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Investigating vocal tract modifications during saxophone performance

Montserrat Pàmies-Vilà
Department of Music Acoustics, University of Music and Performing Arts Vienna, Vienna, Vienna, AT1030, AUSTRIA; pamies-vila@mdw.ac.at

Gary Scavone
Computational Acoustic Modeling Laboratory, Schulich School of Music, McGill University, Montreal, CANADA; gary@music.mcgill.ca

Alex Hofmann and Vasileios Chatziioannou
Department of Music Acoustics, University of Music and Performing Arts Vienna, Vienna, AT1030, AUSTRIA; hofmann-alex@mdw.ac.at, chatziioannou@mdw.ac.at

Vocal tract resonances are used by single-reed woodwind players for tuning purposes, timbre modification and other musical effects. Using pressure or impedance measurements, the vocal tract influence on saxophone playing has been previously studied for isolated tones. The present study considers note transitions in which the players might perform vocal tract modifications. Mouth pressure, mouthpiece pressure and reed bending are measured in order to analyze the vocal tract while monitoring the tongue-reed interaction. A method to identify vocal tract modifications is proposed, in which the envelopes of the pressure signals are compared in the time domain. The results show that, during large pitch bends or when playing the harmonic series of a certain fingered note using the vocal tract, the amplitude of the mouth pressure is larger than the amplitude of the mouthpiece pressure. When playing fast intervals in legato articulation, this method allows to detect vocal tract modifications between notes. In some cases, an increase in the amplitude of the resonance inside the player's mouth is observed at the end of a high note to support the production of the next low note. This is a strong indicator of the importance of vocal tract tuning in ordinary saxophone performance.

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1. INTRODUCTION

The mechanism of sound production in single-reed woodwind instruments involves the coupling between the vibrating reed on a mouthpiece (a non-linear excitation) and the bore of the instrument (a linear resonator).[1] The vocal tract has been described as a second resonator responsible for shaping the air-stream arriving to the instrument from the player's lungs.[2] The properties of the organs inside the mouth and throat (shape, elasticity...) influence the behavior of the air passing through them as well as its spectral content. Being a space where the air-stream resonates, the vocal tract is able to modify the reed vibrations and it is used to perform timbre and pitch modifications.[3,4] Many studies have concentrated on the vocal tract effects on the saxophone, where the resonances of the air-stream in the vocal tract were measured in real playing conditions via pressure measurements[4,5] and via impedance measurements.[6,7]

Scavone et al.[5] studied the vocal tract effects used by professional saxophonists and obtained a relative comparison of the upstream and downstream air column impedances by considering the ratio between the spectrum of the mouth pressure and that of the mouthpiece pressure. They reported that players can create an upstream wind-way resonance that is strong enough to override the downstream system in controlling the reed vibrations, especially for notes with fundamental frequencies above the air column cutoff frequency and particularly in the case of bending the pitch. A similar procedure was used in Ref. 4 to analyze the playing technique on the saxophone. Chen et al.[6,8] used an impedance head to measure the acoustical impedance spectrum in the mouth of saxophonists while playing common and advanced techniques in a tenor saxophone. Both teams reported that the bugling technique (keeping constant fingering and overblowing to play the harmonic series) consists in using prominent vocal tract effects to choose which of the bore harmonics operates the reed.[5,8]

These two approaches have focused on the role of the vocal tract to perform some musical effects that can be observed in the steady state or in slow-varying pitch. But still no consensus exists as to what extent these intra-oral resonances influence the resulting sound, and more concretely how can the vocal tract influence the transitory phenomena of the sound. To give an insight into this direction, the present study aims at finding a procedure based on the pressure-measurements approach[5] that is able to detect fast vocal tract modifications like the ones that might occur during the transients of tones. As transients are linked to the articulation technique, the current study monitors the tongue-reed interaction by making use of a sensor technology previously used to analyze the articulation technique on the saxophone[9] and on the clarinet.[10] Pressure measurements are combined with reed-bending measurements to perform a simultaneous analysis of vocal tract modifications and articulatory actions. In the following sections the experimental procedure and the methodology are described and the results on playing four different exercises are shown and discussed.

