This is the regeneration mode for an *outward swinging* valve, or *swinging door* valve.

For B♭3, $X_{bore} > X_{mouth} > 0$. Then, a (−1, +1) valve always satisfies the auto-oscillation condition with any positive value of the real part R_{mouth}. By giving plausible order of magnitude to the model parameters, $\bar{p}_1$ = 2kPa, W = 1cm and $\bar{x}_1$ = 1mm, the simple model predicts that a (−1,−1) valve could also auto-oscillate. But this also depends on the real part of Z_{mouth}. As a result, in the higher range, our results and this model together suggest that the brass player's lips probably do not operate as a (+1,+1) valve but more likely as a (−1,+1).

5. THE TIME SIGNALS

In the next experiment, we investigate the phase relationship between the pressure in the mouthpiece p_{mp} and the motion of the lips. As detailed in Section 2, the contact electrodes on the experimental mouthpiece allow us to measure the AC component of the electrical admittance between the lips y_{lip}. During the previous experiment, as we asked the performers to play B♭2 and B♭3, we measured y_{lip} and the pressure in the mouthpiece p_{mp} simultaneously. The signal shown on Figure 6 is inversely related to this admittance: it is a minimum when the contact area between the lips is maximum and *vice versa*. For this reason, we call this the open variable $OV(t)$. Copley and Strong [1] show that the lips of a trombonist close completely during each cycle, as do those of a hornist [2]. This was also observed by high speed video in the present study.

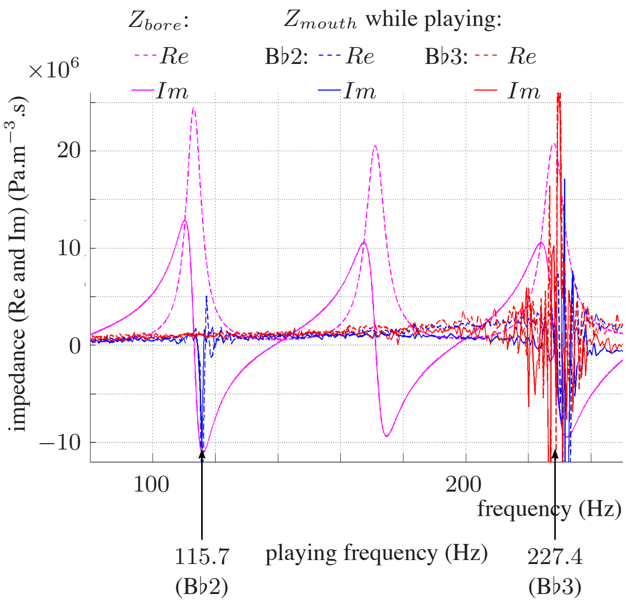

Figure 5. This plot shows the real and imaginary parts of the bore impedance (after playing 10s) and of the vocal tract impedance of the musician while adopting two different vocal tract positions: tongue in low position to play a B♭2 and in higher position to play a B♭3.

During this closed phase, air flow between the lips is zero, y_{lip} is maximum and OV is a minimum.

Figure 6 shows an example of $OV(t)$ and $p_{mp}(t)$. For each of the played notes, the pressure in the mouthpiece starts to increase before the lips begin to open and reaches its minimum value just before the lips close completely. This feature was observed for each note played and each performer. The air flow between the lips is zero when the lips are closed. When the lips are open, however, it is not simple to relate the flow to the lip opening or to OV.

For the higher played note B♭3, the impedance measurements show that Z_{bore} is inertive at the playing frequency (Figure 4), so one would naïvely expect the flow into the mouthpiece to lag the pressure p_{mp}. (In practice, the flow between the lips is broadly related to lip opening, but the motion is complicated by higher harmonics, whose phase relations may in principle be different from that of the fundamental.)

In contrast, for the lower note B♭2, Z_{bore} is compliant at the playing frequency and so the flow in the mouthpiece U_{bore} is expected to lead the mouthpiece pressure p_{mp}. This raises an obvous question: how can the flow into the mouthpiece begin while the lips are still closed?

Yoshikawa and Muto [2] provided images from side viewing of the lip motion in a transparent horn mouthpiece. They show that the upper lip moves outward significantly in the lower range and that the lips separate after they have moved forward into the mouthpiece.

Video images taken in the present project give similar results: for B♭2, the lip motion has a large component in the direction of the flow, and this motion leads the transverse motion in phase. In contrast, for B♭3 the motion is almost entirely transverse. For B♭2, this sweeping motion

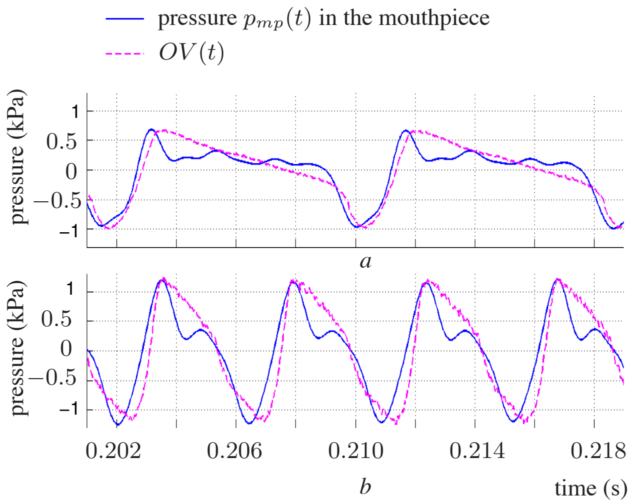

Figure 6. The pressure in the mouthpiece $p_{bore}(t)$ and the open variable $OV(t)$ (OV is inversely related to the electrical admittance between the upper and lower lip and is a maximum when the lips are separated and a minimum when they are in contact). (*a*) the musician played a lower pitch (B♭2) note, and (*b*), a higher note (B♭3)

generates a positive flow into the mouthpiece before the lips separate and before pressure begins increasing in the mouthpiece. In this preliminary account, we do not report the magnitudes of this 'sweeping' current, but simple calculations show that its magnitude is of the same order as the total acoustic flow into the mouthpiece. In contrast, for the higher note B♭3, the lip motion is almost entirely perpendicular to the flow, so U_{bore} essentially equals the air flow between the lips, and this current can start to increase only when the lips open.

