Sensing lip protrusion and vibratory motion in the mouthpiece during trumpet playing using a Theremin

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Methods of measuring the acoustic variables in the mouthpiece of a brass instrument using microphones are well developed. Optical techniques are often used to good effect to visualise the lips of the player but determination of the three dimensional nature of the motion is hindered by refraction due to the shape of the mouthpiece. The electrical conductivity between the lips has also been utilised recently to study lip motion. In this study the protrusion into the mouthpiece and vibratory motion of the lips is sensed using their effect on the capacitance of a Theremin pitch antenna. The lips are found to generally protrude into the mouthpiece to a greater extent for higher pitch ranges and for higher dynamic levels. Bending significantly flat of an instrument resonance is found to require greater amplitude of lip motion (and implicitly greater mouth pressure) in order to maintain radiated sound pressure.

1 Introduction

The motion of the lips in playing brass instruments can be studied using a strain gauge [1], and optical methods [2, 3, 4, 5, 6]. Recently the electrical conductivity between the lips has been used [7, 8, 9]. These methods can obtain information about the phase and amplitude of the lip motion during playing while optical methods allow direct observation of the open area between the lips. The force between the lips and the mouthpiece also gives interesting data on the gestures of the player and, generally, the force has been found to increase with increasing dynamic level and pitch [10]. While the protrusion of the lips into the mouthpiece can be determined using optical methods, sensing the proximity of the lips to the far wall of the mouthpiece cup using capacitance effects through the use of a Theremin is the goal of the current paper. This method of sensing changes in the mean position of the lips in addition to their pitch and amplitude of vibration is an alternative to optical methods that is worthy of investigation to demonstrate the viability of the method and because it has the potential to be cheap in terms of equipment and data processing.

The volume of the mouthpiece excluded by the lips of the player has an impact on the effective volume of the mouthpiece and therefore the effective height and tuning of the impedance peaks in different frequency ranges [11]. Experiments will therefore be performed to assess whether the lips protrude to a greater or lesser extent under different playing scenarios.

2 Apparatus

A metal nail was superglued into a drill hole in a black plastic mouthpiece (Kelly model 1 1/2 C) and this was used with a B♭ trumpet (Kanstul 1537 for player BW and John Packer JP251(SW) for player MV). A photograph of this apparatus arrangement is shown in figure 1. The (flat) head of the metal nail was countersunk to sit just inside the upper wall of the mouthpiece cup near the throat of the mouthpiece at an axial distance of approximately 11 mm from the rim, the internal bore of the mouthpiece was made flush with a small piece of poster adhesive putty and the other end of the nail was protruding through the mouthpiece. This was then connected to a brass cheese block screw terminal connection to a metal wire (paperclip), which was in turn is connected to the pitch antenna of the Moog Etherwave Theremin using a small metal hose clip. Mounting the Theremin on its back (such that the pitch antenna was parallel to the ground and pointing at right angles to the mouthpiece axis) maximised the distance between the antenna and nearby objects (the metal trumpet and the player). The electrical output from the Theremin was then sampled at 192 kHz using a commercially available sound card (RME Fireface UFX). In addition to this a studio microphone (AMT model P800) was recording approximately 5 cm outside the bell of the trumpet in order to check the playing frequency and relative dynamic range of the radiated sound. Signals were processed in MATLAB.

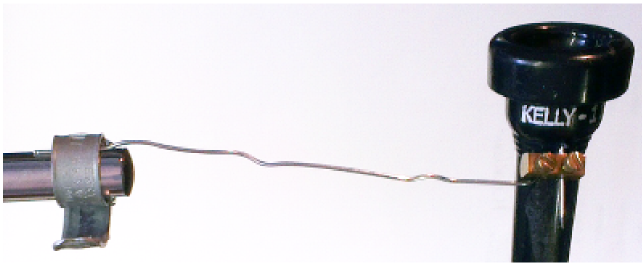

Figure 1: Apparatus (viewed from above) featuring a metal nail with the flat head countersunk on the inside wall of the plastic trumpet mouthpiece and the other end connected to the pitch antenna of a Theremin

3 Method

The pitch of the Theremin output signal increases when the lips are in closer proximity to the nail, thus allowing the position of the lips to be sensed. Care was taken during measurements to keep still as the proximity of the players head to the antenna can cause noticeable frequency drifts which would confound the results. When notes are sounded on the trumpet the Theremin output is frequency modulated by the motion of the lips. The acoustic motion and mean position of the lips can thus be recovered by tracking the frequency of the Theremin output.

