Proceedings of the International Symposium on Music Acoustics
(Associated Meeting of the International Congress on Acoustics)
25-31 August 2010, Sydney and Katoomba, Australia

How players use their vocal tracts in advanced clarinet and saxophone performance

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PACS: 43.75.Pq, 43.75.St (Reed instruments; Musical performance)

ABSTRACT

How and when is the player's vocal tract important in clarinet and saxophone performance? In a simple model, the acoustical impedances of the instrument (a resonator downstream from the reed) and the player's tract (an upstream resonator) appear in series and in their sum is in parallel with that of the reed. Using impedance heads built into functioning mouthpieces, we made measurements of the acoustical impedance spectrum inside the mouths of clarinettists and saxophonists as they played. Acoustic impedance spectra of the clarinet, soprano and tenor saxophone bores were also measured for all standard fingerings, and some others. From these, we calculate the series impedance, and add it in parallel with the inferred reed reactance. For fingerings high in the tenor saxophone's second register, impedance peaks of the bore decrease rapidly with increasing pitch, making playing the altissimo range of this instrument more difficult than that of the clarinet, which has strong peaks into the fourth octave. Peak values on the saxophones fall below 30 MPa.s.m^{-3} above the first 2.7 octaves, ending the standard range available to amateurs. To play the altissimo notes, experts produced strong vocal tract resonances upstream with impedances 10-40 MPa.s.m^{-3} and tuned them so that the peak in the combined bore-tract-reed impedance corresponded to the desired note. While expert saxophonists adjust their vocal tracts thus for altissimo playing, inexperienced players do not and consequently cannot produce these notes. Similar vocal tract adjustments were observed for other advanced techniques such as bugling and multiphonic selection. When pitch bending in the second (clarino) register of the clarinet, experienced players produced strong tract resonances with impedances up to 60 MPa.s.m^{-3}, comparable in magnitude with those of the clarinet bore (40-50 MPa.s.m^{-3}). Thus during pitch bending, the sounding pitch is controlled by smoothly varying a strong resonance in the player's vocal tract. The phases of the bore, tract and reed impedances explain why pitch bending downwards is easier than upwards. In contrast, during normal playing on both the clarinet and saxophone, both amateur and experienced performers produced vocal tract impedance peaks with only moderate magnitude, and do not tune that resonance specifically to the note being played.

BACKGROUND

Different musicians playing the same instrument, even on a single note, can sound very different, and this is especially true for wind instrument performance. When a bad instrument downstream is replaced with a good one, it will usually sound better – though sometimes the difference is subtle for listeners. But what happens if you substitute a poor player upstream with a good one? The differences can sometimes be dramatic. Hence it is interesting to examine the differences among players, as well as the acoustics of the instrument.

Some of these differences are due to obvious control parameters, such as mouth pressure and how and where the player's lips exert force on the reed. But how much is due to the acoustical effects inside the player?

This study examines the role of the player's vocal tract in saxophone and clarinet playing and provides experimental results to demonstrate how players engage and manipulate their vocal tract during advanced clarinet and saxophone performance (*e.g.* bugling, altissimo playing, multiphonic playing, and pitch bending) and also during normal playing.

Advanced woodwind performance

With the development of jazz techniques, cross-over influences between popular and classical music, as well as the increasing demands of contemporary music, dramatic woodwind performance techniques are now employed by both composers and performers alike. These advanced techniques are described below:

1. *Bugling* on the saxophone (and less commonly, the clarinet) involves maintaining a constant fingering on the instrument, and by appropriately adjusting the breath, lips, tongue and throat, produce one or more other notes ('overtones') successively without engaging the register key. For example, while fingering the lowest note on the saxophone, written A#3 (sounding G#2, 104 Hz on the tenor saxophone), expert saxophonists may sound a series of notes falling close to the harmonic series, similar to that played on the trumpet or bugle. A related technique is to maintain the same fingering but sound different registers without using the register key.

