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Investigation of the effect of upstream airways impedance on regeneration of lip oscillations in trombone performance

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In this study we make use of a new sensor that measures the variations of electrical conductance across the lips in brass instrument performance, and therefore enables the evaluation of the phase of the lip opening area. By combining this value with the phase of the acoustic pressures on the downstream and upstream sides of the lips, we investigate the nature of the coupling between the lips, the downstream air-column and the vocal-tract in trombone performers. This method allows for the study of vocal-tract tuning at any frequencies where energy is present in the resulting sound with a high temporal resolution (within a tone), as well as characterization of the oscillatory mechanism of the lips (dominant outward versus dominant upward striking behaviour). Experimental results from measurements on a trombone player are discussed in light of numerical simulations where a two-dimensional model of the vibrating lips is coupled to both a downstream and upstream reflectance.

1 Introduction

The theory of regeneration in brass instruments as reported by Elliot and Bowsher [1], implies that self-oscillations of the reed are supported by a strong aero-acoustical coupling with the downstream air-column (resonator). In brass instruments, such as the trombone, the conditions under which this coupling is established require the musician to precisely adjust the mechanical properties of the lips, so that a lip mechanical resonance matches with a specified impedance maximum of the downstream air-column at the sounding frequency.

Upstream from the lips, the player's airway (vocal-tract) constitutes an additional resonator likely to offer a non-negligible acoustical feedback. Observation of the relative influence of the upstream and downstream systems has been possible by measuring the ratio of the acoustic pressure created at the input of the vocal-tract and the downstream air-column [2]. Significant support of the vocal-tract has been observed in the high register of the instrument in trombone performance, which suggests a strategic vocal-tract adjustment from the players. However this approach does not provide further details regarding the modalities of this upstream "tuning". Multiplying the complex ratio of the upstream and downstream pressures by the complex input impedance of the downstream system Z_d measured experimentally has enabled the evaluation of the complex value of the upstream impedance Z_u at the playing frequency [3]. However, this estimation may be particularly sensitive to the accuracy of Z_d measurement.

In this study, we propose a new experimental approach for the study of vocal-tract tuning, and characterization of lip vibratory mechanism, based on the observation of the phase of dynamic quantities measured at the interface between the player and his/her instrument. Results from pilot experiments are discussed in light of numerical simulations involving a two-dimensional model of the lips as proposed by Adachi and Sato [4], coupled to a downstream and upstream reflectance.

2 Experimental approach

2.1 Lip conductance measurement

A lip-conductance sensor (Figure 1) was developed in order to extract the phase of lip opening area S_{lip} in brass performers. This sensor is based on the principle of electroglottography (EGG), commonly applied to the investigation of vocal-fold contact area in the voice. A high frequency modulated current is sent through the lips by mean of two electrodes located across the lips (one electrode on the upper lip and one on the lower lip). Contact electrodes are made of tin-plated copper foil shielding tape glued on the rim of a plastic mouthpiece designed by CFMI Université Lille 3 in France. The resistance of the electrode pair was raised to 40Ω by a resistor soldered to one of the electrodes in order to fit with the signal conditioner requirements. Electrodes were connected to a commercial Voce Vista EGG signal conditioner and the analog output sent to a National Instrument converter.

After demodulation, the recorded signal is therefore proportional to variations of electrical conductance across the lips C_{lip}, assumed to be proportional to the variation of contact area between the lips [5]. Thus, we can reasonably postulate that C_{lip} is inversely proportional to the lip opening area S_{lip}, in other words that C_{lip} and S_{lip} are out of phase by 180 degrees.

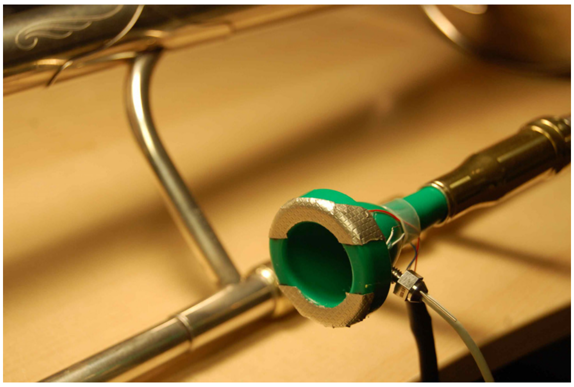

Figure 1: Lip conductance sensor and pressure transducer embedded in a plastic trombone mouthpiece and mounted on a King 2102 Silver Sonic tenor trombone.

