Lipping down on the trombone: phases of lip motion and pressures

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Simple physical models describe the motion of brass player's lips as a superposition of two modes: in one, the upper lip bends like a cantilever into the mouthpiece; in the other, one or both lips undergo vertical strain to vary the aperture. These motions are investigated here on a trombone using high speed video and microphones to record mouth and mouthpiece pressures. In all cases studied, the lips move horizontally into the mouthpiece before the pressure increases in the mouthpiece, which in turn precedes the lip opening. The horizontal component of the lip deflection leads the mouthpiece pressure by a small phase angle. For low pitch notes, both modes have significant amplitudes while the motion is mostly vertical at higher pitch. In all cases the playing frequency f_0 appears to lie between those of the cantilever mode and vertical modes. . The opening of the inter-lip aperture is close in phase to the mouthpiece pressure. By 'lipping down', players can vary the playing frequency smoothly between compliant and inertive loads. All of the observations are consistent with a simple model in which each lip is superposition of a horizontal cantilever mode and a vertical mode, with frequencies that the player lowers when lipping down.

1 Introduction

A number of previous studies [1-8] have contributed to our understanding of the physics of the motion of brass players' lips. The motion of each lip is sometimes regarded as a superposition of two eigenmodes driven by the pressure on either side of the lip valve. One mode is similar to the first bending mode of a cantilever beam. That can be driven by the difference between the acoustic pressure in the mouth p_{mouth} and that in the mouthpiece p_{MP}. In this mode, the longitudinal deflection is rather greater than the vertical motion. Thus, to a first approximation, its direction is parallel to the air flow between the lips – hereafter the x direction. The other mode causes a roughly symmetrical, vertical deflection of both lips – hereafter the z direction. This mode, perpendicular to the air flow between the lips, may be driven by the pressure in the channel between the lips. If the jet leaving this channel is turbulent, then the pressure in this channel is equal to p_{MP}.

Players of brass instruments typically play at frequencies slightly above the resonances of the bore [4, 9, 10]. They can smoothly vary the pitch of the note without using the slide or valves, a practice called *lipping up* or *down*. To investigate lipping up and down, we measure the pressure in the mouth and in the mouthpiece while playing. Then we compare the phase differences between the pressure signals that drive the lip oscillation and the different components of the motion, when the performer plays notes at normal frequencies and lips down. From the results of these experiments, we present a simple two dimensional model of lips and use it to explain aspects of lipping up and down on the trombone.

2 Materials and methods

The instrument is a Yamaha YBL 321 used as a tenor trombone. The main slide was fixed in its shortest (first) position throughout and the tuning slide at 18 mm. A transparent mouthpiece with two plane glass windows made of microscope slides allowed front- and side-view video images of the motion of the lips without distortion, using a high speed camera (X-stream VISION^{TM} XS-4 with Nikon Nikkor 35mm lens, IDT Inc. FL, USA). The cylindrical mouthpiece cup had the same volume as the mouthpiece (6½ AL-L) normally used with this instrument. The brass shank connecting the cup to the bore is parallel to the plane of the rim: Figure 1.

Two metal electrodes mounted in the mouthpiece rim made contact with the players' lips. The electrodes were connected to an electroglottograph, *EGG*, in order to measure the electrical conductance between the lips. An 11025 Hz square wave triggers the acquisition of an image at each rising edge.

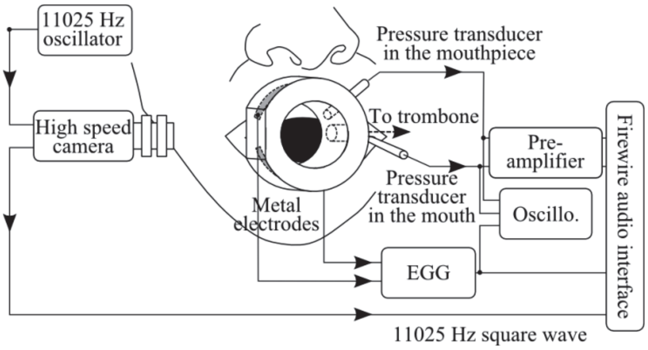

Figure 1: The experimental setup. For clarity, the trombone and the mirror used to film the front and side views of the lip motion are not shown.

A pressure transducer (8507C-2, Endevco, CA) located inside the mouthpiece wall measured the mouthpiece pressure during playing. A similar transducer, placed between the teeth as close as possible to the player's lips, measured the pressure in the player's mouth.