2. *Altissimo playing* refers to performing in the uppermost register of the instrument. On the saxophone, this extends beyond the 'standard' range of 2.7 octaves, sounding up to the fourth octave. In addition to using special fingerings, playing in this range further requires extensive practice and is usually not possible for amateurs or even some experienced saxophonists. Players often report that different configurations of the vocal tract, including different tongue positions and/or different imagined vowels, must be used in order to sound different notes in this range (Raschèr, 1941). In contrast, the clarinet's third register is relatively easy to sound, and fingerings are included in beginner's guides.

3. *Multiphonic playing* allows the player to sound two or more pitches simultaneously on a woodwind instrument by using special fingerings; for particular fingerings, multiphonics may only be achieved by combining these fingerings with careful adjustments in breath, embouchure and the vocal tract (Bartolozzi, 1967). The same fingering may produce one or more different pitches simultaneously, depending on how adjustments are made by the player (Rehfeldt, 1977).

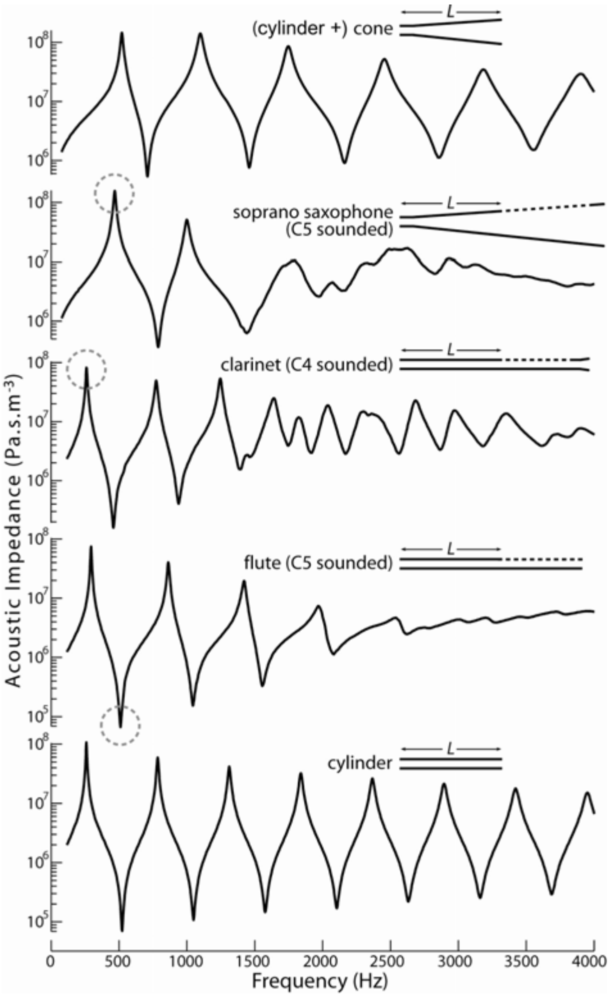
4. *Pitch bending* refers to the continuous deviation of pitch from one note to another, and is a technique widely used in jazz, rock, and folk music traditions such as *klezmer*. On the saxophone and the clarinet (which additionally allows pitch bending by gradually uncovering open tone-holes with one's finger), the pitch sounded can be altered, sometimes by large amounts using playing techniques that involve the player's breath, bite and vocal tract (Rehfeldt, 1977). Furthermore, although expert players can use their vocal tract and embouchure to lower the pitch by as much as several semitones, they are able to raise the pitch only slightly (Rehfeldt, 1977).

Acoustics of the clarinet and saxophone

The clarinet and saxophone are related: both are single reed instruments with similar reed oscillation generation mechanisms, driven by bore resonances. However, the clarinet bore is largely cylindrical while the saxophone bore is largely conical, with a relatively wide half angle (1.7º and 1.5º for the soprano and tenor saxophone respectively, compared with 0.7º and 0.4º for oboe and bassoon respectively). The saxophone is louder than the clarinet – one of the objectives of the instrument's inventor – partly because of this relatively wide cone (Dalmont and Nederveen, 1997). Figure 1 compares the acoustic impedance measured for a simple cylinder, flute, clarinet, soprano saxophone and a truncated cone, all of equivalent acoustic length.

