Acoustical properties of the vocal-tract in trombone performance

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Summary
The study of the acoustical influence of the upstream (vocal-tract) airway in wind instrument performance has been a growing subject of interest in musical acoustics. In a recent study performed on trombone players, we observed a noticeable increase of the acoustic pressure near the fundamental frequency at the input of the vocal tract relative to the acoustic pressure at the input of the instrument with increase in pitch. Upstream pressure particularly overtook downstream pressure amplitude for tones above the theoretical cut-off frequency of the air column (around 700 Hz), as well as in pitch bends for which players sound a tone on the lower side of an input impedance peak of the air-column. Overall, these observations suggest that vocal-tract manipulations may be used for upstream tuning in supporting the oscillation of the lips when the magnitude of the downstream input impedance is low enough. However, these results did not provide any evidence of a consistent adjustment of vocal tract input impedance during these tasks. In this study, we evaluate the amplitude of vocal-tract input impedance in trombone performance from upstream and downstream pressure spectra and measurements of the input impedance of a trombone. Measurements are conducted during high pitches, pitch bends, as well as timbre manipulations. We evaluate the consistency of vocal-tract impedance magnitudes across subjects with the aim of identifying whether a vocal-tract tuning occurs during these specific tasks.

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1. Introduction

Over the past few years, there have been numerous investigations of possible vocal-tract influence in the control of wind instrument sound production. Particular interest has been focused on this effect in reed woodwind instrument performance [1, 2, 3, 4, 5]. In the case of reed instruments such as the saxophone or clarinet, the reed's natural frequency is usually high compared to the playing frequency. Consequently, a significant resonance of the downstream or upstream system can control the reed oscillation below the resonance frequency of the reed [6]. Tuning of vocal tract resonances (usually evaluated as the input impedance at the lips) was shown to be consistently used by performers in some specific tasks, especially in the higher register and in pitch bends [1, 2, 3, 4]. Most recent results demonstrate the ability of the player to adjust vocal-tract resonances in range from 400 to 1400 Hz in tenor saxophone [5]. In the field of singing voice, vocal-tract tuning was observed in sopranos who demonstrate the ability to match the first formant resonance with the fundamental frequency of the sound in the upper range [7, 8].

Concerning lip reed instruments, the question of vocal-tract influence is complicated by the mechanical characteristics of the lips. By adjusting lip tension and vibrating mass through muscular recruitment and changes in mouthpiece constraints, the player is able to control the frequency, magnitude and damping of lip resonances and therefore facilitate bifurcation of the lips towards an oscillating regime at a frequency close to a resonance of the air column [9, 10]. A fundamental question is whether brass instrument players make use of upstream resonances to help initiate and support lip vibrations, especially when the magnitude of the downstream impedance at the lips is weak. Didjeridu performers demonstrate a clear influence of vocal tract adjustments on the characteristics of the radiated sound. Some formants in the radiated sound spectrum were shown to result from vocal-tract impedance minima measured at the lips [11]. A recent study conducted on trombone performance [12] revealed an increase of the ratio of the mouth to mouthpiece acoustic pressure during ascending overtones and pitch bends. In the higher register (near the

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cut-off frequency of the air column), the ratio of the upstream to downstream pressure at the fundamental frequency reached values above one, which suggests a higher magnitude of the vocal-tract impedance compared to the corresponding downstream impedance at this frequency.

However, variations of this ratio do not necessarily provide any evidence of an actual adjustment of vocal-tract resonances from the player. As a matter of fact, a decrease of the magnitude of the downstream impedance with no variation of amplitude of the upstream impedance will result in an increase of the upstream to downstream pressure ratio that does not reflect a tuning of the vocal-tract from the performer. Therefore, only a quantitative estimation of upstream input impedance is able to provide evidence of vocal tract adjustments that accompany a specific task. This will determine whether vocal-tract tuning can be considered as part of a strategy undertaken by the player to support lip oscillations.