Simultaneous signals from the microphones, EGG and external oscillator were recorded via a multichannel soundcard (MOTU828, MA) at a rate of 44.1 kHz.

Ten players took part in the experiment: three professional players, four players with extensive experience in brass bands and orchestras and three players with little experience in trombone playing.

3 Results

3.1 Mouth and mouthpiece pressures

Players played notes of the harmonic series starting at B♭2 (usually the lowest note played using this position). When no further information was given about pitch, the playing frequencies are called normal frequencies, in contrast with those reached while lipping up or down.

All the notes were played *mp*. To achieve a constant amplitude in different repetitions, the pressure signals were displayed on an oscilloscope. Two horizontal cursors showed the desired peak-to-peak amplitude.

Figure 2 shows the values of the acoustic pressures in the mouth and in the mouthpiece averaged over all players.

For all notes, acoustic pressure in the mouth p_{mouth} is at most 0.13 times that in the mouthpiece p_{MP} and usually smaller. Thus, in a first approximation, the horizontal vibration mode of each lip, is driven by $-p_{MP}$.

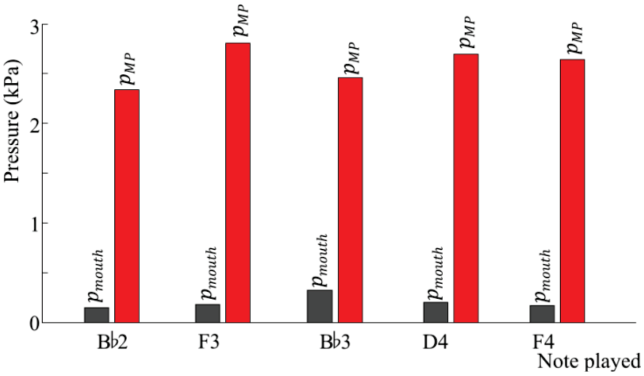

Figure 2: Acoustic pressures in the mouth (black) and in the mouthpiece (red), while the trombone players played the first notes of the harmonic series with the slide in first position: B♭2 to F4. The values were averaged over all the notes played by the different groups of players (beginners, advanced and professional players).

3.2 Lipping down

Players report that the pipe in the corner of the mouth perturbs playing and that, while this does not affect their normal playing significantly, it limits their ability to lip up or down. Further, because p_{mouth} was measured to be much smaller than p_{MP}, the transducer was removed from the performer's mouth. The rest of the experimental setup was unchanged. The professional players were unavailable for this experiment, so two beginner players first played a low pitch note B♭2, normal playing, at 117 Hz, with the same p_{MP} amplitude as before, and then decreased the playing frequency as much as they could without changing register. Then they repeated the experiment at B♭3, from which they were able to decrease significantly the playing frequency. Both were able to lip down significantly. One of them, an experienced trumpeter, was used to this technique.

The acoustic pressure in the mouthpiece was recorded as soon as the frequency and the amplitude of the signals were stable. At the same time the electrical conductance between the lips was measured by the EGG. It was expected to be approximately proportional to their surface of contact. Thus the inverse of this signal was expected to be maximal when the mouth is fully open and minimal when it is closed and so to be approximately in phase with the opening area of the aperture between the lips. Conducting electrodes on either side of the lips and connected to an EGG have been used in previous studies [10-12] to determine the phases of the lip opening.

The side view images show that the horizontal deflections of the different points on the edge of the lips have significantly different phases. Thus, for the trombone, one cannot choose a single point on one of the lips and use it to represent the horizontal component of the lip motion. Instead, for each lip, we measure the area of vertical cross section of the portion of tissue observed inside the mouthpiece cup for each lip in the side view. We then divide this area by the height of that lip in the mouthpiece to gain an average horizontal deflection of the upper and lower lips, called x_{up} and x_{low} respectively. The maximum vertical separation between the lips, called z, is measured on the front view.

To create Fig 3, two instants in the pressure signal separated by 12 vibration cycles were chosen at a time during the note when the amplitude was constant. For each measured signal, this time interval was divided into 11 groups of two consecutive vibration cycles, each group overlapping its predecessor by one cycle. Then these groups were averaged. Fig 3a shows B♭2 at normal frequency (117 Hz). In 3b, the player lips down to 104 Hz. In these figures, all signals were normalised to unit amplitude to allow easy comparison of phase differences.