When compared with the clarinet, the saxophone's wide conical bore has acoustical consequences that intimately affect its sounding range (Benade and Lutgen, 1988). Firstly, the peaks in the saxophone's acoustical impedance spectrum decrease more rapidly with frequency than on the clarinet (Figure 1, 2). Secondly, the typical cut-off frequency, f_c (above which, acoustic waves in the bore propagate past an array of open tone holes), for the tenor saxophone occurs around 760 ± 250 Hz and 1340 ± 240 Hz for the soprano (Chen *et al.*, 2009a), which is less than three octaves above the frequency of their lowest notes (sounding G#2 and G#3 at 104 and 208 Hz respectively), while on the clarinet, this occurs around 1500 Hz (Dickens *et al.*, 2007b), three octaves and a third above the lowest note (sounding D3 at 147 Hz).

Consequently, no strong peaks are typically seen in the saxophone's impedance spectrum at frequencies three octaves above its lowest fundamental frequency. On the other hand, the clarinet bore continues to show strong peaks in its impedance spectrum well over four octaves above its lowest note.



Source: (Chen *et al.*, 2009a)

Figure 1. The acoustic impedance of (bottom to top) a simple cylinder, flute, clarinet, soprano saxophone and a truncated cone, all of an equivalent acoustic length. The circle indicates the maximum or minimum where each instrument operates.

The relative spacing in frequency of the impedance peaks between the two instruments is also different. Because the clarinet overblows a musical twelfth, the range of each register is also wider than on the saxophone: for low notes, the first three saxophone resonances have frequency ratios approximately 1:2:3, while those of the clarinet are approximately 1:3:5 (Figure 1, 2). Consider: on the clarinet, the first altissimo (or third register) note and the lowest note to use the third bore impedance maximum, written C#6 (sounding B5, 988 Hz), is almost three octaves higher than the lowest note on the instrument, written E3 (sounding D2, 147 Hz).

In both the saxophone and the clarinet, the fundamental frequency of notes in the first register corresponds to the first impedance peak (Figure 1, circled) and the first mode of standing waves in the instrument bore. In the second register, register keys weaken and 'detune' the first impedance peak, and the instruments now operates at the second impedance peak (and second mode) to play notes in this register. For both instruments, the first two registers cover a range of 2.7 octaves. (To compensate for its narrower gap between registers, the saxophone has extra keys to extend the second register up and the first register down.)

On the saxophone these two registers constitute what is usually considered its standard range. In contrast, the standard range of the clarinet includes a third register (the altissimo register) which is activated by using the hole that is normally closed by the index finger of the left hand.

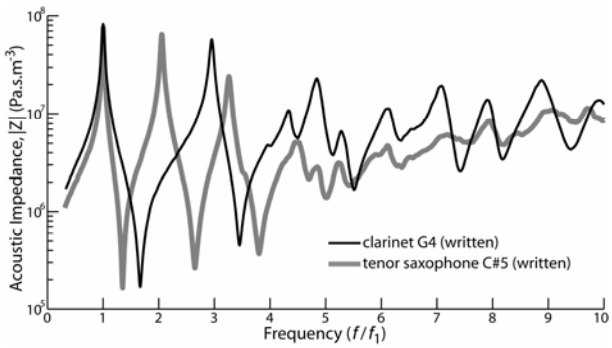


Figure 2. The acoustic impedance of the clarinet and tenor saxophone bore (Z_{Bore}) shown for the fingering with “all fingers off” – written G4 (349 Hz) on the clarinet and written C#5 (247 Hz) on the tenor saxophone. Both fingerings are a musical minor 10th above the lowest note on both instruments. To facilitate comparison, frequencies are scaled to the sounding frequency, f_1, in each case.

To first order, stable reed oscillation (at the sounding frequency, f_1) on the clarinet and saxophone occurs at one of the maxima in the acoustic impedance Z_{Load} loading the reed generator, which determines the airflow into the instrument, along with the pressure difference between the bore and mouthpiece (Fletcher and Rossing, 1998). (Other factors such as lip damping, bite configuration, jaw force and blowing pressure also contribute, but are modest.)