2.2 Upstream and downstream pressure

Synchronously to the lip conductance signal C_{lip}, the acoustic pressure at the input of the instrument P_d, and acoustic pressure at the input of the vocal-tract P_u were recorded using a pair of miniature Endevco microphones [2, 3]. The downstream microphone measured the acoustic pressure in the mouthpiece cup while the upstream microphone was held in the player's mouth cavity, as close as possible from the lip opening. The three signals were recorded with at 12kHz sampling rate on a 24-bit National Instrument acquisition board.

2.3 Recording and processing

C_{lip}, P_d, and P_u were recorded during performance of an ascending and descending overtone series without tonguing by one trombone player, also first author of this paper. Experiments could not be extended to further subjects for ethical reasons due to potential health risks of electrodes (new material and techniques are being explored to replace existing electrodes).

A Fast Fourier Transform was applied on each signal over a 1024-sample sliding window with 93.75% overlap. An example of acquired waveforms is represented in Figure 2.

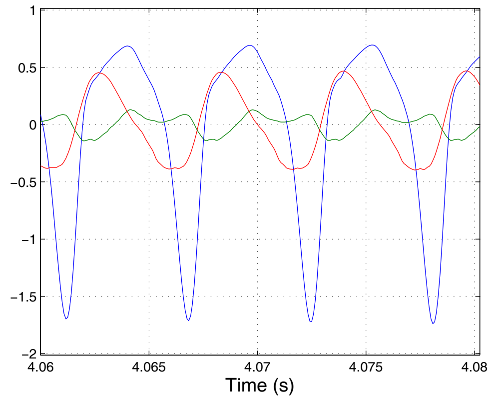

Figure 2: Waveforms of the lip conductance C_{lip} (red), downstream pressure P_d (blue), and upstream pressure P_u (green) during a sustained tone played on trombone.

2.4 Analysis

The response of the lip motion to the downstream driving pressure is defined by Elliot and Bowsher [1] as:

$$G_d(\omega) = \frac{S_{lip}(\omega)}{P_d(\omega)} \quad (1)$$

We call $G_d(\omega)$ the lip mobility. According to the theory of regeneration, the magnitude of $G_d(\omega)$ should have a peak around the resonance frequency of the lips, and the frequency dependent phase of $\angle G_d(\omega) = \angle S_{lip}(\omega) - \angle P_d(\omega)$ characterizes the lip vibration mechanism (outward vs. inward mechanism).

Following this approach, we define the upstream lip mobility $G_u(\omega)$, and the corrected downstream lip mobility $G(\omega)$ such as:

$$G_u(\omega) = \frac{S_{lip}(\omega)}{P_u(\omega)} \quad (2)$$

$$G(\omega) = \frac{S_{lip}(\omega)}{(P_d - P_u)(\omega)} \quad (3)$$

Since we know that S_{lip} and C_{lip} are π radians out of phase, we are able to derive the values of $\angle G_d(\omega)$, $\angle G_u(\omega)$, and $\angle G(\omega)$ by substituting $S_{lip}(\omega)$ with $-C_{lip}(\omega)$ in Eq. (1), (2) and (3).

Within the scope of linear theory of oscillation, the phase regeneration condition that needs to be satisfied at the sounding frequency f_0 is given by the following expression:

$$\angle G(\omega) + \angle Z(\omega) = 0, \quad (4)$$

where $Z(\omega)$ is the total effective impedance governing lip oscillation. Analogously, we can define downstream and upstream phase conditions of regeneration where $Z_d(\omega)$ and $Z_u(\omega)$ denote respectively the input impedance of the downstream air-column and input impedance of the vocal-tract.

$$\angle G_d(\omega) + \angle Z_d(\omega) = 0 \quad (5)$$

$$\angle G_u(\omega) + \angle Z_u(\omega) = \pi \quad (6)$$

Therefore, if we assume that regeneration occurs on both sides of the lips, we may postulate that $\angle G_d(\omega)$, $\angle G_u(\omega) - \pi$, and $\angle G(\omega)$ are respectively estimates of $-\angle Z_d(\omega)$, $-\angle Z_u(\omega)$, and $-\angle Z(\omega)$. These values tell us about the nature of the coupling on both sided of the lips: a positive value of $\angle G_d(\omega)$ implies a negative value of $\angle Z_d(\omega)$ i.e. capacitive downstream reactance at the sounding frequency. On the contrary, if $\angle Z_d(\omega)$ is positive, it implies an inertive downstream reactance at f_0. This same rational can be applied to $\angle Z_u(\omega)$.