2. METHODOLOGY

A. EQUIPMENT

For this experiment a sensor-equipped mouthpiece is used to analyze vocal tract modifications together with articulation-related actions. The pressure is measured inside the player's mouth and in the mouthpiece of the instrument, and the articulation is assessed by considering the bending of the reed. All participants used the same alto saxophone (Selmer Series II Alto Sax), mouthpiece (Vandoren mouthpiece, AL 3 optimum) and synthetic reed (Légère, strength 2 ¾). The acoustic pressures in the player's mouth and in the mouthpiece are recorded via two piezo-resistive pressure transducers (Endevco 8507C-2). One transducer is attached at the side of the mouthpiece, next to the reed tip, and remains inside the player's mouth. The second is inserted via a side hole into the mouthpiece, at 5.7 cm from the tip, as shown in Fig. 1. As we are interested to know when the players are using the tongue, a strain gauge is attached to the reed surface to measure the reed bending, as described in Ref. 11. No concerns were raised among players about the comfort of playing with these sensors.

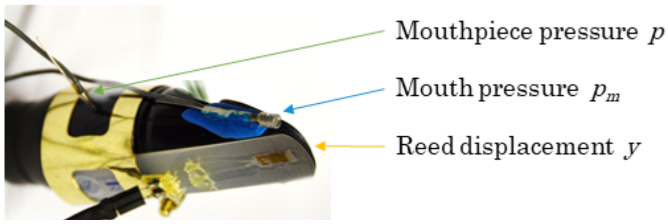

Figure 1: Main sensors on the saxophone mouthpiece: strain gauge to measure the reed displacement, pressure transducers to measure mouth and mouthpiece acoustic pressures. The colors correspond to those used in Section 3.

Three more sensors are attached to the saxophone: a force sensor (FSR) under the upper teeth pad to track changes in embouchure, and two piezo-sensors under two keys to track their open-close configuration. These sensors provide complementary information to consider during the data analysis but are not systematically studied in this research. The mouth pressure, the mouthpiece pressure, the strain-gauge signal, the metronome signal and the three complementary sensors are simultaneously recorded at 50 kHz using an acquisition platform and software (NI 9220 and LabView, by National Instruments).

B. EXPERIMENTAL DESIGN

In the experiment, five players with either classical or jazz backgrounds were invited to the laboratory to play exercises in which vocal tract effects might be used. All participants were over 18 years old, two of them were professional players (16 and 40 years of practice) and three of them were students at the Schulich School of Music in McGill University (average of 8 years of practice). When the session started, they were provided with a consent form and they were informed about the protocol (hygienic conditions, anonymity, right to stop their participation). The study met the guidelines of the ethics review committee at McGill University. Then, they were asked to play a pitch bending exercise, a bugling exercise and two more exercises with wide intervals. At the end, they were requested to fill a form with information about their instrument practice. All participants volunteered to participate in the experiment and received a nominal fee.

In the pitch bending task, they were asked to maintain the fingering of a certain note and modify the pitch down and up, playing a glissando. They repeated this task 3 times (low, medium, high pitch). For the bugling task, they were asked to maintain the fingering of a low note and play the harmonic series, as high as they could reach. They repeated this task for the 3 lower tones of the saxophone. For the first wide-interval exercise, they were asked to play a series of octaves using the register key following the tempo given by a metronome click (quarter notes at 80 bpm). This exercise was played once without tonguing (legato or slurred) and once with soft tonguing (portato). For the second wide-interval exercise, they were provided with a melody that combined narrow and wide intervals, with fast varying pitch. This exercise was played without tonguing (legato or slurred), with tonguing and long tones (portato) and with tonguing and short tones (staccato), following the tempo given by a metronome click (eighth notes at 100 bpm).