In this study, we evaluate the complex input impedance of the vocal-tract in trombone players when performing overtones and pitch bending. Our approach is based on the simultaneous recording of the acoustic pressure at the input of the vocal-tract and input of the of the air column during performance. If one considers Z_d and Z_u, the input impedance of the downstream and upstream systems and P_d and P_u, the acoustic pressure measured at the downstream and upstream sides of the lips, an assumption of continuity of the volume flow at the reed junction leads to Eq. 1 below. This expression enables an estimation of $Z_u(\omega)$ as a function of $Z_d(\omega)$, $P_d(\omega)$ and $P_u(\omega)$.

$$Z_u(\omega) = Z_d(\omega)\frac{P_u(\omega)}{P_d(\omega)} \tag{1}$$

The complex input impedance Z_d is measured using a system described in a companion paper [13]. This allows us to estimate the complex upstream input impedance Z_u at frequencies where significant acoustic energy is observed. This occurs at the fundamental frequency f_0 and harmonics of the played tone $(f_1, f_2, ..., f_n)$. Figure 1 displays the magnitude of the input impedance normalized by its characteristic impedance of the King 2102 Silver Sonic tenor trombone in closed position (with mouthpiece) used for the experiments to be described..

2. Methods

2.1. Experimental procedure

We apply the same experimental procedure as in [12]. An Endevco miniature microphone (8507C-1) was attached to a short tube (2 centimetres long), which was inserted into the mouth of the player near the corner of the lips. The subjects were instructed to keep the tube end as close as possible to the inside wall of the teeth so that the recording is performed as close as possible to the lips. For the downstream pressure, an Endevco 8510B-1 microphone was mounted on a customized mouthpiece so that its distance to the edge of the lips is about 5 millimetres.

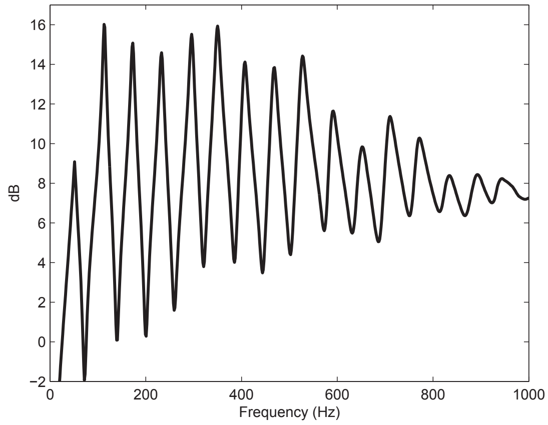

Figure 1. Magnitude of the input impedance normalized by its characteristic impedance of a King 2102 Silver Sonic tenor trombone with the customized mouthpiece used for the experiments.

Six subjects from classical and jazz performance programs at McGill University participated in the experiments. Four of them were tenor trombone players (subjects A, D, E and F), and the two others (subjects B and C) were bass trombone players. Despite these distincts profiles, all the subjects played on the same trombone with the same mouthpiece (a King 2102 Silver Sonic tenor trombone and a plastic mouthpiece with dimensions close to a small shank Vincent Bach 6 1/2 AL). In a first step, after being familiarized with the mouth microphone, subjects were asked to perform an overtone series from F3 to F5 and back to F3 with the slide in closed position. In a second step, they were asked to perform pitch bends from B2-flat to A2 and A2-flat while keeping the slide in closed position. Subjects were instructed to perform this harmonic motion as in a glissando manner. Eventually, they were instructed to perform the same glissando effect from B2-flat to A2 and then from B2-flat to A2-flat in normal condition, that is to say by pushing the slide for A2 and A2-flat respectively in 2nd and 3rd positions. Slide positions were instantiated for later measurements of the trombone input impedance. Measured Z_d were normalized by the characteristic impedance and a 3 mm length correction factor was applied to take into account the lip incursion into the mouthpiece. Figure 2 shows the waveform of the upstream and downstream pressure recorded for subject A during ascending and descending overtones. The center of the figure (around 5 seconds) corresponds to the highest tone (F5) whereas the edges correspond to the lowest (F3).

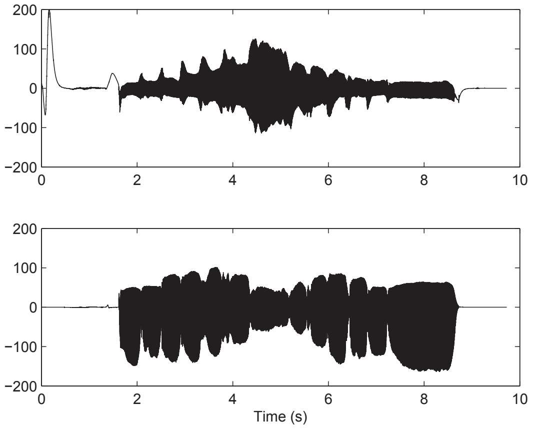

Figure 2. Waveform of the upstream pressure (top) and downstream pressure (bottom) during an ascending and descending overtone series from F3 (175 Hz) to F5 (700 Hz).