Furthermore, by considering $\angle G_d(\omega)$, $\angle G_u(\omega) - \pi$ and $\angle G(\omega)$, and looking at the relative distance between these three quantities, we may also evaluate to what extent the downstream and upstream systems are involved in the regeneration of lip oscillations.

Finally, independently from the nature of the coupling with the downstream and upstream airways at f_0, the sign of $\angle G(\omega)$ provides us with the dominant mechanism which regulates lip oscillation: outward striking for positive values of $\angle G(\omega)$, and inward striking for negative values.

We therefore conclude that this approach enables the study of three aspects of the performance:

- The nature of lip vibration mechanism (dominant outward vs. dominant inward striking behaviour).
- The relative contribution of $Z_d(\omega)$ and $Z_u(\omega)$ to the regeneration of lip auto-oscillations at at any frequencies where energy is present in the resulting sound.
- The nature of the downstream and upstream coupling at f_0, which indicates the degree of "tuning" of $Z_d(\omega)$ and $Z_u(\omega)$.

3 Experimental results

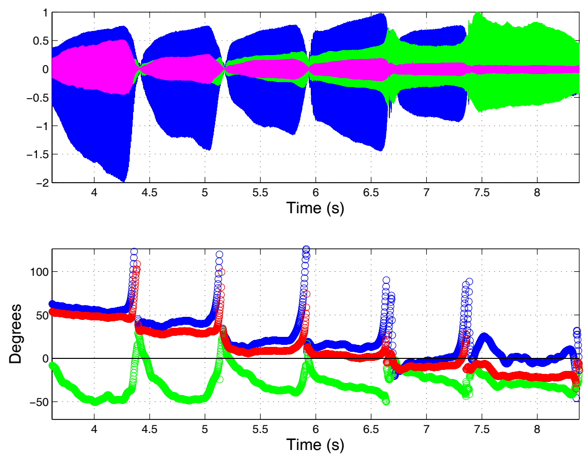

Figure 3: Top: Waveforms of the high-pass filtered lip conductance C_{lip} (magenta), downstream pressure P_d (blue), and upstream pressure P_u (green). Bottom: $\angle G_d(f_0)$ (blue), $\angle G_u(f_0) - \pi$ (green), and $\angle G(f_0)$ (red) during ascending overtones from F3 to D5.

Results obtained for an ascending overtone series from F3 to D5 (F3 B3-flat D4 F4 B4-flat D5) are shown in Figure 3. Waveforms of P_d, P_u, and the oscillating component of C_{lips} (high-pass filtering of the lip conductance signal) are