C. SIGNAL CONDITIONING

The pressure signals measured in the mouth and in the mouthpiece consist of AC and DC components. The AC measures the pressure oscillations and the DC is related to the pressure offset with respect to the ambient pressure. In the mouth pressure signal, the pressure offset corresponds to the blowing action of the player.[10] In the mouthpiece, there is no pressure offset. As we are not interested to account for blowing changes but only for the oscillatory part of the mouth pressure, the DC signal is removed from the mouth pressure by subtracting its low-pass-filtered version (moving average filter with window-size of one period of oscillation). Hereafter, p_{m} refers to the AC part of the mouth pressure after discarding the blowing actions thus only considering the resonance in the mouth of the player, and p refers to the mouthpiece pressure (the resonance in the instrument bore).

The reed bending signal is first calibrated to obtain the reed-tip displacement y.[12] This signal is used to locate the tongue-reed interaction in the recorded signals. The strain gauge reacts to both the reed oscillation and the motion of the reed in the presence of the tongue. When the tongue strikes the reed, the vibrations are damped and the reed closes towards the mouthpiece lay. Considering the low-pass filtered strain-gauge signal $\hat{y}$ (in red in the bottom of Fig. 2 to 5), the tongue-reed interaction appears as an upwards change in the displacement of the reed (see e.g. the portato playing in Fig. 4). When the player stops blowing or opens the mouth, this signal presents a downwards movement, corresponding to widening the reed-tip opening (see e.g. t = 20 s in Fig. 3).

D. DATA ANALYSIS

Previous studies identify the prominent effect of the vocal tract in playing music effects (pitch bending, bugling, among others).[5,8] In these studies the analysis consists of comparing the spectra of the mouthpiece and the mouth resonances. In the current study we provide a methodology to identify vocal tract effects by comparing mouth and mouthpiece pressure envelopes in the time domain. In order to compare the two signals, their Root-mean-square (RMS) envelopes are computed ($\tilde{p}$ and $\tilde{p}_{\mathrm{m}}$ in dark green and dark blue in Fig. 2 to 5). These envelopes give a measure of the energy of the vibration in the considered time interval (window-size of 20 ms). Using the RMS envelope allows to analyze the mouth and mouthpiece amplitude of oscillation regardless of the asymmetry with respect to the zero-amplitude value, which is present in the pressure measurement at the saxophone mouthpiece (see e.g. $t \in [1, 5]$ s in p in Fig. 4).

By comparing the two RMS envelopes, we can detect in which parts of a performed task the vibration at the mouth is greater than the vibration at the mouthpiece, which would indicate that the reed is driven by the oscillations in the mouth rather than by the oscillations in the instrument bore. By comparing the growth of the two RMS envelopes, we can determine in which parts of the performed task one of the envelopes rises when the other does not. In absence of any vocal tract modification, the RMS of the mouth oscillation grows proportionally to the RMS in the mouthpiece. However, different growths between the two envelopes can appear when the player performs a vocal tract modification. In this case, the envelope of the mouth pressure might rise while the envelope in the mouthpiece stays constant or decreases. These two approaches (comparing the envelopes and comparing the envelopes' growths) are two similar methods to detect vocal tract modifications: comparing the envelopes is suitable in slow-varying tasks (pitch bending, bugling) and comparing the envelopes' growth is suitable for fast-varying tasks (when playing note intervals).

3. RESULTS

A. VOCAL TRACT MODIFICATIONS IN SLOW-VARYING CONDITIONS

In the first approach, we identify the vocal tract effect at the instants where the RMS envelope of the mouth pressure oscillation $\tilde{p}_\mathrm{m}$ is greater than the RMS envelope of the mouthpiece pressure oscillation $\tilde{p}$. By doing so, we can distinguish in which parts of the performed task the reed oscillates according to the bore resonances ($\tilde{p}_\mathrm{m} < \tilde{p}$) from the parts where it oscillates under the influence of the vocal tract resonances ($\tilde{p}_\mathrm{m} > \tilde{p}$). This method is used to identify the vocal tract effects in slow-varying tasks, such as a pitch bending and a bugling exercise.