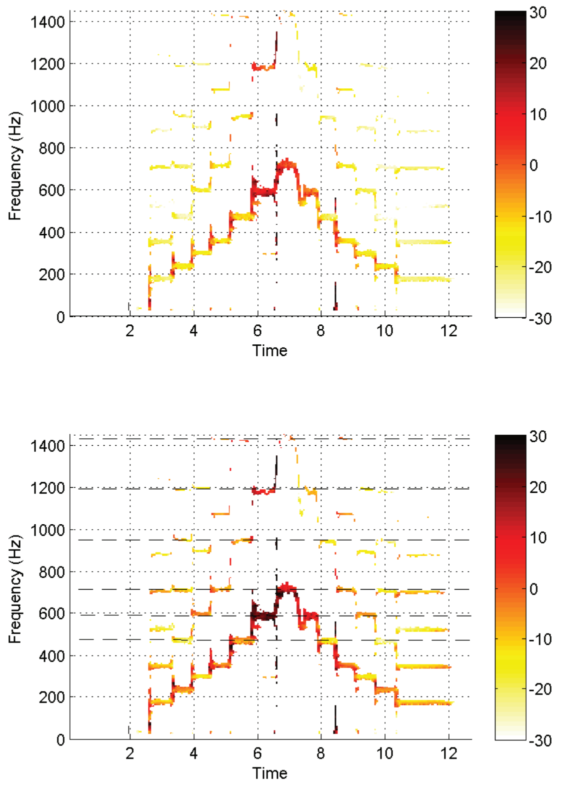

Figure 3. Top: spectrogram of the SPL ratio in dB of the upstream to downstream pressures for Subject C playing an overtone series from F3 up to F5 back to F3. Bottom: magnitude of the upstream input impedance in dB for Subject C playing an overtone series from F3 up to F5 back to F3.

2.2. Evaluation of upstream influence

It is clear that this method does not consist of a direct measurement of vocal-tract input impedance as it was performed in previous studies [2, 4, 5, 11, 7, 8]. Indeed, at each time step, we are only able to derive Z_u at frequency points where acoustic energy is observed, that is at the fundamental frequency f_0 and at harmonics of f_0. However, in the case of overtones, a number of harmonics are shared across the tone series. For example the third harmonic of the F3 tone appears around 700 Hz which is also close to the frequency of the second harmonic of B3-flat, close to the frequency of the first harmonic of F4, and close to the fundamental frequency of F5. Therefore, by applying this rational to the entire overtone series we are able to track the value of Z_u for given frequency landmarks f_l as a function of f_0. If we observe variations of Z_u along f_0 at these frequencies f_l, this will demonstrate that some vocal-tract adjustments occur during the musical task.

For bending, no harmonics are shared between B2-flat, A2 and A2-flat so it is not reasonable to only rely on observations of Z_u during the bending, although the fundamental frequencies of these three tones are very close. Therefore, in order to identify whether pitch bending involves vocal-tract adjustments, we compare Z_u for A2 and A2-flat in both bent and normal conditions. Normal conditions refer to A2 and A2-flat sounded respectively in second and third positions of the slide, that is when A2 and A2-flat fundamental frequencies are close to the 2nd resonance of the air column.

This approach is based on the assumption of a linear interaction between the lips and the air column, that is to say that the acoustical coupling between the downstream resonances and the vibrating lips is identical at f_0 and at harmonics f_n.

3. Results and Discussion

3.1. Overtones

In Figure 3, the spectrogram of the ratio of the sound pressure levels (SPL) in dB of the upstream and downstream pressures is plotted for an overtone series by Subject C from F3 to F5 and back to F3 (top graphic). In this same figure, we represent the magnitude of the vocal-tract input impedance calculated by multiplying the upstream to downstream pressure ratio by the input impedance of the air-column normalized by its characteristic impedance (bottom graphic). The horizontal dashed lines connect the points located around the same frequency f_l.