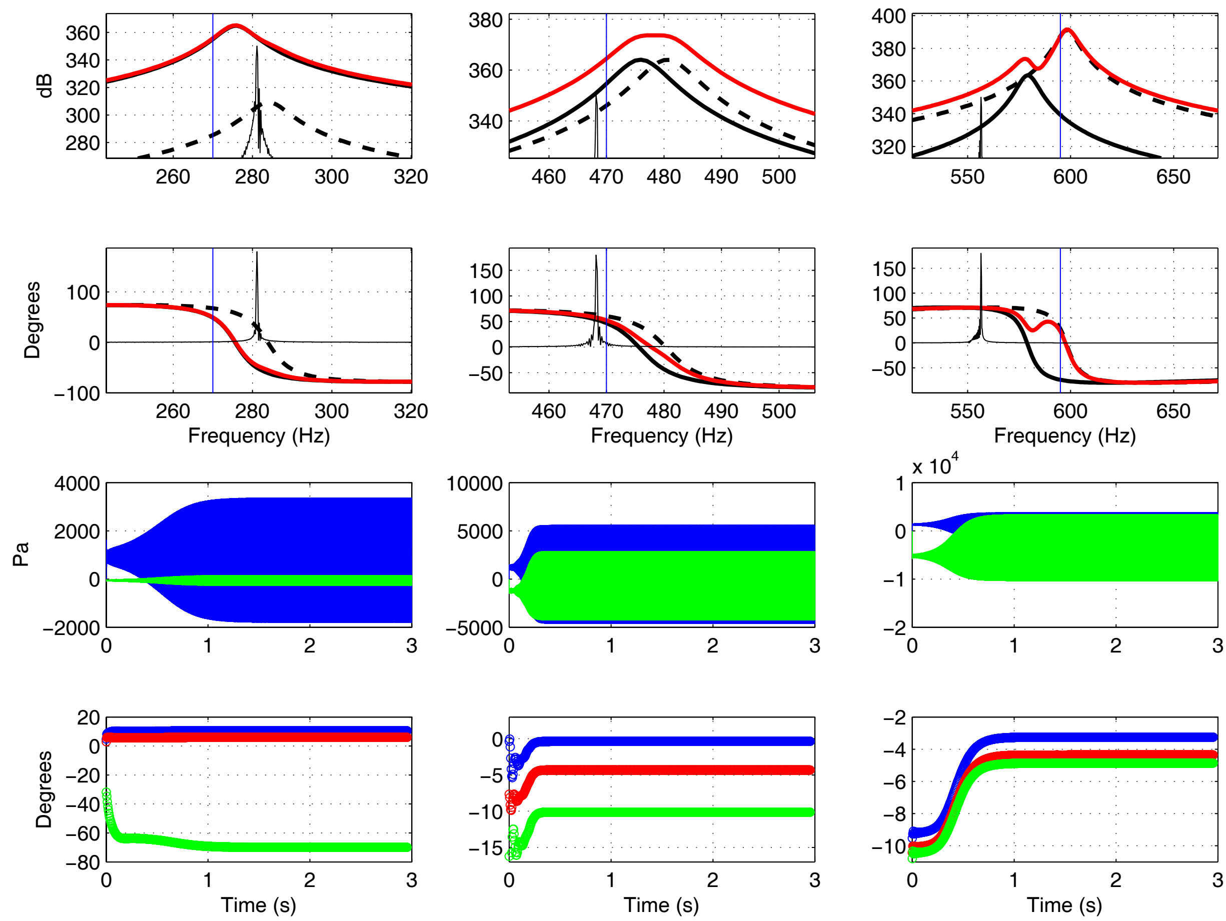

Figure 4: Numerical simulation of three tones at 282Hz (left column), 468Hz (middle column), and 555Hz (right column). Top graphics: magnitude and phase of the downstream (solid line), upstream (dashed line), and sum of the downstream and upstream impedances (red line). The spectrum of the downstream pressure is plotted (thin black trace) to indicates the sounding frequency f_0. The vertical blue line indicate the resonance frequency of the lips. Bottom graphics: waveforms of the downstream pressure P_d (blue) and upstream pressure P_u (green). Values of $\angle G_d(f_0)$ (blue), $\angle G_u(f_0) - \pi$ (green), and $\angle G(f_0)$ (red) calculated from simulation results.

represented in the top plot, and $\angle G_d(f_0)$, $\angle G_u(f_0) - \pi$, and $\angle G(f_0)$ in the bottom graphic.

3.1 Lip mechanism

The phase of $G(f_0)$, which represents the response of the lip motion to the driving pressure difference across the lips, varies from 50 degrees for the lowest tone (F3) to -20 degrees for the highest tone (D5). This indicates a transition between a dominant outward to dominant inward or upward striking regime of oscillation. These results therefore corroborate previous estimations [6].

3.2 Vocal-tract tuning

From Eq. (1), (2) and (3), it can be shown that the relative contributions of the upstream and downstream systems to lip regeneration are given by the distances, respectively, $|\angle G(f_0) - \angle G_d(f_0)|$ and $|\angle G(f_0) - (\angle G_u(f_0) - \pi)|$, normalized by the distance $|\angle G_d(f_0) - (\angle G_u f_0) - \pi)|$. In other words, the position of $\angle G(f_0)$ curve relative to to $\angle G_d(f_0)$ and $\angle G_u(f_0) - \pi$ indicates to which extent the downstream air-column and upstream vocal-tract participate in providing feedback to lip oscillations.