When performing a pitch bending, the players maintain a certain fingering and modify the pitch. Figure 2 plots the mouthpiece pressure p (green) and the mouth pressure p_m (blue), together with their RMS envelopes (dark green and blue). To identify vocal tract predominance, the RMS difference is represented as the result of subtracting the two RMS envelopes $\tilde{p}_\mathrm{m} - \tilde{p}$. At the bottom, the reed displacement is provided to verify that the reed does indeed oscillate during the entire task, even when the oscillations in the mouthpiece are drastically reduced (e.g. $t = 3$ s). On the right, the spectrogram of the reed signal shows the pitch change during the task. When the RMS difference is positive ($\tilde{p}_\mathrm{m} - \tilde{p} > 0$; in red in Fig. 2), the pitch of the reed vibration deviates from the pitch fingered at the instrument bore, indicating that the mouth oscillation drives the behavior of the reed.

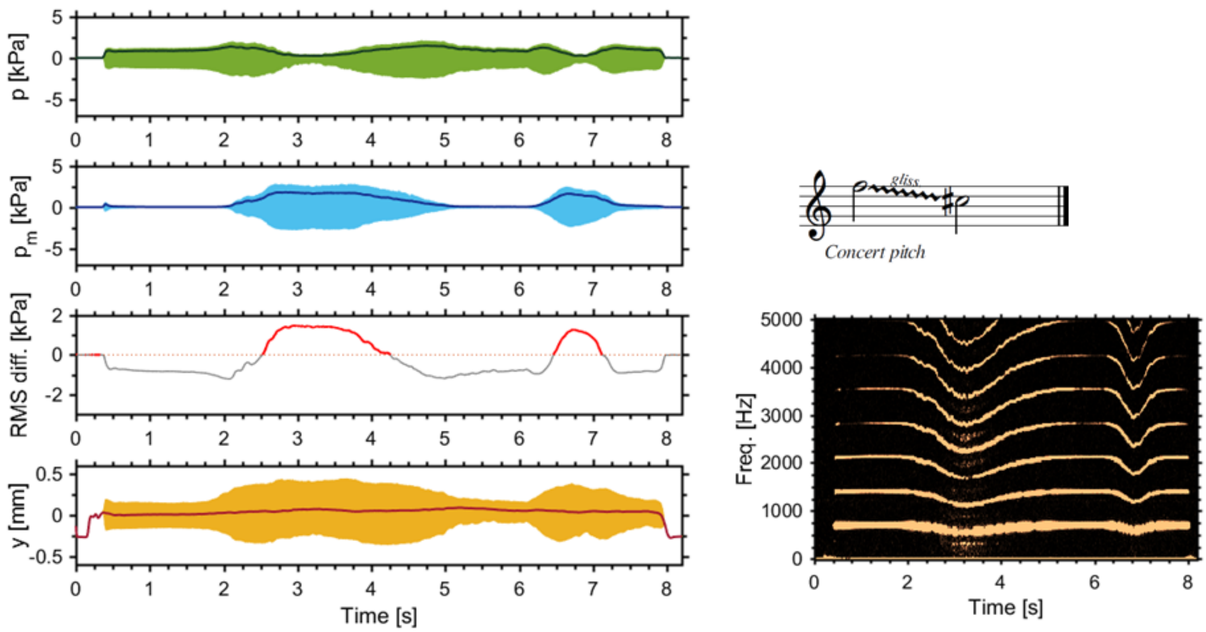

Figure 2: Pitch bending exercise played by an experienced player. On the left, mouthpiece pressure p, mouth pressure p_m, RMS difference $\tilde{p}_\mathrm{m} - \tilde{p}$ (red identifies $\tilde{p}_\mathrm{m} > \tilde{p}$) and reed-tip displacement y. On the right, spectrogram of the reed signal.