The pitch control of the Theremin was adjusted full clockwise to give the greatest sensitivity, resulting in a waveform with a fundamental frequency in the range 2000 ± 300 Hz when the head of the player was placed on the mouthpiece. Pitch tracking was achieved by searching for zero crossings in the amplitude of the sampled waveform from the Theremin. The period time for the waveform corresponds to approximately 96 time samples (at a sample rate of 192 kHz).

3.1 Zero crossing frequency tracking

Zero crossings were detected in the time domain by finding where the sign of the Theremin output signal, v, changed. If there was a zero crossing detected between $v(m)$ and $v(m+1)$ (where m is the time domain sample number) then the time for the zero crossing, t_i, was calculated using linear interpolation using:

$$t_i(n) = \frac{1}{f_s}\left(m + \frac{|v(m)|}{|v(m+1)| + |v(m)|}\right). \quad (1)$$

where n is an integer counting number incrementing with each zero crossing observed in the Theremin signal. The subscript i is a label to denote that the vector is irregular in its sampling or of variable sample rate due to the frequency modulating during the experiment. Odd entries, $t_i(n = 1, 3, 5...)$ give the time points for crossing from negative to positive amplitude and the even entries, $t_i(n = 2, 4, 6...)$, give the time points for crossing from positive to negative amplitude (or vice versa). The time between zero-crossings from the positive and from the negative directions are not equally spaced within each period (even when the fundamental frequency is constant) as the waveform is selected using an uncalibrated control. For this reason the frequency was estimated by taking the inverse of the time between adjacent transitions in the same direction:

$$f_i(n) = \frac{1}{t_i(n+2) - t_i(n)}. \quad (2)$$

This (irregularly sampled) frequency tracking data may then be plotted to give information on the proximity of the lips to the nail in the far wall of the mouthpiece and may be used without further processing to deduce whether the lips are protruding into the mouthpiece to a greater or lesser extent during playing.

3.2 Resampling

In addition to providing (uncalibrated) information on the mean position of the lips during playing, the theremin signal is observed to undergo frequency modulation due to each acoustic cycle in the motion of the lips. This means that each single vibratory cycle of the lips creates a single period of oscillation in the pitch tracking data. In order to make this lip motion signal suitable for plotting in a spectrogram or indeed for audible playback (using a sound card), the signal must be resampled to a fixed sample rate. This was achieved using linear interpolation. First a vector, t_r, was created with a constant sample rate such that the sampling period is equal to the mean inter-sample duration in the irregularly sampled data t_i. Next linear interpolation was used to create a vector of regularly sampled frequency tracking data f_r such that

$$f_r(p) = f_i(n-1) + \frac{t_r(p) - t_i(n-1)}{t_i(n) - t_i(n-1)}\left(f_i(n) - f_i(n-1)\right) \quad (3)$$

gives the frequency tracking data (at time $t_r(p)$ where p is the sample number for the regularly sampled data) using the frequency information calculated for the adjacent irregularly sampled data (i.e. such that $t_i(n-1) \leq t_r(p) < t_i(n)$).

The vector f_r was then high pass filtered using a Hann high pass filter to filter frequencies with a cut-off of 40 Hz before the plotting the spectrogram (using the spectrogram function in MATLAB) and making the vibration audible (using the sound card).

3.3 Limitations

The method described can sense changes in the mean position, amplitude of vibration and frequency of the vibration of the lips. The information on the mean position and amplitude is uncalibrated, however, as the changes in frequency as the lip approaches the nail are not currently known. Condensation can build up in the mouthpiece, causing a frequency drift. This generally produces a slight upward trend in the pitch tracking data during a recording. Player movement can also cause confounding Theremin pitch drifts as mentioned above. Care must be taken therefore to ensure that conclusions on mean lip position are repeatable for upward and downward transitions in trumpet playing pitch and dynamic. Another limitation in the current setup is that disturbances in the measurement are sometimes produced when individual water droplets pass close to the nail.