Overall, we observe a decrease of $\angle G_d(f_0)$ and $\angle G(f_0)$, and increase of $\angle G_u(f_0) - \pi$, with increase in playing frequency. $\angle G_d(f_0)$ are comprised between about 60 degrees and -20 degrees, whereas $\angle G_u(f_0) - \pi$ are comprised between -50 degrees and 25 degrees. Only focusing on the steady portion of each tone, the sign of $\angle G_d(f_0)$ suggest a capacitive downstream coupling in the low register moving towards an inductive coupling in the high register. However the negative sign of $\angle G_u(f_0) - \pi$ suggests a predominant inductive upstream coupling during this exercise. From F3 to F4, $\angle G(f_0)$ and $\angle G_d(f_0)$ almost overlap, indicating that the lips are predominantly driven by the downstream impedance. For B4-flat, the three curves significantly overlap at the beginning of the tone which suggests that $Z_d(\omega)$ and $Z_u(\omega)$ are in phase at the sounding frequency. This tendency is not followed over the rest of the tone. An important change is observed for D5 where $\angle G(f_0)$ becomes closer to $\angle G_u(f_0) - \pi$, indicating a dominant coupling with the vocal-tract in that case.

By looking at the variations of $\angle G_d(f_0)$ and $\angle G_u(f_0) - \pi$ over the course of the task, we observe that tone transitions are characterized by an abrupt growth of $\angle G_d(f_0)$ at the end of each tone. This is justified by the "jump" to a new downstream impedance peak during tone transitions, which implies a discontinuous variation of $\angle G_d(f_0)$. However, $\angle G_u(f_0) - \pi$ does not display any discontinuous behaviour at tone transitions; $\angle G_u(\omega) - \pi$ increases to positive or almost null values and overlaps with $\angle G(f_0)$ at the beginning of all tones. It then decreases back to negative values. This continuous and "cyclic" behaviour" may indicate that upstream control occurs in a "continuous manner": upstream impedance is adjusted continuously by the player according to the playing frequency. The overlapping of $\angle G_u(f_0) - \pi$ and $\angle G(f_0)$ at tone onsets indicates that vocal-tract impedance may have a significant role in supporting tone transitions in the context of ascending overtones.

4 Numerical simulations

To further analyze our experimental results, we implement a mechanical model of the lips interacting with both a downstream and upstream impedance. To simplify the simulation, downstream and upstream impedances are modeled by single resonances. By varying control parameters of the lip model, as well as the characteristics of downstream and upstream impedance, we try to simulate experimental results observed in the previous part, based on the phase value of $G_d(f_0)$, $G_u(f_0)$, and $G(f_0)$. Our focus is on the sustained portions of the tones.

4.1 Lip-model and windway resonances

As we want the lip to be able to oscillate with either a positive or negative phase difference relative to the driving pressure difference across the lips, we implement a two-dimensional model of the lips as proposed by Adachi and Sato [4]. A time-domain simulation is carried out using the forward Euler method for the discretization of the mechanical and non-linear airflow equations. The feedback equation in [4] is replaced by two single second-order digital resonators to model the downstream and upstream resonances. The static mouth pressure component of the model is extracted and added to the reflected upstream pressure component.

4.2 Simulations of three tones

Three different tones are simulated around 282Hz, 468Hz, and 555Hz, corresponding approximately to D4, B4-flat, and D5. For each condition, the center frequency and amplitude of the downstream and upstream resonances are adjusted in order to approximate experimental observations. One lip parameter (lip thickness) is adjusted for each tone in order to favor one or the other outward or inward striking regime of oscillation. Other geometrical parameters are unchanged across the three simulations. The static mouth pressure is ramped up following a raised cosine trajectory until the maximum value is reached. The maximum value is set independently for each tone so that stable oscillations are obtained.

4.3 Numerical simulation results

Results are displayed on Figure 4. Each column corresponds to one tone. The two top graphics represent the magnitude and phase of the input impedance (seen from the lips) of the downstream, upstream, and sum of the downstream and upstream resonances. The two bottom graphics represent the simulated waveforms of P_d and P_u, and the phase values $\angle G_d(f_0)$, $\angle G_u(f_0) - \pi$ and $\angle G(f_0)$, respectively.