By simplifying the processes at the reed junction, applying continuity of volume flow and assuming the acoustic pressures upstream (in the mouth near the reed) and downstream (in the mouthpiece near the reed) both act on equal areas of the reed, Benade (1985) estimated that the impedance loading the reed is $Z_{Load} = (Z_{Tract} + Z_{Bore}) \parallel Z_{Reed}$.

In this simple model, which considers only the linear acoustics of the bore and the vocal tract, their sum in series is in parallel with the reed (the last treated as a pure compliance). When the vocal tract impedance is small compared to the bore impedance, Z_{Load} is determined by Z_{Bore} and Z_{Reed} alone – indeed, the maximum in measured impedance of the bore in parallel with the reed corresponds closely to the pitch in normal playing for the tenor saxophone (Chen *et al.*, 2007, 2008a, 2009a) and the clarinet (Dickens *et al.*, 2007b). On the other hand, if the player were able to make Z_{Tract} large and comparable to Z_{Bore}, the player's vocal tract could influence, or even determine, the sounding frequency of the player-instrument system.

Using data published earlier for the saxophone (Chen *et al.*, 2009a) and the clarinet (Dickens *et al.*, 2007b), Figure 3 compares the acoustic impedance magnitudes for operating bore resonances (with the reed accounted for in parallel) in the clarinet, soprano saxophone and tenor saxophone across their respective playing ranges. The first, second and altissimo registers are distinguished.

As discussed earlier, because the saxophone is largely conical while the clarinet is largely cylindrical, some acoustic differences are apparent: the standard playing range of the clarinet reaches about four octaves, while both the tenor and soprano saxophone have a more modest standard playing range of 2.7 octaves. Further, the operating resonances of both the tenor and soprano saxophone vary over an order of magnitude in the acoustic impedance across registers, whereas in the clarinet resonances vary less widely. In the tenor saxophone, resonances of the lowest notes of the instrument, as well as notes in the upper second and altissimo register, have weak impedance magnitudes, reflecting player observations that these notes are difficult to sound easily.

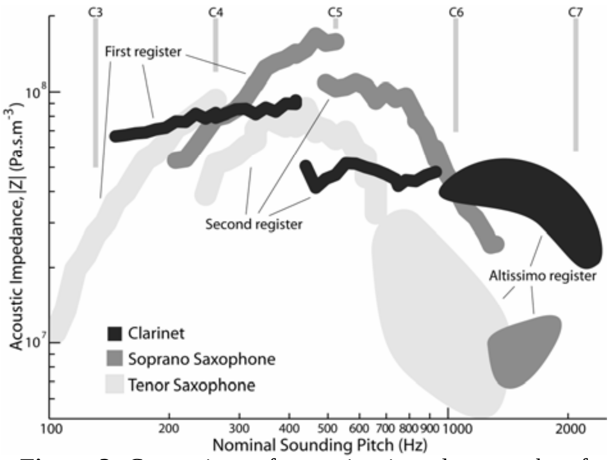


Figure 3. Comparison of operating impedance peaks of the clarinet (dark), soprano (grey) and tenor saxophone (pale) (with the reed combined in parallel), plotted against the nominal sounding frequency. Regions indicating bore resonances used to play in the first register, second register and altissimo register are labelled. Grey vertical bars indicate the sounding pitch in musical notation.

Previous studies of the player's vocal tract

Various empirical studies (Watkins, 2002), pedagogical studies (*e.g.* Pay, 1995; Rehfeldt, 1977) and numerical investigations (Sommerfeldt and Strong, 1988; Scavone, 2003) support musicians' opinions that the vocal tract influences the note sounded during performance. However, when investigating changes in vocal tract geometry, Clinch *et al.* (1982) reported “vocal tract resonance must match the frequency of the required notes” while Backus (1985) concluded instead “resonances in the vocal tract are so unpronounced and the impedances so low that their effects appear to be negligible”.

These studies concentrated primarily on standard performance techniques, and did not examine advanced playing techniques in particular. However, Wilson (1996) investigated the influence of the clarinettist's vocal tract for playing techniques including pitch bending, playing second register notes without using the register key (*cf.* bugling), and multiphonic playing using a technique which indicates indirectly the relative acoustic impedance of the player's tract to the clarinet bore, at harmonics of the sounding reed. In this way, Wilson was able to surmise that vocal tract resonances are increased and adjusted in frequency when performing such techniques.