The magnitude of Z_u at the fundamental frequency varies between -7.5 dB at F3 and 23.3 dB at D5. For the highest tone (F5), Z_u reaches 10 dB, which is slightly below the downstream impedance at this frequency (Z_d=11.5 dB). The magnitude of Z_u at f_0 for D5 is the only case where the upstream impedance is higher than the downstream impedance (Z_d=12 dB). Regarding the values of Z_u at f_l, we observe an increase of Z_u with f_0 at every frequency, especially

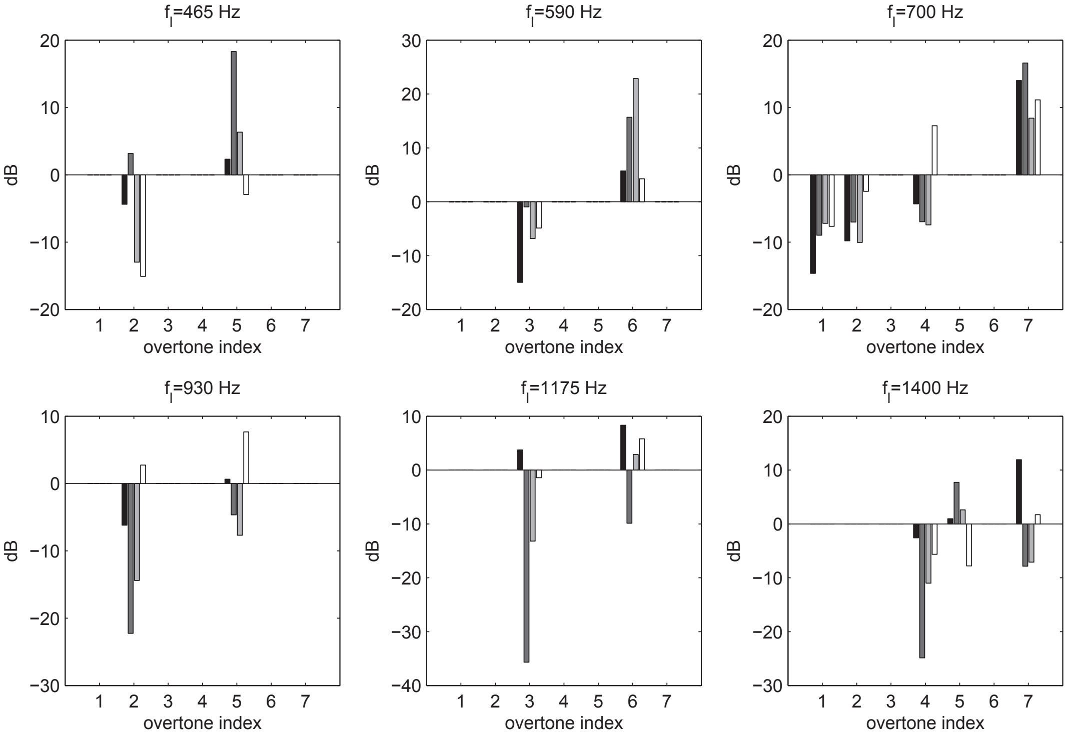

Figure 4. Magnitude of vocal-tract input impedance during an ascending overtone series evaluated at six values of f_l. The horizontal axis represents the overtone index (1=F3, 2=B3-flat, 3=D4, 4=F4, 5=B4-flat, 6=D5, 7=F5). Results represented for subjects A (dark), B (dark gray), C (light gray) and D (white).

around 590 Hz and 700 Hz, respectively the fundamental frequencies of D5 and F5. This is also visible on the top graphic by looking at the evolution of the upstream to downstream pressure ratio at a given value of f_l since the downstream impedance is theoretically constant for a constant f_l.

Furthermore, one may notice that Z_u does not take the same values in the ascending and descending phases of the overtone series. This hysteresis may arise from the non-linear coupling between the air-column and the lips and/or a performance strategy used by the player. That is, vocal-tract manipulations may be more necessary when ascending (versus descending) through the overtone series.