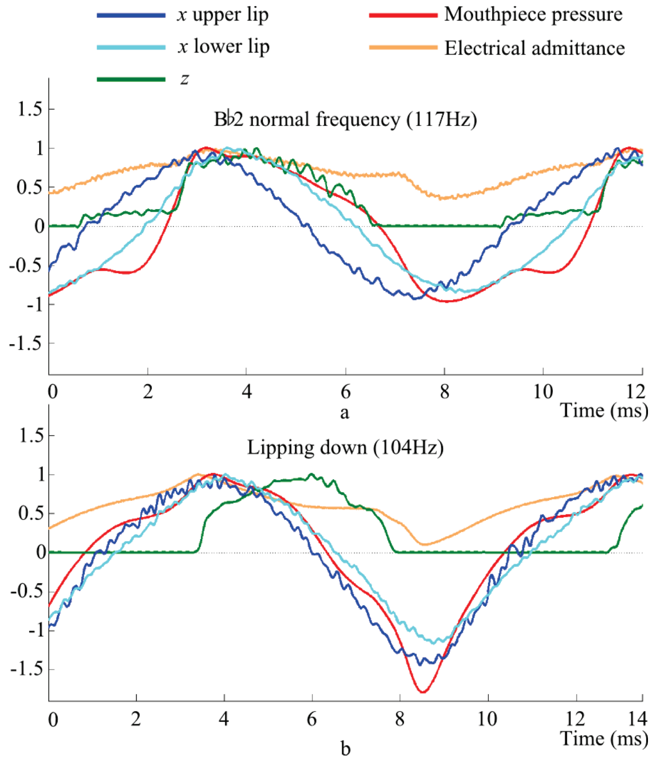

Figure 3: (a) Normalised waveforms when playing B♭2 at normal frequency (117 Hz) and (b) while reducing the playing frequency to 104 Hz ("lipping down").

For each measurement, the electrical admittance signal provided by the EGG and the distance between the lips are not in phase. Further, unlike z, the admittance does not maintain its minimal value throughout the time when the lips are closed. Thus this signal did not allow us to estimate accurately the period over which the mouth is closed.

When B♭2 is played at its normal frequency, z is approximately in phase with p_{MP} whereas it is significantly delayed at the lower playing frequency. In contrast, x_{up} is well ahead of p_{MP} when the playing frequency $f_p = 117$ Hz, while both signals are approximately in phase when lipping down. In this example, the average horizontal component of the lower lip lags behind that of the upper lip at both playing frequencies. However, this phase relation was not systematic: for different players and notes played, the horizontal deflection of the lower lip was sometimes ahead of the upper lip. Hereafter, the lip whose x-displacement leads in phase (moves forward earlier) is called *leading* lip.

The experiments for B♭3 normal (227 Hz) and lipping down (224 Hz) gave similar results: the phase of x_{up} and z

were respectively ahead of and behind that of p_{MP}, for both normal and lipping down, and they occurred later in the cycle for lipping down.

To compare the phase relations between x_{up}, x_{low}, p_{MP} and z, the spectra of these signals were calculated, and the magnitude and phase of the fundamental frequency are displayed in the phasor diagrams of Fig 4.