Later, Fritz and Wolfe (2005) measured acoustic impedance directly inside the player's mouth by having the clarinettist mime with the instrument for various musical gestures. They report that, when playing in the clarinet's altissimo register, players adjust their vocal tract configuration, often drastically. The impedance peaks measured in the mouth were as high as a few tens of MPa.s.m^{-3}, comparable with those of the clarinet bore, but no relation between the frequencies of the peak and the note played was reported.

More recently, Scavone *et al.* (2008) investigated pitch bending, bugling, altissimo and multiphonic playing on the alto saxophone using Wilson's technique to reflect in real-time, the relative impedances of the player's vocal tract. In their measurements, they found that the pressure component at the playing frequency was larger in the player's mouth than in the bore when executing these techniques, and reported that players can “create an upstream windway resonance that is strong enough to override the downstream system in controlling reed vibrations” in order to elicit these effects. Also, the real-time feature in their system may be useful in teaching resonance adjustment techniques to saxophonists.

At the same time, we measured acoustic impedance spectra directly in the player's mouth during altissimo performance on the tenor saxophone and pitch bending on the saxophone (Chen *et al.*, 2007, 2008a), and clarinet (Chen *et al.*, 2008b, 2009b). In both instances, experts were observed to produce simultaneously a strong vocal resonance, such that maxima in Z_{Tract} becomes comparable with that in Z_{Bore}, and additionally tune its resonance frequency near the intended pitch, in order to determine at what frequency the reed sounds, in order to perform these effects.

From these studies, it is clear the player's vocal tract is required in order to execute these advanced techniques. This paper offers an overview of the nature of the interaction of player's vocal tract with the clarinet and tenor saxophone during musical performance, while differences and similarities in vocal tract strategies employed by expert clarinettist and saxophonists are highlighted.

Measurement methodology and protocol

Measuring the clarinet and saxophone bores. The acoustic impedance spectra of the clarinet and saxophone bores (Z_{Bore}) were measured on a Yamaha model CX B-flat soprano clarinet and Yamaha Custom EX tenor saxophone using the three-microphone-two-calibration (3M2C) method calibrated with two non-resonant loads (Dickens *et al.*, 2007a): an open circuit (nearly infinite impedance) and an acoustically infinite waveguide (purely resistive impedance, independent of frequency). Z_{Bore} was measured from 80 to 4000 Hz with a spacing of 1.35 Hz. Databases containing these data are available (Dickens *et al.*, 2007b, Chen *et al.*, 2009a).

Measuring reed compliance. Representative values for the effective compliance of clarinet and tenor saxophone reeds under playing conditions were measured using Benade's technique (1976), in which the reed is considered as a pure compliance terminating a bore. Synthetic clarinet and saxophone reeds from Légère Reeds Ltd. (Canada) were studied, as the physical properties of synthetic reeds remain constant whether wet or dry, and are stable over time. The measured compliance of clarinet reeds yielded an average equivalent volume of 1.1 ml of air, while tenor saxophone reeds averaged 3.2 ml of air. These values treated as (pure) compliance are used for Z_{Reed} in this study.

Measuring acoustic impedance of the player's mouth. The acoustic impedance of the clarinettists and saxophonists' vocal tracts was measured directly during performance using a technique based on the capillary method (Benade and Ibisi (1987), Dickens *et al.*, 2007a). By incorporating transducers within the instrument mouthpiece (Chen *et al.*, 2007, 2008a, 2008b, 2009b), we are able to measure the impedance "looking into" the player's vocal tract from a location in the mouth within a few millimetres of the vibrating reed. Modifications made to the mouthpiece result in an increase in thickness of about 1.5 mm at the bite point. However, this does not affect the players because the mouthpiece geometry remains otherwise largely unchanged.

