VOCAL TRACT EFFECTS ON THE TIMBRE OF THE SAXOPHONE

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ABSTRACT

For notes sounded over the normal and altissimo playing range, experienced saxophonists can produce changes in the spectral envelope of the radiated sound by adjusting their vocal tract configuration. Measurements of the vocal tract acoustic impedance, Z_{mouth}, during performance showed that, when Z_{mouth} was comparable with the input impedance of the bore, Z_{bore}, *i.e*. several MPa·s·m^{-3} or more, harmonics of the radiated sound falling near these peaks in Z_{mouth} were substantially enhanced. In contrast, the broadband noise in the radiated sound produced by upstream turbulence was attenuated in the frequency range over which the magnitude of Z_{mouth} was large.

1. INTRODUCTION

The shape of the vocal tract during woodwind performance is widely regarded by woodwind instrument performers to be of great importance to both pitch selection and control and to the quality of the sound. Recent advances in understanding this relationship involve direct measurements of the acoustic properties of the vocal tract during performance: the acoustic impedance of the vocal tract [1,2] and measurements of the ratio of the sound pressure inside the mouth and to that in the mouthpiece [3].

Expert saxophonists and clarinettists have been shown to use their vocal tracts for executing advanced performance techniques that involve controlling the fundamental frequency: performing in the altissimo register, bugling, multiphonics, pitch bending and glissando [2-5]. In a simple model, Benade [6] showed that the bore (downstream) and the vocal tract (upstream) impedances (Z_{bore} and Z_{mouth}), as 'seen' by the reed, are effectively in series. For these techniques, players tune a vocal tract resonance near to the desired frequency and this, in series with the bore, determines the playing pitch [2,4,5].

Woodwind players also report varying their vocal tract configuration to produce different timbre in different musical styles and contexts. These vocal tract configurations are often described by players in terms of various vowel-like mouth shapes (*e.g*. 'oo', 'ee', 'ah'). Presumably, varying the upstream geometry changes Z_{mouth} and thus influences the amplitude of higher harmonics in the produced sound.

In the previous SMAC (2003), we used artificial playing systems to show how changes in the upstream geometry, analogous to a changing tongue position, can produce different spectral envelopes (as well as different pitches) in trombone and didjeridu playing [7]. We later showed that for didjeridu playing, formants (or broad peaks in the envelope) of the radiated sound coincided with minima in the acoustic impedance measured in the mouth, and that the broad minima in the spectral envelope corresponded with impedance peaks in the mouth [8].

How might changes in vocal tract shape influence the amplitude of a harmonic of the output sound? One possibility is that a peak in Z_{mouth} at a particular frequency could vary the Fourier component of the pressure acting on the reed at that frequency and thus affect the shape of its vibration. Another possibility is that a peak in Z_{mouth} inhibits flow past the reed at that frequency, which explains the timbre changes of the didjeridu. A third possibility is that the variation in the upstream geometry changes the pitch of the note played. A small change in fundamental frequency has an n times greater effect on the nth harmonic, which may be enough to shift it from coinciding with a bore resonance to not coinciding, or *vice versa*. Whether or not a harmonic coincides with a bore resonance has a large effect on the radiated sound because of the production of standing waves [8].

To investigate this effect, the acoustic impedance in the mouth of experienced saxophonists was measured while they played notes with different timbre.

2. MATERIALS AND METHODS

For this study, a Yamaha Custom EX Tenor Saxophone with Yamaha 5C mouthpiece is used. The mouthpiece is fitted with a Légère synthetic saxophone reed (hardness 3), chosen for its stability, hygiene and stable physical properties. The input impedance data of the tenor saxophone bore used in this study comes from a database [9] obtained using the three-microphone-two-calibration method with non-resonant calibration loads [10].

To measure directly the acoustic impedance of the player's vocal tract during playing, an acoustic impedance measurement head based on the capillary method was modified from Chen *et al*. [2]. The measurement head (Figure 1) consists of a narrow stainless steel tube with internal cross sectional area of 2 mm^2 integrated into the saxophone mouthpiece which supplies the acoustic current source with harmonics from 500 to 4000 Hz at a spacing of 5.38 Hz. This is injected into the player's mouth during playing. Next, an Endevco 8507C-2 miniature pressure transducer of 2.42 mm diameter similarly fitted in the mouthpiece, adjacent to the stainless steel tube, is used to measure the sound pressure in the player's mouth, which includes both that produced by the vibrating reed and the response of the vocal tract to the injected probe current. These modifications increase the thickness of the mouthpiece by 2 mm at the bite point. However, this is not regarded as a significant disturbance by players [5], some of whom use different geometry mouthpieces for different styles of music.

The impedance measurement system is calibrated by connecting the modified mouthpiece to an acoustically infinite pipe (length 197 m, internal diameter 26.2 mm). To make a measurement, the player is asked to sustain a note for at least 6 seconds, while the broadband probe signal is injected into the player's mouth and its response recorded.

Three expert saxophonists, each with more than 10 years' classical and/or jazz background, participated in the study. Using the modified mouthpiece described above, the players were asked to achieve different timbre by only adjusting the tongue position while keeping other control parameters constant (*e.g.* biting force on the reed, embouchure, pitch and loudness).