For a better evaluation of the evolution of vocal-tract input impedance with increase in pitch across subjects, we represent the magnitude of the upstream impedance on a histogram at frequencies f_l for all performers. Figure 4 shows six histograms, each of which displays the evolution of the Z_u magnitude at different values of f_l as a function of the overtone index, for the four subjects. In the three top graphics of Fig. 4, the last overtone index for which the Z_u magnitude is represented (respectively at the 5th, 6th and 7th overtone index) is also the value for the fundamental frequency of the played tone. From this perspective, we clearly observe an increase of Z_u magnitude with increase in overtone index at f_l=465 Hz, f_l=590 Hz and f_l=700 Hz. The most consistency across subjects is observed for f_l=700 Hz: we observe particular consistency between subjects for the Z_u magnitude for f_l=700 Hz at overtone 7. For higher f_l values (three bottom graphics), the evolution of Z_u magnitude is less consistent; results are characterized by a high variability among subjects and no general trends can be identified.

That said, some correlations between the subjects' profiles and the magnitude of Z_u for this task can be observed. Given that the bass trombone players are represented by the two gray bars and the tenor players are represented by the black and white bars, we observe higher values of Z_u magnitude at the fundamental frequency of B4-flat (f_l=465 Hz, overtone index 5) and of D5 (f_l=590 Hz, overtone index 6) for bass trombone players. Tenor and bass players display more consistency in Z_u magnitude at the fundamental frequency of F5 (f_l=700 Hz, overtone index 7). On the other hand, tenor players show higher Z_u magnitudes than bass players across overtone index at f_l=930 Hz and f_l=1175 Hz. Still, the small size of the subject pool makes it difficult to generalize about a common strategy used by trombone players according to their background.

Overall, these results support the idea that an adjustment of the vocal-tract is part of performer's strategy during ascending overtones. These adjustments are reflected by the increase in the magnitude of the

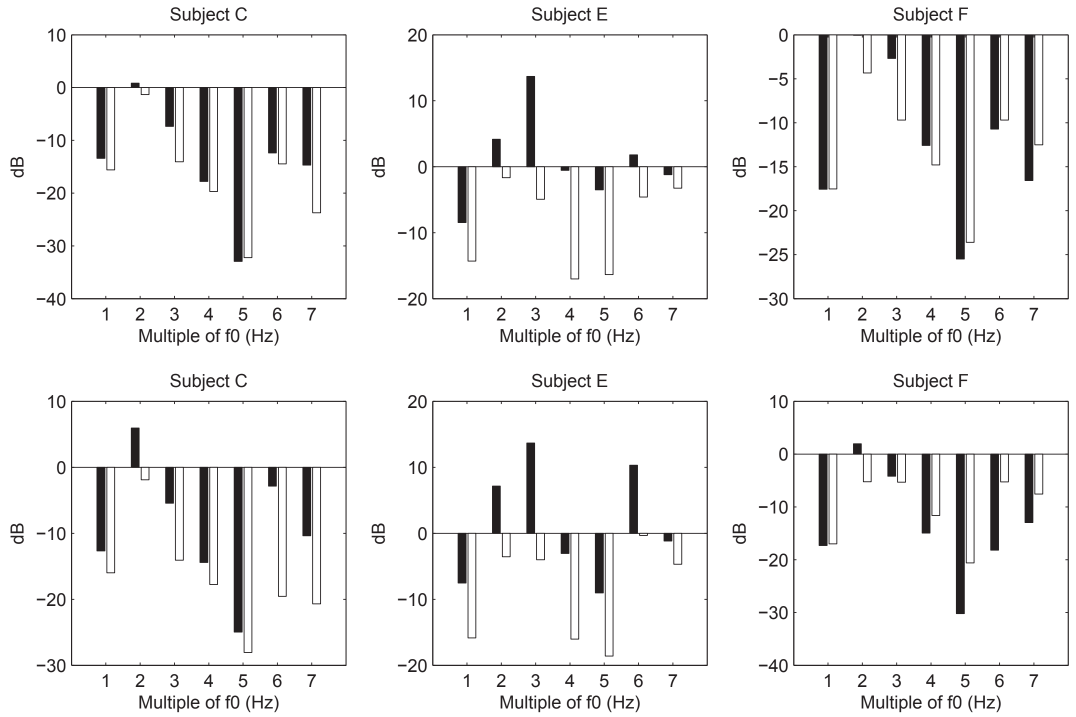

Figure 5. Magnitude of vocal-tract input impedance at f_0 and harmonics for a bent tone (black bar) and the same tone played normally (white bar). The three top graphics represent results obtained for an A2 bent with the slide in closed position and played normally in second position. The three bottom graphics represent results obtained for an A2-flat bent with the slide in closed position and played normally in third position.

vocal-tract input impedance around 590 Hz and 700 Hz, which are respectively located at the fundamental frequencies of the two highest tones of the overtone series (D5 and F5), which also happen to be near the cut-off frequency of the downstream system.