When playing a bugling exercise, players are asked to play the harmonic series of some notes, while keeping the fingering corresponding to the fundamental. This task is not straightforward, and the players can rarely perform the series without hesitation. In Fig. 3, a bugling task is shown for the low B of the saxophone. The RMS difference is positive starting from the 5$^{\mathrm{th}}$ harmonic ($t \in [13, 25]$ s). The players that were not able to control the vocal tract resonances could achieve the harmonic series only up to the 4$^{\mathrm{th}}$ harmonic, but the players that performed vocal tract modifications could reach up to the 7$^{\mathrm{th}}$ or to the 9$^{\mathrm{th}}$ harmonics.

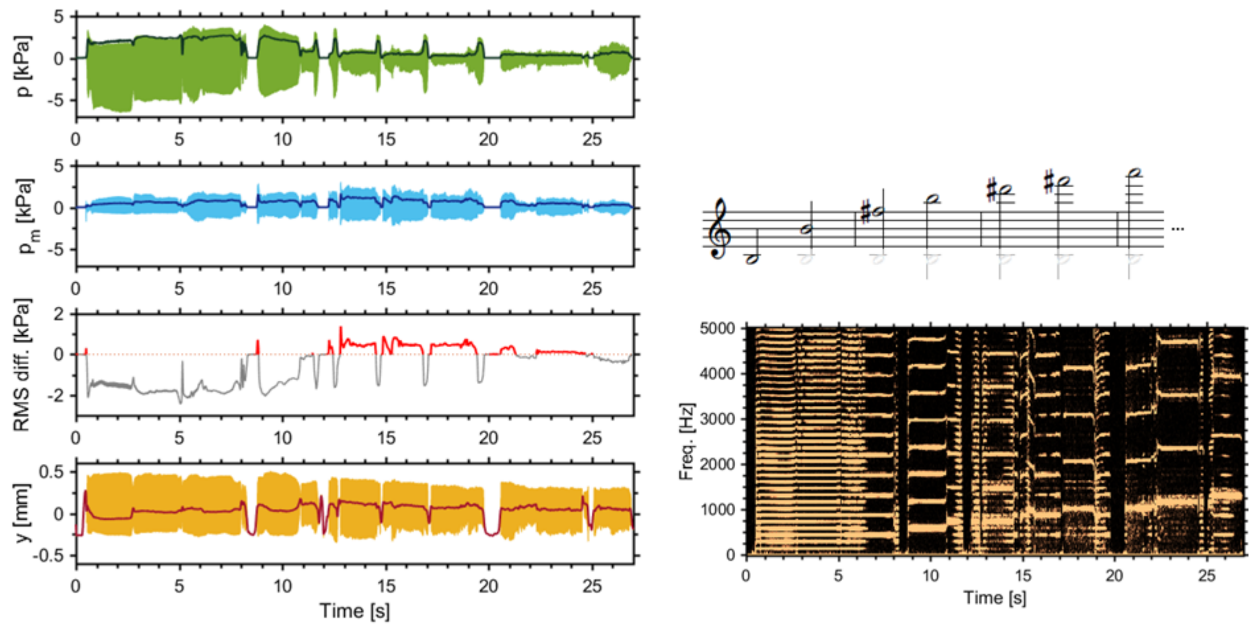

Figure 3: Bugling exercise played by an experienced player on the lower B of the alto saxophone. On the left, mouthpiece pressure p, mouth pressure p_{m}, RMS difference $\tilde{p}_{\mathrm{m}} - \tilde{p}$ (red identifies $\tilde{p}_{\mathrm{m}} > \tilde{p}$) and reed-tip displacement y for the first 9 harmonics. On the right, spectrogram of the reed signal with superposed notation of the harmonic series.