The bandwidth of the measurement is limited by the frequency with which pitch tracking data can be obtained. With the zero crossing method we may obtain pitch tracking data twice every cycle of the Theremin audio output which means that a Theremin audio output modulating around a nominal frequency of 2000 Hz can have its frequency tracked with updates roughly 4000 times a second. After the signal is resampled using interpolation, the signal can have a constant sample rate, typically at 4000 Hz, and therefore a typical Nyquist frequency of 2000 Hz. It should be noted that the zero crossing frequency tracking data is based on adjacent transitions in the same direction (spaced by approx. 1/2000 seconds) as described in equation 2 meaning that the experiment loses sensitivity to lip oscillation components at the Nyquist frequency. Lip vibration frequency components above the frequency tracking data Nyquist (typically 2000 Hz) will show up as aliases. The lip vibration features a small number of harmonics (so is relatively sinusoidal) in comparison to the pressure vibrations in the mouthpiece (as the high frequency harmonic components are created by the on/off gating of the supply pressure as the lips close and open) meaning that reasonable measurements can be performed under these limitations. Custom designed Theremin style circuits with a higher audio output frequency would provide an improvement in the bandwidth.

4 Results

Upward slurs were performed on the trumpet with each note being bent sharp until the pitch jumped to the next resonance, while downward slurs were performed with each note being bent flat until the pitch jumped to the next resonance. No valves were activated. Figure 2 shows the results for an upward lip slur by a professional player (BW) while 3 shows the results for a downward lip slur by the same player. The spectrogram of the Theremin output signal is shown in the subplots marked (a). It may be noted that the fundamental frequency component of the Theremin's output signal is accompanied by noticeable side bands in several places due to frequency modulation by the vibration of the lips (particularly noticeable in figure 3(a) from 13 to 16 secs). Zero crossing frequency tracking data (calculated from the same Theremin output signal) is shown in the subplots marked (b), with the frequency data increasing when the lips bulge into the mouthpiece to a greater degree and showing oscillations (whose amplitude is apparent in the thickness of the lines when viewed at this zoom scale). The spectrogram of the (high pass filtered) frequency tracking data (again calculated from the same Theremin output signal) is shown in the subplots marked (c) and the vibration frequencies of the lips (responsible for the frequency modulation of the Theremin signal) are clearly visible in this data meaning that the motion of the lips is indeed being detected remotely using their effect on the capacitance of the Theremin antenna. Microphone data is only used for plotting the spectrogram, seen in the subplots marked (d) and the audio waveform, seen in the subplots marked (e) and these allow allowing for comparison with the pitches and amplitudes of signals observed in the above Theremin data.

In repeated tests the pitch of the Theremin (seen in subplots marked (b)) was generally, but not always, found to increase for notes higher in the range and this suggests that the player's lips bulge into the mouthpiece to a greater extent when accessing the higher ranges of the instrument. This is partly explained by trumpet being compressed onto the lips to a greater extent by the player when playing high notes in order to support high lip tension. An additional beneficial effect of this is the reduction of the apparent mouthpiece volume, leading to an increase in the height of the higher frequency input impedance peaks.

As may be expected, the motion of the lips shows a greater amplitude and appears to be less sinusoidal for lower notes (as may be observed in figure 3 in particular in the amplitude of the oscillations in the pitch tracking curve (b) and the greater number of harmonics in (c)). It is not established how linearly the lip motion amplitude is reflected in the pitch tracking oscillations, however, so more experimentation would be required to demonstrate the relative sinusoidal nature of the lip motion at different pitches and amplitudes using this technique.