Additional evidence of an adjustment of vocal-tract acoustical properties during overtone playing is offered by looking for sign changes in the phase of Z_u. We observed such sign changes between f_0 and f_1 at f_0=465 Hz for subject A, B and D, between f_0 and f_1 at f_0=590 Hz for subject D, and between f_0 and f_1 at f_0=700 Hz for subject A and B. These results further support the hypothesis of an upstream impedance maxima close the fundamental frequency of the sound when reaching the higher register.

3.2. Pitch bending

Experiments on pitch bending were conducted with subjects C, D, E and F. The subjects performed pitch bends from a closed position B2-flat to A2 and to A2-flat. The recorded upstream pressures for subject D for this task were significantly lower than for all other subjects and we suspect this was due to poor positioning of the upstream probe tube. The results obtained for the three other subjects are shown in Fig. 5. The top graphics display the magnitude of the upstream input impedance at the fundamental frequency and harmonics for a bent A2 (f_0=110 Hz), and A2 played normally with the slide in second position. The bottom graphics display the magnitude of Z_u for a bent A2-flat (f_0=104 Hz) and A2-flat played normally with the slide in third position.

In the case of the bent A2, subject E shows the most significant variations between both conditions whereas differences are more subtle for subjects C and F. For the three players, noticeable increase of the impedance magnitude is observed at the second harmonic ($3f_0$) and at the first harmonic ($2f_0$) for subject E and F. However no convincing variations appear at f_0 for subjects C and F.

In the case of the bent A2-flat, upstream impedance variations observed at the first and second harmonics are emphasized in the three subjects. A consistent increase in Z_u magnitude at the 5th and 7th harmonics is noticed in subject C and E despite the inverse behaviour observed in subject F. As in A2, only subject E showed differences in Z_u magnitude at f_0 between both conditions. Overall, we notice a relative adjustment of the vocal-tract input impedance at the first and second harmonics in all subjects. This increase in Z_u is emphasized for the larger pitch bend (A2-flat), possibly because the downstream impedance is weaker in this case. However, these results are not convincing since no clear variations of Z_u were observed at f_0 as in the overtones series results. Therefore, we might suggest that pitch bends are primarily controlled by lip adjustments rather than vocal-tract tuning in trombone performance.

4. Conclusions

In conclusion we have found that the magnitude of the vocal-tract input impedance at given landmarks f_l varies significantly during ascending overtones. Therefore, these results highlight possible adjustments of the vocal-tract acoustical properties by the player as observed in saxophone playing [6] and singing [9]. In overtones, these adjustments are consistently managed in favour of an increase of the Z_u magnitude at the fundamental frequency of the highest tones (B4-flat, D5 and F5). In bending, less significant upstream magnitude variations were observed which tempers our previous hypothesis about an influence of the vocal-tract at the first harmonics during bending [12]. In both musical tasks, it is not clear whether these variations involve a displacement of vocal-tract resonances and/or an increase in a peak magnitude without a shift in frequency. Therefore only direct measurements of Z_u as performed in [2, 4, 5, 6, 8, 11] would allow an accurate description of this vocal-tract tuning (though it is not clear how such a measurement could be performed given lip/mouthpiece constraints).

At this point, these results motivate further investigations about correlations between vocal-tract impedance and other control parameters. Qualitative observations during the measurements suggested that subjects A and B were more comfortable in reaching F5 during overtones than subjects C and D. These observations correlate well with the higher values of Z_u magnitude found at the F5 fundamental frequency for these subjects. Thus, one may suggest an interdependence between vocal-tract impedance at f_0 and other parameters such as static mouth pressure.

Finally, although this method only provides an evaluation of Z_u at f_0 and harmonics (f_n), it allows observation of variations of Z_u with good time resolution because the measurement approach does not require that the player hold a vocal-tract setting for a long period of time. Thus, one could attempt to identify how past and future musical events affect a player's control of his/her upstream airways.

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