The raw acoustic impedance measured in the player's mouth is then analysed and smoothed (method described by Chen *et al.*, 2009b) to remove noise arising from the strong reed signal and turbulent airflow in the mouth – the resulting spectrum is a measurement of acoustic impedance in the player's mouth, very near the position of the reed. During performance, the saxophone reed radiates at a high sound level in the player's mouth, and produces an artefact that appears as sharp narrow peaks in the raw impedance spectra at harmonic frequencies of the note sounded. Although this artefact is removed, interpolated and smoothed over for the treated Z_{Mouth} spectra used in calculations, this narrow peak in Z_{Mouth} indicates conveniently what note is being played and which resonance peak in Z_{Bore} might be driving the reed. Therefore the artefact is deliberately retained for treated Z_{Mouth} spectra shown here (*e.g.* Fig. 4).

Volunteer players. Eight saxophonists, from both classical and jazz backgrounds, were engaged. Five were expert players (all professionals) and three were amateurs. They played on a Yamaha Custom EX tenor saxophone using the modified mouthpiece provided. Additionally, five expert clarinettists were engaged and played on a Yamaha model CX B-flat soprano clarinet. To measure the acoustic impedance in the player's mouth, each note was sustained for several seconds.

HIGH REGISTER PLAYING

The altissimo range on the clarinet refers to the third (and highest) register of its standard range. On the saxophone, however, altissimo playing refers to playing in the uppermost register of the saxophone which extends *beyond* the standard 2.7 octave traditional range which is covered using standard fingerings, rather than cross-fingerings.

Altissimo on the saxophone

For fingerings in and above the second register in the tenor saxophone, the magnitude and sharpness of the operating impedance peak decreases with rising pitch as visco-thermal losses near the walls and radiation at the bell increase with frequency. Above about 650 Hz (near written F#6, sounding E5, and the upper limit of the standard range) operating impedance peaks fall below 30 MPa.s.m^{-3}: these resonances are 'weak' and will not support notes 'on their own', thus limiting the standard range to the first and second registers (which have stronger resonances).

However, using particular vocal tract adjustments and special fingerings, expert players can play above the standard range – the altissimo range – sounding notes up to the fourth octave. These notes operate at the third (or higher) Z_{Bore} maxima (*e.g.* Figure 4), and magnitudes vary from 5 MPa.s.m^{-3} at written D7 (sounding C6, 1046 Hz) to 31 MPa.s.m^{-3} at written A6 (sounding G5, 784 Hz). Alternative fingerings are available for each altissimo note, offering players a range of possible impedance maxima with differing Z_{Bore} and intonation.

Figure 4 compares representative bore impedance (Z_{Bore}) and the corresponding acoustic impedance typically measured in the player's mouth (Z_{Mouth}) when playing a note in the standard range (written A5, sounding G4, 392 Hz) and in the altissimo range (written C7, sounding A#5, 932 Hz). To show the combined acoustic impedance of the player and instrument bore in series, (Z_{Bore} + Z_{Mouth}) is also included. Two features are seen in the Z_{Mouth} spectra: broad peaks indicating tract resonances, while harmonics of the note sounded are superimposed as sharp peaks; these are aggregated later in Figure 10 for playing in the standard and altissimo range.

For playing in the standard range (Figure 4, top graphs), Z_{Mouth} shows a resonance at 549 Hz with an impedance maximum 12 MPa.s.m^{-3} (broad peak) while harmonics of the note sounded, written A5, are seen at 393, 786 and 1174 Hz (sharp peaks). The resonance in Z_{Mouth} here is smaller than the operating Z_{Bore} maximum at 398 Hz at 64 MPa.s.m^{-3}, five times greater. For the much of the standard range of the saxophone, peaks in Z_{Bore} are much greater than that in Z_{Mouth} and thus dominate the series combination (Z_{Mouth} + Z_{Bore}); Z_{Bore} peaks therefore support stable reed oscillations on its own to determine the sounding frequency. The resonance in Z_{Mouth} shows no particular relation to the note played.