Another microphone (Rode NT3) was positioned one bell radius from and on the axis of the bell of the saxophone to record the radiated sound for spectral analysis.

The raw acoustic impedance spectra were then analysed and treated [4] to remove the harmonics generated by the vibrating reed and to smooth the airflow turbulence measured inside the mouth.

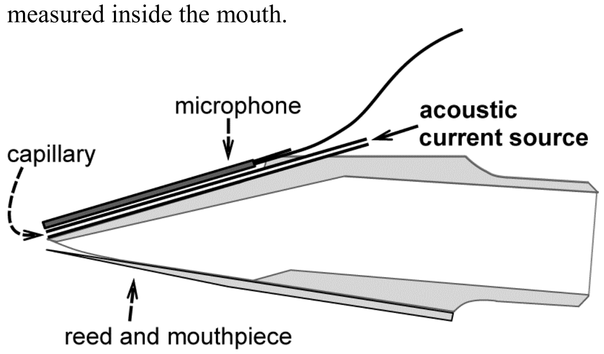

Figure 1. A schematic cross-section of the mouthpiece shows the capillary method used in the measurement of the vocal tract impedance during playing.

3. RESULTS AND DISCUSSION

All our subjects were able to produce different timbre by changing their tongue position, for notes across the normal and altissimo playing range, without much difficulty.

One general observation applies to all players: variation of the sound spectrum inside the mouth was much greater than that of the radiated sound. The player can hear the sound inside the mouth via transmission from mouth to ear through the bones and tissues, which explains why timbre changes may sometimes seem significant to the player, but rather less so to listeners.

Further, the players were usually able to produce larger timbre changes when they also changed the pitch, typically by ten or so cents. An obvious explanation is that large changes in the vocal tract configuration produce a change in the acoustic load on the reed that not only changes the harmonic content, but also the frequency of vibration. When constrained to keep constant pitch, the players were probably limited to a smaller range of vocal tract changes, for which the pitch could be compensated using other control parameters, such as the biting force on the reed.

Nevertheless, all the players in this study could produce significant changes in the spectral envelope of the radiated sound while maintaining a constant pitch. Here, we restrict discussion to the changes at constant pitch only.

The execution of these changes seems to vary from one player to another, and slight adjustments of the tongue can result in subtle timbre variations. This highlights the difficulty of comparing across different players, so in this study, we compare only the timbre variation with different tongue positions (vocal tract configuration) for the same player. In particular, two of our subjects report that the 'ah' tongue position is their default position during normal performance, especially for jazz playing. While the 'ee' tongue position is unusual, some players use it to create a subtle timbre variation. One subject noted that the 'ah' tongue position provides brightness while the 'ee' tongue position gives a 'dark and nasal' sound.

Figure 2 shows the sound spectra of one note (written C5 on tenor saxophone, sounding A#3, 233 Hz) and the measured vocal tract impedance spectra of one subject playing that note with different timbre by adjusting tongue position, (a) for the normal 'ah' tongue position and (b) for the 'ee' tongue position. The spectral envelopes in Figure 2 (a) and (b) clearly show the timbre variation. The amplitude of the third and fourth harmonics in the spectrum of the 'ee' tongue position is much greater: about 10 dB larger than those of the 'ah' tongue position. Other harmonics in the frequency range from 1.5 to 3.0 kHz all have about 5 dB difference than those of the 'ah' tongue position. The sound spectrum of the 'ee' tongue position also shows broad peaks (formants) at about 1.8 and 2.3 kHz, whereas that of the 'ah' tongue position, shows formants at about 1.6 and 2.5 kHz. How do these modifications in the spectral envelope relate to the resonances in the vocal tract?

In the Z_{mouth} spectrum for the 'ee' tongue position, the second and third impedance maxima shift to about 0.9 and 1.8 kHz, and their magnitudes are increased to about 8 and 3 MPa·s·m^{-3}, respectively, which is comparable with the magnitude of Z_{bore}. Figure 2(b) shows that, over the frequency range where Z_{mouth} exceeds Z_{bore}, the amplitude of harmonics here are substantially increased above their amplitude for the normal 'ah' tongue position. In other words, the biggest increase of the amplitude of the harmonics seems to correspond to the maxima in the vocal tract impedance of the 'ee' tongue position, when the magnitude of Z_{mouth} is sufficiently large. This is consistent with an observation by Scavone [3]: for one of the players in that study, the fifth and eighth harmonics in the radiated sound increased when the ratio of the pressure in the mouth to that in the mouthpiece increased.