Figure 4 shows the results for an experienced jazz player playing the concert pitch B$\flat_4$ at four different dynamic levels (ranging from piano to fortissimo) while figure 5 shows the results of the same player bending the same pitch significantly downwards (approx. 140 cents) and back repeatedly (on the same y axis scales). It should be noted that the Theremin pitch increases with dynamic level (and this effect is noted before the starting transients) indicating a relationship between mouth pressure and the extent to which the lips bulge into the mouthpiece. The lips bulge into the mouthpiece slightly more while the note is bent flat, suggesting a higher supply pressure is used to maintain radiated loudness away from resonance. It is clear that the player thus increases the amplitude of the lip motion for sounding significantly below the resonance frequency (visible in the dark red patches in figure 5(c) occurring at around 430 Hz) in order to prevent significant volume drops in the radiated sound far from the instrument resonance (hence relatively light red patches in figure 5(c) occurring at around 430 Hz).

5 Conclusion

The results presented demonstrate a sensor containing no moving parts that can track both the acoustic vibrations and the mean position of the lips subject to the limitations described above.

Preliminary results show that the method is useful, particularly implying that the lip protrusion into the mouthpiece generally increases with increasing pitch and mouth pressure (though the tension of the lips is of primary significance to the control of the pitch and may be independently controlled by the player).

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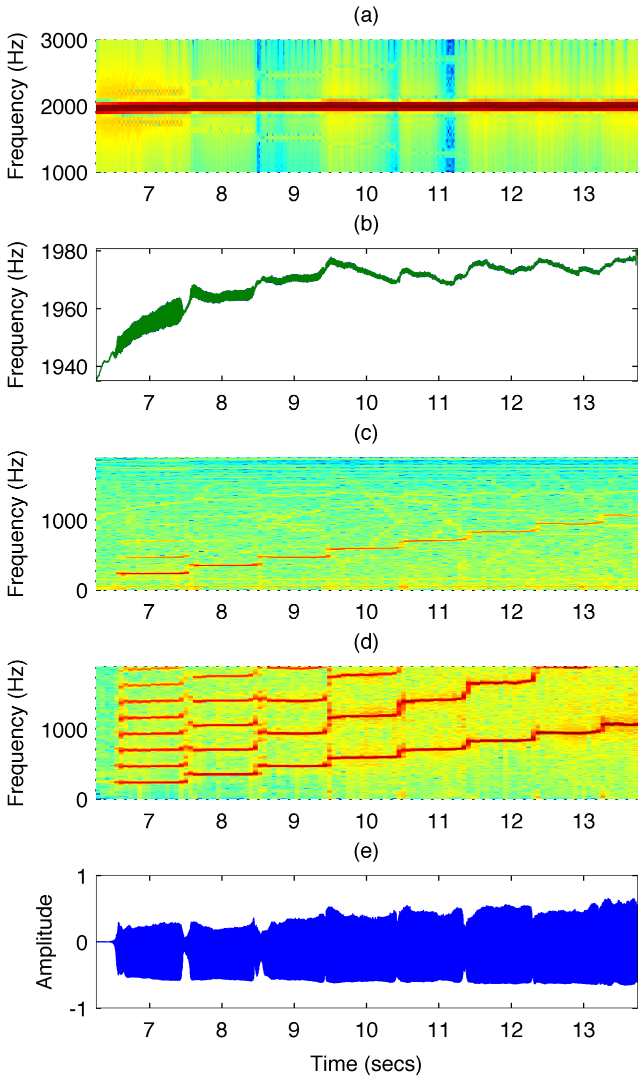

Figure 2: Plots derived for a recording of an upward lip slur through the resonances at concert pitches $B\flat_3$, F_4, $B\flat_4$, D_5, F_5, $A\flat_5$, $B\flat_5$ and C_6 being sounded by a professional player (BW) on the trumpet. (a) Spectrogram of the Theremin output signal. (b) Frequency tracking data calculated from Theremin output signal. (c) Spectrogram of the (high pass filtered) frequency tracking data calculated from the Theremin output signal. (d) Spectrogram of the external microphone signal (e) Audio waveform of the external microphone signal