B. VOCAL TRACT MODIFICATIONS DURING NOTE TRANSITIONS

In the second approach, we identify the vocal tract modifications in the time intervals where the envelope of the mouth pressure $\tilde{p}_{\mathrm{m}}$ grows faster than the envelope of the mouthpiece pressure $\tilde{p}_{\mathrm{m}}$. This approach is based on the fact that an increase of mouth-pressure envelope cannot occur if there is no increase in the mouthpiece pressure, unless there is a vocal tract modification. To obtain this comparison, we compute the first derivative (slope of the envelope at every time instant) of both envelopes $\mathrm{d}\tilde{p}_{\mathrm{m}}/\mathrm{d}t$ and $\mathrm{d}\tilde{p}/\mathrm{d}t$.

Figure 4 plots two examples of octaves played using the register key, for legato articulation (without tonguing) and for portato articulation (short tonguing). The first aspect to consider is that the oscillation of the mouth ($p_{\mathrm{m}} \in [-1, 1]$) is always smaller than the oscillation of the mouthpiece ($p \in [-5, 3]$). In this case, the reed always vibrates according to the resonance of the instrument bore. Yet when considering the legato articulation (left of Fig. 4), the mouth pressure envelope rises in some time intervals where the mouthpiece pressure decreases. These instants correspond to the preparation of every low tone, as highlighted in red in the zoomed-in p_{m} signal in Fig. 4. In this case, the player intentionally modifies the vocal tract to prepare the low note.

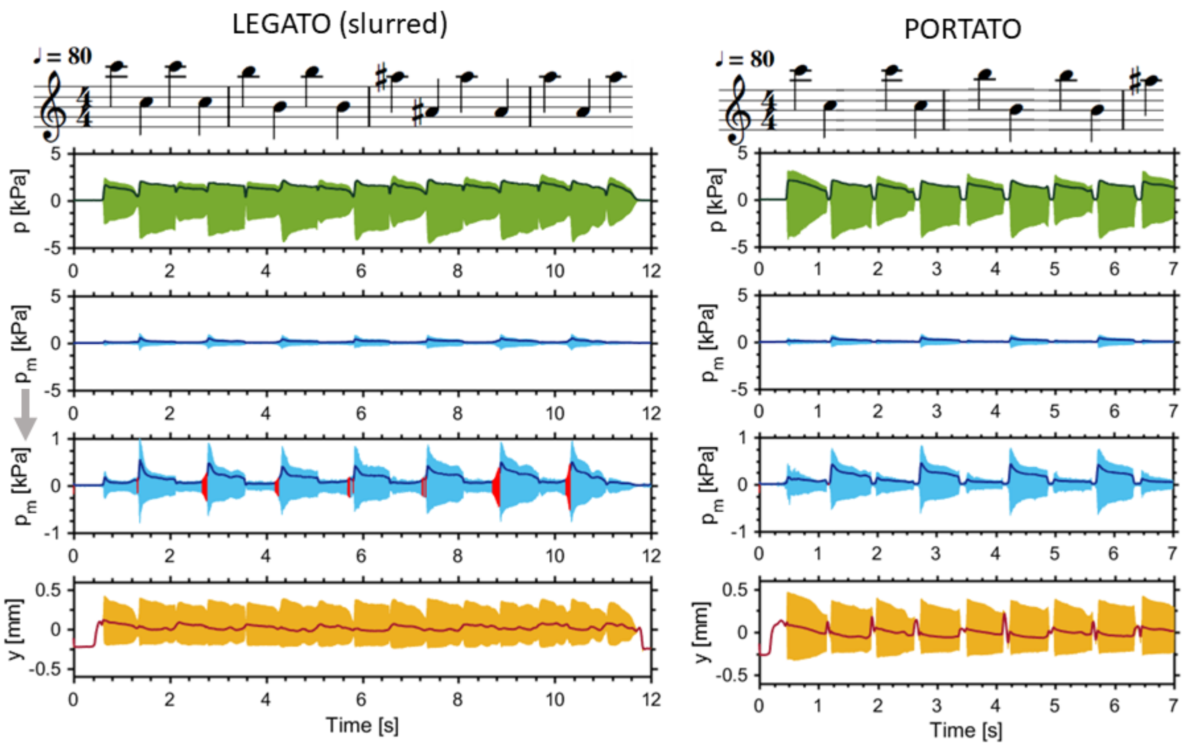

Figure 4: Octaves played using the register key for legato (without tongue) and for portato articulation (with tonguing). Mouthpiece pressure p, mouth pressure p_{m}, zoomed-in mouth pressure (red identifies $\mathrm{d}\tilde{p}_{\mathrm{m}}/\mathrm{d}t > \mathrm{d}\tilde{p}/\mathrm{d}t$) and reed-tip displacement y.