4.3.1 Observations for individual tones

In the D4 case, the magnitude of the downstream impedance is high compared to the upstream impedance. Lip oscillations occur on the negative phase side of the downstream impedance peak and on the positive phase side of the upstream impedance peak. This corresponds to a positive phase value of the downstream lip mobility ($\angle G_d(f_0) \simeq 10°$) and the negative phase value of the upstream lip mobility ($\angle G_u(f_0) - \pi \simeq -70°$). The strong downstream coupling predominantly supports regeneration, and $\angle G(f_0) \simeq \angle G_d(f_0)$. This condition favors an outward regime of oscillation. This is confirmed by the value of the sounding frequency f_0, higher than both the lip frequency (vertical blue line) and the peak frequency of $Z_d(\omega) \simeq Z(\omega)$.

In the B4-flat case, the magnitude of the downstream and upstream impedance are identical and the downstream and upstream peaks are about 5Hz from each other. Lip oscillations occur on the positive side of $\angle Z_u$ peak as confirmed by the negative phase value of $\angle G_u(f_0) - \pi \simeq -10°$. However, although $\angle Z_d$ is positive at f_0, $\angle G_d(f_0)$ is found around zero ($\angle G_d(f_0) \simeq -0.4°$). This observation highlights the nonlinear relationship between S_{lip}, P_d, P_u, and U carried by the airflow equation of the model [4]. The value of $\angle G_d(\omega)$ lies about the same distance from $\angle G_d(f_0)$ and $\angle G_u(f_0) - \pi$ which suggests that both downstream and upstream systems participate to support the lip oscillations to a similar extent. As the phase of $G(f_0)$ is negative, this condition supports an inward regime of oscillation, as supported by f_0 value lower than both the lip frequency and $Z(\omega)$ peak frequency.

In the D5 case, the magnitude of the upstream impedance is higher than the downstream impedance. Lip oscillations occur on the positive side of both impedance peaks as confirmed by the values of $\angle G_d(f_0) \simeq -3.3°$ and $\angle G_u(f_0) - \pi \simeq -4.9°$ when the steady state is reached. Upstream feedback is predominant as Z_u magnitude is higher than Z_d magnitude at the playing frequency, and $\angle G(f_0)$ is closer from $\angle G_u(f_0) - \pi$. However, $\angle G_d(f_0)$ and $\angle G_u(f_0) - \pi$ are close enough to consider that Z_d and Z_u are "in tune" at the playing frequency; $\angle Z_d(f_0) \simeq \angle Z_u(f_0)$. The negative phase of $G(f_0)$ also supports an inward regime of oscillation, as attested by f_0 value significantly lower than both the lip frequency and $Z(\omega)$ peak frequency.

4.3.2 General observations

We notice that each tone displays a transitory phase of varying length. This feature is particularly visible in the variation of $\angle G_d(f_0)$, $\angle G_u(f_0) - \pi$ and $\angle G(f_0)$ at the onset. These variations are correlated with fluctuations of f_0 that occur during the transitory phase. Further investigation may be required to ascertain these observations but this is out of the scope of this paper.