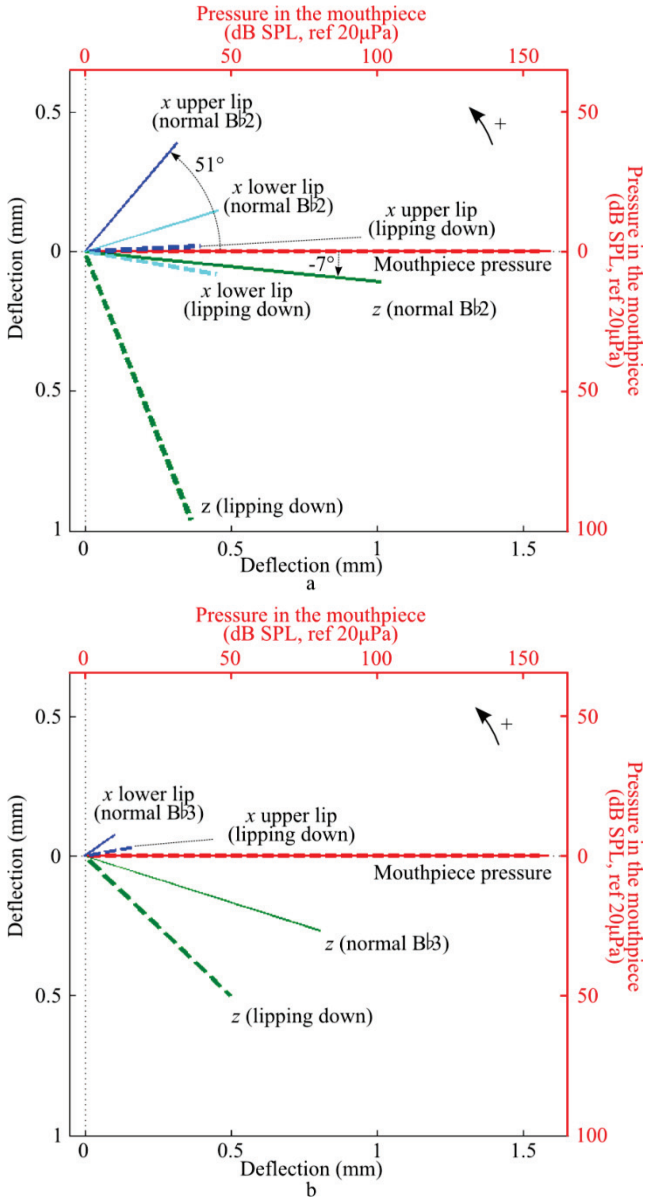

Figure 4: Phasor diagrams of pressure and horizontal and vertical displacements while a player plays B♭2 at normal frequency and lips down (a) and while he plays B♭3 and lips down (b). The pressure signals are expressed on the red axis in dB Sound Level Pressure relative to 20 µPa and the mean lip displacements in millimetres on the black axis. Solid lines are for normal frequencies (117 Hz and 227 Hz) and dashed lines for lipping down.

Figure 4a shows an example for the low note B♭3 for both normal pitch $f_p = 117$ Hz and lipping down, 104 Hz. These plots use the same time signals as those in Fig 3. Figure 4b shows the note B♭3 at the normal frequency $f_p = 227$ Hz and while lipping down to 224 Hz. The length of each line is proportional to the amplitude of the fundamental component of the signal, in mm for the deflections and in dB sound level relative to 20 µPa for the pressure. The angles show the relative phases, with the mouthpiece pressure arbitrarily chosen as the reference, 0°.

The amplitude of the deflections in both x and z directions appear to be larger for the lower pitch note. The diagrams of Figs 4a and 4b were measured with two different players. The same tendency was observed comparing measurements obtained in both ranges of frequency with the same player.

In both examples, the phase of the mouthpiece pressure at each playing frequency lies between the phases of the horizontal and the vertical components of the upper lip: $\varphi_z < \varphi_{p_{MP}} < \varphi_{x_{up}}$. In the measurements where the leading lip was the lower lip, the relation is $\varphi_z < \varphi_{p_{MP}} < \varphi_{x_{low}}$. In general, $\varphi_z < \varphi_{p_{MP}} < \varphi_{x_1}$ where x_1 refers to the horizontal deflection of the leading lip. In addition, the horizontal deflection of the other lip, x_2, sometimes lags behind the mouthpiece pressure, as in Fig 4a when lipping down.

Figure 4 shows that $\varphi_{x_{up}} - \varphi_{p_{MP}}$ and $\varphi_{p_{MP}} - \varphi_z$ are between 0 and 90° for each measurement. In addition, as described in Figs 3a and 3b, these phase differences significantly decrease when the players lip down, so that x_{up} and p_{MP} are almost in phase at the lowest pitch the player could reach before changing register.

4 Discussion

For this simple discussion, we treat each lip as a single mass. Their displacements in the plane (x, z) are modelled by the mean x displacements and the distance z between them. The vibration of each mass is a superposition of oscillations in the x-direction and z-direction, as described in section 1.

The first mode is driven by the pressure difference $p_{mouth} - p_{MP} \sim -p_{MP}$ since $p_{mouth} \ll p_{MP}$, see section 3. Like the components x_{up} and x_{low} measured in section 3, in general, the horizontal deflections $\hat{x}_{up}$ and $\hat{x}_{low}$ of the model are not in phase. Hereafter $\hat{x}_1$ refers to the leading lip, whose deflection leads in phase and $\hat{x}_2$ to the other.