When playing portato (right of Fig. 4), the player uses the tongue to interrupt the reed vibrations between notes, as shown by the spikes in the reed displacement signal (y). In this case, there is no coexistence of two consecutive notes in the instrument bore, as every note starts form a zero-amplitude p. Therefore, the player does not need to provide an extra preparation to play the low note. However, as there is no oscillation between consecutive tones, the two RMS envelopes drop to zero-amplitude, and the proposed approach would not be able to measure the changes in vocal tract that could occur.

A melody combining repetitions of narrow and wide intervals is played to analyze vocal tract modifications at the note transitions (top of Fig. 5). The players are asked to play the same melody in legato (without tonguing), portato (short tonguing) and staccato (long tonguing). As it has been reported for the octaves task, in portato and staccato the players separate the tones by damping the vibrations of the reed with the tongue, therefore no vocal tract modification can be observed. For legato, the players are particularly requested not to touch the reed with the tongue. Then, the proposed methodology can be used if the sound does not stop between notes.

When playing wide intervals with legato articulation, the players might perform vocal tract modifications at the note transition or right before the note transition. This vocal tract modification is highly player-dependent, as some players do not ever use such a modification, other players use it to prepare both the low and the high notes of the interval and some other players combine intervals with and without vocal tract modification. When the interval is a major 6^{th} or less, players do not generally use vocal tract modifications, but when the interval is a major 7^{th} or more, some of the players use it. For example, in Fig. 5, the mouth