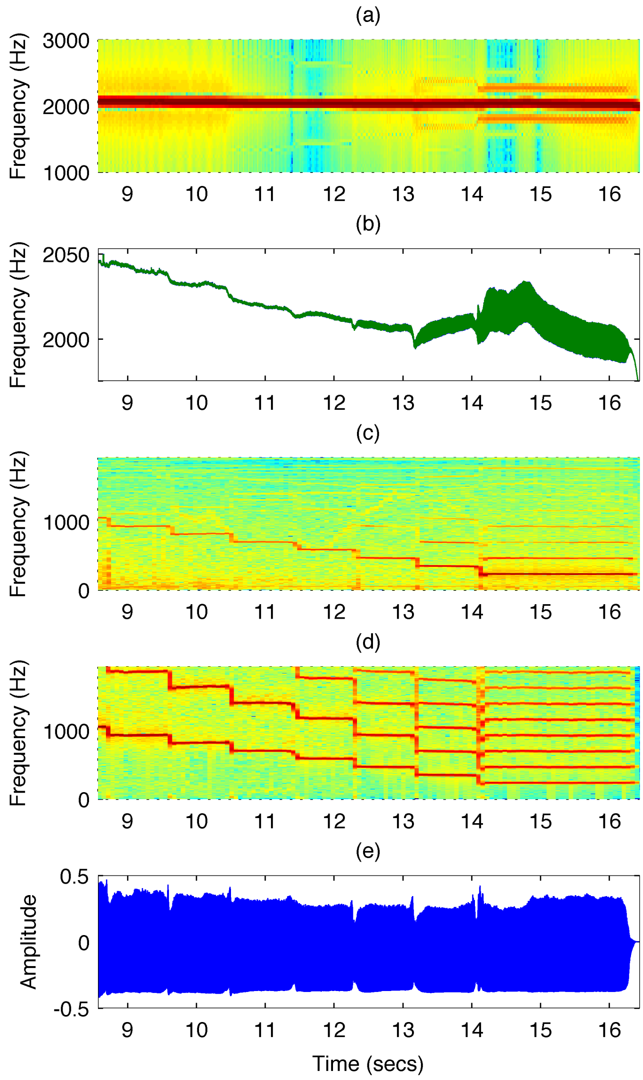

Figure 3: Plots derived for a recording of a downward lip slur through the resonances at concert pitches C_6, $B\flat_5$, $A\flat_5$, F_5, D_5, $B\flat_4$ F_4 and $B\flat_3$ being sounded by a professional player (BW) on the trumpet. (a) Spectrogram of the Theremin output signal. (b) Frequency tracking data calculated from Theremin output signal. (c) Spectrogram of the (high pass filtered) frequency tracking data calculated from the Theremin output signal. (d) Spectrogram of the external microphone signal (e) Audio waveform of the external microphone signal