Treating $\hat{x}_1$ and $\hat{x}_2$ as independent simple harmonic oscillators driven by the mouthpiece pressure:

$$\frac{\hat{x}_i}{-p_{MP}} = \frac{\alpha_x^i}{Q_x^i\left({\omega_{0x}^i}^2-\omega^2\right)+j\omega\omega_{0x}^i}, i \in \{1,2\} \qquad (1)$$

where $\omega_{0x}^i = \sqrt{k_x^i/m_x^i}$, $f_{0x}^i = \omega_{0x}^i/2\pi$ and Q_x^i denote the resonance frequency and the Q-factor respectively and m_x^i and k_x^i denote the modal mass and stiffness respectively of the horizontal modes of the lips. α_x^i is a coefficient related to the various losses and is assumed to be real.

The second mode is driven by the pressure between the lips, equal to p_{MP} assuming the jet is turbulent downstream from the lip valve. Thus the vertical separation of the masses of the model satisfies:

$$\frac{\hat{z}}{p_{MP}} = \frac{\beta_z}{Q_z(\omega_{0z}^2-\omega^2)+j\omega\omega_{0z}}, \qquad (2)$$

where $\omega_{0z} = \sqrt{k_z/m_z}$, $f_{0z} = \omega_{0z}/2\pi$ and Q_z denote the resonance frequency and the Q-factor respectively and m_z and k_z are respectively the modal mass and stiffness of the vertical mode. Again, β_z is assumed to be real.

To compare the phase of the horizontal and vertical deflections, we calculated the phase differences between $\hat{x}_i, i \in \{1,2\}$ and p_{MP} from (1) and between $\hat{z}$ and p_{MP} from (2). The coefficients $\alpha_x^i, i \in \{1,2\}$ and β_z are not used in the calculation of these phases.

To obtain order of magnitude estimates of parameters for the purposes of plotting curves, consider a lip under the configuration required to play trombone in the low register, with a mouthpiece ring but no instrument. If the lips are displaced and released, we estimate that their number of free oscillations is of the order of 1. The number is larger if we displace the lips in the vertical direction. From these very simple considerations, we give the following rough values to the Q-factors: $Q_x^i = 1, i \in \{1,2\}$ and $Q_z = 5$. The values of the Q-factors have no influence on the following discussion and are kept unchanged.

We calculate the resonance frequencies f_{0x}^1 and f_{0z} so that the differences of phase between $\hat{x}_1$ and p_{MP}, and between p_{MP} and $\hat{z}$, are respectively equal to the values of $\varphi_{x_{up}} - \varphi_{p_{MP}}$ and $\varphi_{p_{MP}} - \varphi_z$ measured on the diagram of Fig 4a for normal playing of B♭2. The phases $\varphi_{\hat{x}_1/p_{MP}}$ and $\varphi_{\hat{z}/p_{MP}}$ are calculated using **(1)** and **(2)** and plotted in solid lines in Fig 5. With the chosen values of parameters, the resonance frequency of the horizontal, 79 Hz, is lower than that of the vertical resonance, 266 Hz.

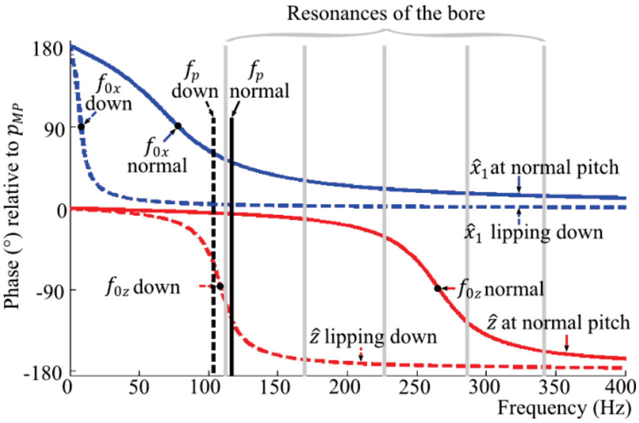

Figure 5: Phase relations for the leading lip in the simple model. Blue curves indicate the horizontal deflection of the leading lip and red curves the vertical distance between the lips. Solid lines are for normal pitch B♭2 (117 Hz) and dashed lines for lipping down (104 Hz).

Yoshikawa and Muto [8] used their stroboscopic data to estimate the elasticity of the lip tissue in the case of a horn player, based upon the assumption that the vertical mode is a Rayleigh surface wave. The pitch range studied was F2 to F4 or about 87 to 350 Hz and the shear modulus deduced ranged from 6×10^3 to 1×10^4 N.m^{-2} with no obvious frequency correlation. Making the simplest assumption of isotropic elastic behaviour, these results give a Young's modulus of between about 2×10^4 and 3×10^4 N.m^{-2}. This predicts a Rayleigh wave speed of 2.3 to 2.9 m.s^{-1}, this figure being based upon the fact that the Rayleigh wave speed is about 0.9 times the shear wave speed [13, 14]. If the lip thickness is about 5 mm and if this corresponds to a half-wave Rayleigh resonance, then the vertical mode frequency should be about 230 to 290 Hz, which is in agreement with the value of f_{0z} estimated here.