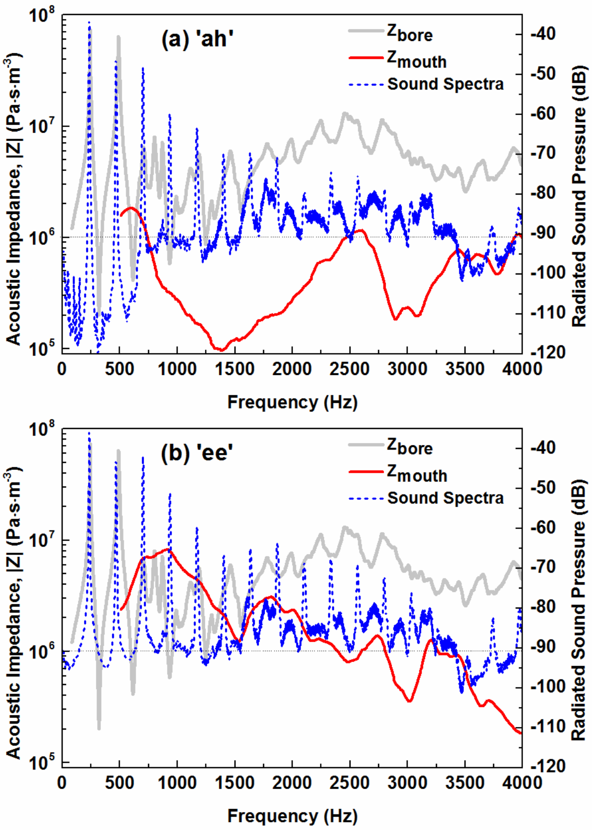

Figure 2. The sound spectra of the note (dashed blue line, A#3, nominally 233 Hz) and the measured vocal tract impedance spectra (continuous red line, measured from 0.5 to 4.0 kHz). Subject A plays the same note with different timbre by adjusting tongue position: (a) 'ah'-like and (b) 'ee'-like vowel. In both (a) and (b), the pale grey line shows the impedance spectra of the bore.

When we compare the broadband noise in the sound spectra with the impedance spectra, it is found that the background noise exhibits the complementary behaviour, *i.e*. the minima of the background noise correspond to the maxima of the Z_{mouth} and *vice versa*. This can be explained in the following way: the maxima of Z_{mouth} give minima in the acoustic flow at the reed, so there is little power input into the mouthpiece over this range of frequencies and thus little power in the radiated sound spectra. Similar behaviour was also observed in didjeridu playing [8], but for the harmonics of the played note.

Figure 3 shows the frequencies of the harmonics having the largest increase in amplitude when compared with the normal sound, plotted against the frequency of the peaks in Z_{mouth} for the cases where Z_{mouth} is comparable with Z_{bore}. From the figure, we can see that the correlation between the enhanced amplitude of the harmonics of the sound and peaks in Z_{mouth} occurs over the entire frequency range measured.

From Figure 3, we conclude that strong peaks in Z_{mouth} enhance the power of harmonics falling in or near the range of those peaks. The correspondence is not exact: for high notes, the harmonics are widely spaced, so few may fall near a peak.

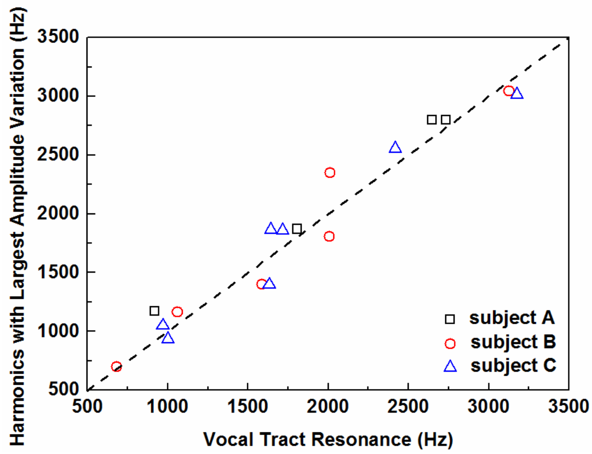

Figure 3. The harmonics with largest increase in amplitude in the radiated sound spectra against the nearest vocal tract resonance (maxima). Different sets of symbol stand for the results of different subjects.

In the case of didjeridu playing [8], the impedance maxima of the vocal tract correspond closely to minima in the spectral envelope of the radiated sound, while maxima in the radiated sound spectrum are correlated with the minima in the impedance spectra. Thus, the vocal tract configuration has a distinct effect on the timbre variation of the didjeridu. For the trombone [7,11], different vocal tract configurations (high tongue and low tongue) also produce timbre variations, but the effect is much less dramatic than during didjeridu playing because the Z_{bore} of the trombone is much higher than that of the didjeridu and consequently changes in Z_{mouth} have a reduced effect. The Z_{bore} of the saxophone also has a larger magnitude than that of the didjeridu [12], so the timbre change in Western wind instruments is substantially less than that in the didjeridu, but still of considerable musical importance.

4. CONCLUSIONS

When a player alters their vocal tract configuration, the changes in the spectral envelope of the sound radiated from the saxophone are rather smaller than those of the sound inside the player's mouth. Nevertheless, experienced players can vary the spectral envelope substantially at constant pitch and loudness. When the amplitude of the peaks in Z_{mouth} is at least comparable with those of Z_{bore}, the harmonics of the radiated sound are enhanced in the radiated sound. In contrast, the broadband noise is suppressed within this range.

Acknowledgments

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5. REFERENCES

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