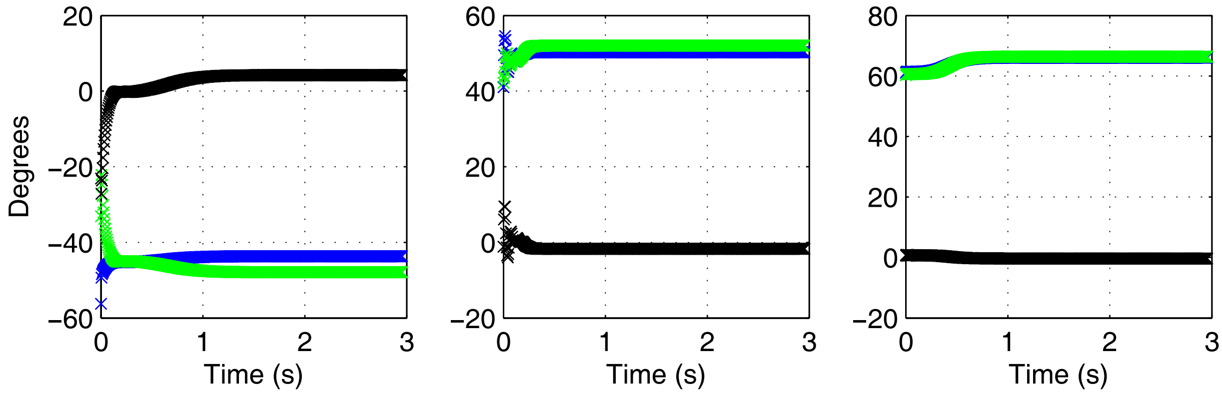

Figure 5: Values of $\angle G_d(f_0) + \angle Z_d(f_0)$ (blue), $\angle G_u(f_0) - \pi + \angle Z_u(f_0)$ (green), and $|\angle G_d(f_0) - (\angle G_u(f_0) - \pi)| - |\angle Z_d(f_0) - \angle Z_u(f_0)|$ (black), for the three simulated tones: 282Hz (left column), 468Hz (middle column), and 555Hz (right column).

Secondly, as the flow equation implies a non-linear relation between U, P_d, P_u and S_{lip}, numerical simulations highlight limitations of the linear theory analysis. Figure 5 represents the sum of $\angle G_d(f_0)$ and $\angle Z_d(f_0)$, $\angle G_u(f_0) - \pi$ and $\angle Z_u(f_0)$, as well as the difference between the distances $|\angle G_d(f_0) - (\angle G_u(f_0) - \pi)|$ and $|\angle Z_d(f_0) - \angle Z_u(f_0)|$, for the three simulated tones. Although significantly non-null values are observed for the sum of $\angle G_d(f_0)$ and $\angle Z_d(f_0)$, and $\angle G_u(f_0) - \pi$ and $\angle Z_u(f_0)$, the difference between the two distances is close to zero. This suggests that $\angle G_d(f_0)$ and $\angle G_u(f_0) - \pi$ are bad estimates of $\angle Z_d(f_0)$ and $\angle Z_u(f_0)$ respectively. However, the distance $|\angle G_d(f_0) - (\angle G_u(f_0) - \pi)|$ provides a reliable measurement of the phase distance between Z_d and Z_u at the sounding frequency. As a matter of fact, we see from Eq. (1) and (2) that $\angle G_d(\omega) - (\angle G_u(\omega) - \pi) = \angle P_u(\omega) - \angle P_d(\omega) + \pi$, while $\angle P_u(\omega) - \angle P_d(\omega) + \pi \simeq \angle Z_d(\omega) - \angle Z_u(\omega)$ within the assumption of continuity of the airflow at the reed junction. Thus, experimental observation of $\angle G_d(f_0) - (\angle G_u(f_0) - \pi)$ in real performers furnishes reliable knowledge on the characteristics of the phase tuning between the upstream and downstream impedance at the sounding frequency.

5 Conclusion

The experimental set-up presented in this study enables the evaluation of variations in vocal-tract support, as well as changes in lip mechanism in a musical task. The relative contribution of the downstream and upstream airways can be estimated by comparing the phase values of the lip mobilities $\angle G_d(\omega)$, $\angle G_u(\omega) - \pi$, and $\angle G(\omega)$ at the playing frequency. Experimental results revealed a "continuous" adjustment of vocal-tract impedance at f_0 denoting significant upstream support during tone transitions and a growing influence of vocal-tract impedance with pitch as observed in previous studies [2, 3] . Moreover, $\angle G(f_0)$ allows the characterization of the lip vibration mechanism, varying from a dominant outward striking regime for the lower register to a dominant inward striking regime in the higher register as expected from former evaluations [4, 6].

In light of numerical simulations including non-linear terms in the flow equation, we have shown that $\angle G_d(f_0)$, $\angle G_u(f_0) - \pi$ are bad estimates of $\angle Z_d(f_0)$ and $\angle Z_u(f_0)$. However they provide an accurate evaluation of the phase difference between Z_u and Z_d at f_0. This latter conclusion suggests that in-vivo measurements of $\angle G_d(f_0)$, $\angle G_u(f_0) - \pi$ may bring reliable information regarding the degree of tuning of the downstream and upstream systems during performance. The further development of the lip conductance sensor using a safer material for the electrodes will enable measurements on a large pool of musicians and a better characterization of intra and inter individuals vocal-tract tuning strategies.

Finally, the characteristics of the lip conductance signal have not been discussed in this study. Further investigations could be potentially applied to C_{lip} waveform for the extraction of additional features regarding lip mechanical behaviour as performed in the study of electroglottograph signals in voice (open quotient for example).

Acknowledgments

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