When the player 'lips' the frequency down to 104 Hz, the resonance frequencies f_{0x}^1 and f_{0z} are modified. They have been evaluated again so that the differences of phase $\varphi_{\hat{x}_{up}}$-$\varphi_{p_{MP}}$ and $\varphi_{p_{MP}}$-$\varphi_{\hat{z}}$ are equal to those measured (the dashed lines on Fig 4a). The values of the Q-factors are unchanged. The curves of phase are plotted in dashed lines in Fig 5.

The vertical grey lines on Figure 5 show the peaks of the bore impedance at the mouthpiece. They were measured with a technique used previously by Tarnopolsky [15, 16] and Chen [17] under playing conditions. These frequencies are slightly lower than the frequencies of the notes played normally in this experiment with the slide in first position: 117 Hz for B♭2, 227 Hz for B♭3. Thus, when the performers were asked to play notes at their normal frequency, the bore impedance was always compliant. However, when the players lipped down, they were also able to play below the nearest bore resonance. Thus the player's lips are capable of auto-oscillation under both inertive and compliant acoustic loads downstream. Further, there is no discontinuity between the two: players smoothly vary the pitch above and below the impedance peak. This observation has potential implications for the vocal folds, whose operation has some similarities with that of the trombonist's lips.

The curves of phase plotted in Fig 5 show that, in the model, the horizontal deflection of the leading lip always leads the vertical distance between the lips. This is in agreement with the orientation of 2-D trajectories of horn players' lips shown by Yoshikawa [8]. Further, both playing frequencies, 117 Hz (normal) and 104 Hz (lipping down), lie between the resonance frequencies f_{0x}^1 and f_{0z}.

Further, the phase differences $\varphi_{\hat{x}_1/p_{MP}}$ and $\varphi_{\hat{z}/p_{MP}}$ are reduced as the playing frequency decreases. Thus, in this simple model, when the player lips down, the resonance frequencies f_{0x}^1 and f_{0z} are significantly lowered. The playing frequency f_p is also reduced but to a much smaller extent.

For both B♭2 and B♭3, the players report that they lip down by reducing the tension of their lips, which one would expect to cause a reduction of f_{0x}^1 and f_{0z} as shown by the dashed curves of Figure 5. Further studies may determine whether the playing frequency necessarily lies between the resonance frequencies f_{0x}^1 and f_{0z}. If so, to lip up or down, the players may control these resonance frequencies in order to apply the desired modification to the pitch.

Modifying the position of the mouthpiece relative to the lips may also change the modal parameters involved in their oscillation. For instance, lowering the mouthpiece increases the effective mass of the lower lip, and perhaps decreases its effective stiffness, while having the opposite effects on the upper lip. As a result, if the mouthpiece is low enough, f_{0x} of the upper lip becomes larger than that of the lower lip. Then $\hat{x}_{up}$ is ahead of $\hat{x}_{low}$ and the upper lip becomes the leading lip. Again further experiments are needed to confirm this interpretation and to determine whether it is used tactically by players.

Conclusion

For all cases studied here, the phase of the horizontal motion of the lips into the mouthpiece leads that of the pressure increase in the mouthpiece by an angle typically lower than 60°. The phase of the mouthpiece pressure, in turn, leads that of the lip opening. The opening of the inter-lip aperture is close in phase to the mouthpiece pressure. For all notes, the phases are consistent with a simple model in which the horizontal motion is a cantilever oscillator with frequency below that of the playing frequency $\boldsymbol{f_p}$, and driven by the negative of the mouthpiece pressure, while the vertical motion is that of a mass on spring with frequency above $\boldsymbol{f_p}$ and driven by the mouthpiece pressure. For low pitch notes, both vertical and horizontal modes have significant amplitudes, while the motion is mostly vertical at higher pitches. Lipping down delays the phase of both displacements with respect to the mouthpiece pressure, and so is consistent with a lowering of the natural frequencies of both oscillators. Players can vary the playing frequency smoothly between inertive and compliant loads.

Acknowledgments

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