6. CONCLUSIONS

These observations suggest that, for B♭2, the lips operate as an outwards opening valve and for B♭3, as a sideways sliding valve. Fletcher's simple model [6] predicts the regeneration conditions for such valves in terms of the acoustical impedance upstream and downstream of the lip valve.

The upstream impedance, Z_{mouth} depends on the configuration of the player's vocal tract and, at the playing frequencies reported here, it increases when the player raises his tongue.

According to the curves of Figure 2, the frequency and amplitude of the peaks in Z_{bore} depend only weakly on the duration of playing, probably because of compensating effects. So the changes in the frequency of these peaks are rather smaller than the displacement of the playing frequency from the peak in Z_{bore}.

Further measurements carried out with six performers showed that Z_{bore} is usually compliant when the note played is B♭2 and inertive when the note played is B♭3. According to a simple theoretical model of valve [6], this change of sign in the imaginary part of Z_{bore} explains why the lip valve cannot have the same operating mode for both played notes. The model predicts that the lip valve is likely to oscillate as a (+1,−1) valve in the low range and as a (−1,+1) valve in the high range.

Plots of $p_{mp}(t)$ and $OV(t)$ (Figure 6) showed that, during playing, the pressure in the mouthpiece leads the lip opening. This result is explained for the higher note, when Z_{bore} is inertive, by flow between the lips. For the lower note, however, this phase relation requires that the flow into the bore has a large component that begins before the lips separate. This is explained by the sweeping action of the lip: for the lower note, the lips move forwards into the mouthpiece before they separate, generating a flow whose magnitude is of the same order as the acoustic flow into the bore.

This preliminary report presents only some of the data in the early part of this study. The conference presentation will have further data on more players, a greater range of notes, and a larger set of techniques.

Acknowledgments

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7. REFERENCES

[1] D. C. Copley and W. J. Strong, "A stroboscopic study of lip vibrations in a trombone," *The Journal of the Acoustical Society of America*, vol. 99, no. 2, pp. 1219–1226, 1996.

[2] S. Yoshikawa and Y. Muto, "Lip-wave generation in horn players and the estimation of lip-tissue elasticity," *Acta Acustica united with Acustica*, vol. 89, no. 1, pp. 145–162, 2003.

[3] A. Z. Tarnopolsky, N. H. Fletcher, L. C. Hollenberg, B. D. Lange, J. Smith, and J. Wolfe, "Vocal tract resonances and the sound of the Australian didjeridu (yidaki) i. experiment," *The Journal of the Acoustical Society of America*, vol. 119, pp. 1194–1204, 2006.

[4] M. J. Newton, M. Campbell, and J. Gilbert, "Mechanical response measurements of real and artificial brass players lips," *The Journal of the Acoustical Society of America*, vol. 123, no. 1, pp. EL14–EL20, 2007.

[5] S. Elliott and J. Bowsher, "Regeneration in brass wind instruments," *Journal of Sound and Vibration*, vol. 83, no. 2, pp. 181–217, 1982.

[6] N. Fletcher, "Autonomous vibration of simple pressure-controlled valves in gas flows," *The Journal of the Acoustical Society of America*, vol. 93, pp. 2172–2180, April 1993.

[7] V. Fréour and G. P. Scavone, "Vocal-tract influence in trombone performance," *Proc. Int. Symp. Music Acoustics, Sydney & Katoomba*, 2010.

[8] J.-M. Chen, J. Smith, and J. Wolfe, "Do trumpet players tune resonances of the vocal tract?" *The Journal of the Acoustical Society of America*, vol. 131, no. 1, pp. 722–727, 2012.

[9] J. Wolfe and J. Smith, "Acoustical coupling between lip valves and vocal folds," in *Acoustics Australia*, vol. 36, 2008, pp. 23–27.

[10] V. Fréour and G. P. Scavone, "Development of an electrolabiograph embedded in a trombone mouthpiece for the study of lip oscillation mechanisms in brass instrument performance," *Canadian Acoustics*, vol. 39, no. 3, pp. 130–131, Oct. 2011.

[11] J. Wolfe, J. Smith, J. Tann, and N. H. Fletcher, "Acoustic impedance spectra of classical and modern flutes," *Journal of Sound and Vibration*, vol. 243, no. 1, pp. 127–144, 2001.

[12] P. Dickens, J. Smith, and J. Wolfe, "Improved precision in acoustic impedance measurements by using calibration loads without resonances," *The Journal of the Acoustical Society of America*, vol. 123, no. 5, pp. 3015–3015, 2007.

[13] R. D. Ayers and M. S. Lodin, "Alternative mouthpiece design for viewing the lip reed in motion," *The Journal of the Acoustical Society of America*, vol. 107, p. 2843, 2000.

[14] J. W. Coltman, "Acoustical losses in wet instrument bores (l)," *The Journal of the Acoustical Society of America*, vol. 114, p. 1221, 2003.

[15] J. Wolfe, J. M. Chen, and J. Smith, "The acoustics of wind instruments-and of the musicians who play them," in *Proceedings of the 20th International Congress on Acoustics, ICA-2010*, August 2010.