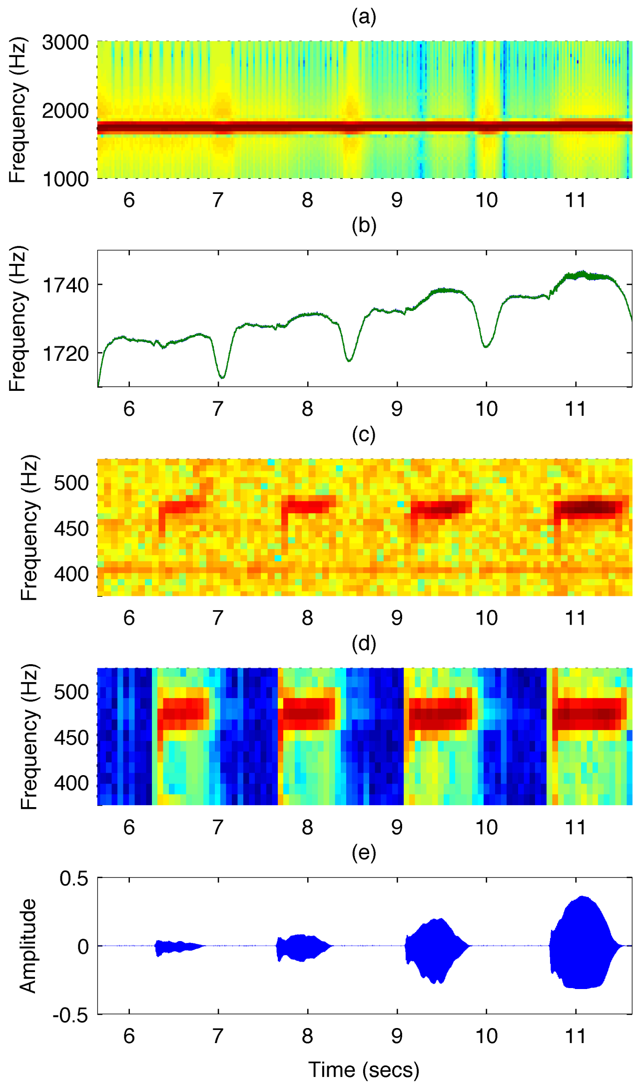

Figure 4: Plots derived for a recording of the note B♭$_4$ being sounded at different dynamic levels by an experienced jazz player (MV) on the trumpet. (a) Spectrogram of the Theremin output signal. (b) Frequency tracking data calculated from Theremin output signal. (c) Spectrogram of the (high pass filtered) frequency tracking data calculated from the Theremin output signal. (d) Spectrogram of the external microphone signal (e) Audio waveform of the external microphone signal

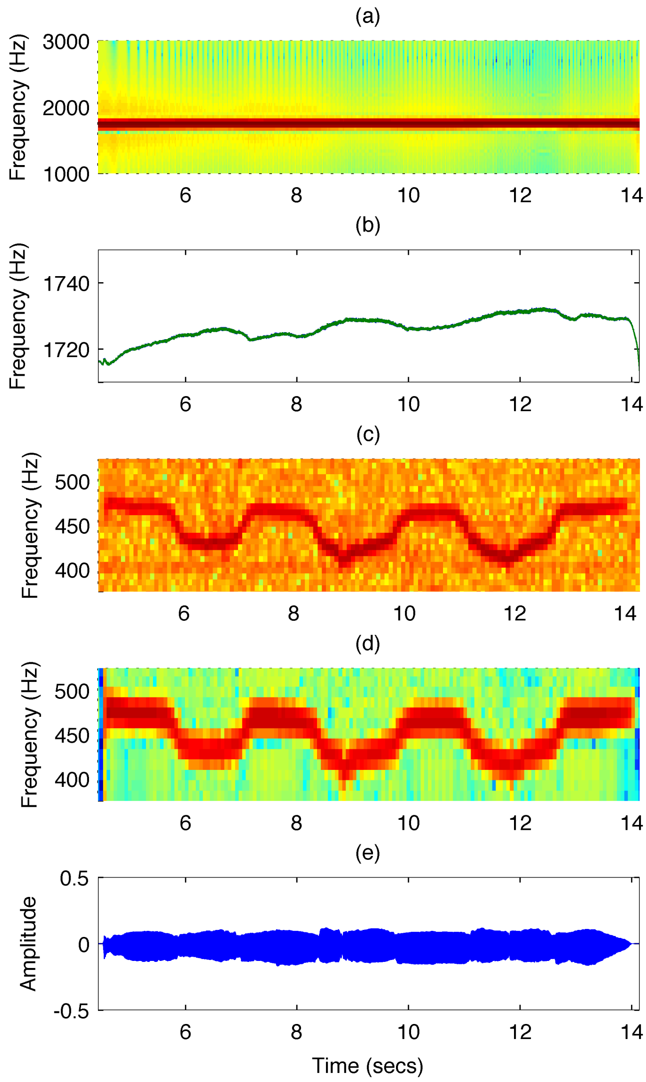

Figure 5: Plots derived for a recording of the note B♭$_4$ being bent down and upwards in pitch by an experienced jazz player (MV) on the trumpet. (a) Spectrogram of the Theremin output signal. (b) Frequency tracking data calculated from Theremin output signal. (c) Spectrogram of the (high pass filtered) frequency tracking data calculated from the Theremin output signal. (d) Spectrogram of the external microphone signal (e) Audio waveform of the external microphone signal