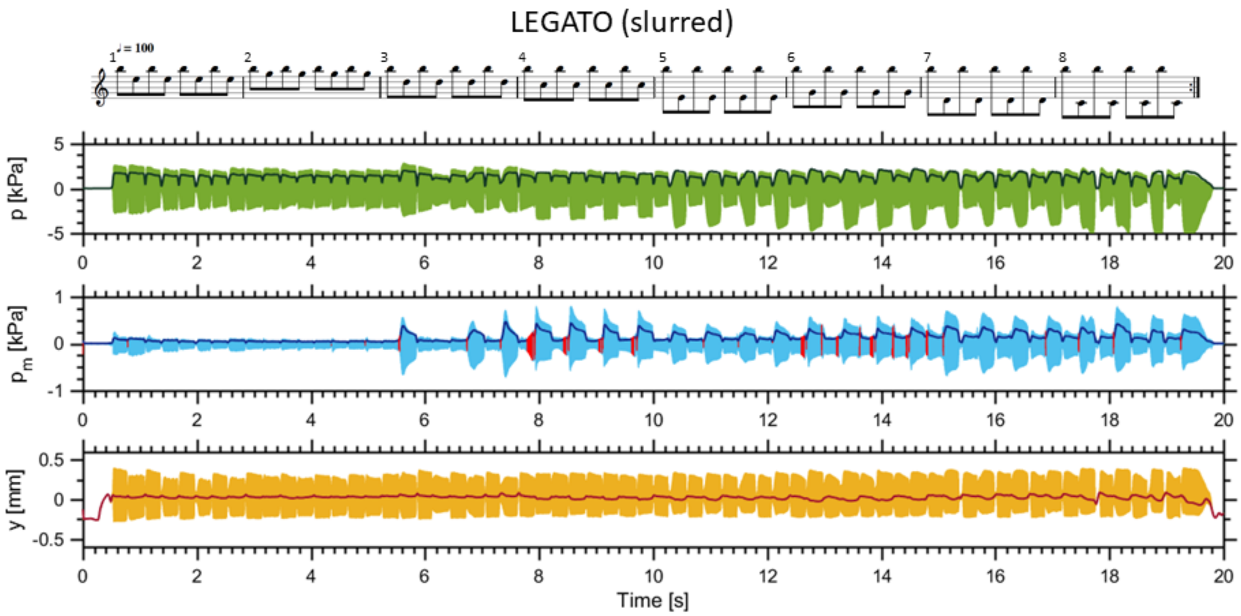

Figure 5: Task with combined narrow and wide intervals played for legato articulation (without tonguing). Mouthpiece pressure** p**, mouth pressure** p_m **(red identifies** $\mathrm{d}\tilde{p}_\mathrm{m}/\mathrm{d}t > \mathrm{d}\tilde{p}/\mathrm{d}t$**) and reed-tip displacement** y**.

oscillation grows at the end of the high note to play a major 7^{th} (bar 4). When the intervals are wider than an octave, in this particular case, the player does not consistently present a vocal tract modification in all intervals. When playing the interval of a minor 10^{th} (bar 6), an increase of mouth oscillation is present both at the end of the high note and at the end of the low note. However, no vocal tract modification can be detected when playing a major 12^{th} and a major 13^{th} (bars 5 and 7). One possible explanation is that, although the player does not use the tongue to stop the reed, the reed vibration is significantly reduced at the note transitions where no vocal tract modification is detected (e.g. $t \in [10, 12]$) compared to the intervals where the vocal tract modification is detected (e.g. $t \in [12.5, 15]$). Another possible explanation concerns the stability of the lower notes, as dropping down to a certain low note might require more vocal tract support than dropping down to a different low note.

4. DISCUSSION

Vocal tract effects in woodwind instruments performance have been the focus of many studies in the last decades. The current research proposes a new methodology to detect vocal tract modifications in the time domain. Two different approaches are implemented to detect the predominance of the pressure oscillation in the player's mouth over the pressure in the instrument's mouthpiece and to detect the faster rising envelope of the oscillating mouth pressure compared to the mouthpiece pressure.

The results show that when keeping the fingering and aiming at creating a certain sound effect (here a pitch bending and a bugling task), only the players capable of modifying the resonance in the mouth are able to accomplish the task. By doing so, these players achieve a mouth pressure oscillation wider than the pressure oscillation in the mouthpiece of the instrument. These results corroborate the findings of previous studies,[5,6] which concentrated on the spectral content of the oscillations taking place in the mouth, in the case of isolated notes when performing some musical effects.

Regarding note transitions, the novelty of the current research is to detect vocal tract modifications that could occur between notes and could be of a duration of a few milliseconds. This approach assumes that, in a lack of vocal tract modifications, the mouth pressure and the mouthpiece pressure RMS envelopes behave proportionally. Therefore, when differences appear between the slopes of the two envelopes, the player must have influenced the system by making some change in the vocal tract. This approach has been used to identify the instants of vocal tract modification when playing note transitions in legato articulation, where the notes are played without stopping the reed vibrations in-between. When playing detached notes (portato or staccato), no vocal tract modifications could be detected because there is no oscillation at the note transition. Nonetheless, one should consider that the difficulty on playing note transitions or harmonic series appears when playing without tonguing, as pointed out in Ref. 13. In the case of playing intervals while articulating with the tongue, the tongue strike dampens the reed vibrations between notes and a new tone is created after the tongue release, thus requiring less vocal tract modifications to support the transition between the high and the low tone.

The methodology presented in this paper can be seen as a straightforward tool to identify the instants when the vocal tract is capable of influencing the reed vibrations, but the obtained values cannot be used as an absolute measure of this influence. A complimentary analysis of the reed oscillation is necessary to determine by how much the vocal tract is modifying the behavior of the reed. The presented methodology can be used to inform players about their playing technique and propose possible reasons to explain why they can or cannot create a certain sound effect.

5. ACKNOWLEDGMENTS

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