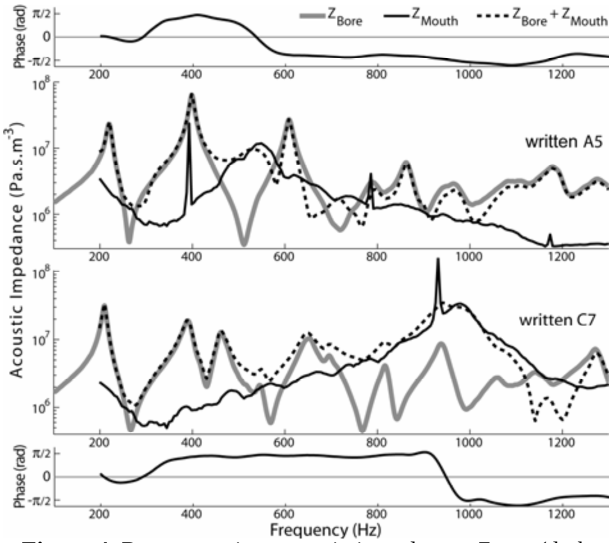


Figure 4. Representative acoustic impedances Z_{Mouth} (dark line) measured in the vocal tract of an expert saxophonist playing (top two graphs) the written note A5 (392 Hz, sounding G4) in the standard range and (bottom two graphs) the written note C7 (932 Hz, sounding A#5) in the altissimo range of the tenor saxophone, indicated as phase (first and last graph) and magnitude (second and third graph) respectively. Sharp peaks in the magnitude graphs indicate harmonics of the note sounded, while broad peaks indicate resonances in the mouth. Respective bore impedance Z_{Bore} for the fingerings used is shown with a pale line, while the combined complex acoustic impedance of the player and instrument bore (Z_{Mouth} + Z_{Bore}) a dashed line.

In contrast, during altissimo playing, the bottom graphs in Figure 4 show a resonance in Z_{Mouth} at 980 Hz with an impedance maximum of 34 MPa.s.m^{-3}, while a sharp spike at 931 Hz indicates the note sounded – written C7. Here, the broad impedance peak in Z_{Mouth} is almost four times greater than the operating peak in Z_{Bore} (8.7 MPa.s.m^{-3} at 938 Hz), and here its resonance is adjusted a mere 50 Hz above the sounding frequency. Although peaks in Z_{Bore} are weak at high frequencies and are unable to support stable reed oscillations on their own, players can adjust a strong peak in Z_{Mouth} to be several times greater than that of Z_{Bore} at these frequencies. Consequently, the resonance in Z_{Mouth} now dominates the series combination (Z_{Mouth} + Z_{Bore}) and the sounding frequency falls near the maximum in (Z_{Mouth} + Z_{Bore}) (Figure 4).

In this manner, the expert player can 'select' a weak resonance in Z_{Bore} by adjusting a strong resonance in Z_{Mouth} in order to facilitate playing in the altissimo range; an appropriate fingering that generates peaks in Z_{Bore} at a suitable frequency must first be supplied, of course.

Both Z_{Mouth} plotted in Figure 4 further indicate the presence of another vocal tract impedance peak at low frequencies. From our measurements, this impedance peak at lower frequencies (~200 Hz) is weak (~3 MPa.s.m^{-3}) and is not found to be adjusted significantly during performance.

Amateur and expert saxophonists

Vocal tract resonance frequency, its corresponding impedance magnitude and frequency of the note played are extracted from 650 measurements for expert and amateur saxophonists playing across the standard range and up through the first octave of the altissimo range, and plotted in Figure 10 later. The transition from standard to altissimo range (written F#6 to G6, sounding 659 to 698 Hz) is indicated by a vertical line. Because players were free to play these notes using their preferred mouthpiece adjustments, dynamics, embouchure and reed hardness, slight variation in sounding frequency is observed, particularly in the altissimo range, where the player further used a fingering of their choice; this does not considerably affect the reliability of the results observed, however.

Discussed earlier and typified by the Z_{Mouth} spectrum in the top graphs of Figure 4, Figure 10 below shows a wide variation in vocal tract resonance (ranging typically from about 500 to 1100 Hz) for both expert and amateur players over the standard playing range; no simple relationship to the note sounded is observed. While experts displayed widely distributed vocal tract resonances, especially over the lower standard range, tract resonances of amateur players remain fairly static: tract resonance data points lie within two horizontal bands at about 650 and 1100 Hz over most of the standard range. Two amateur players in the study relate that they in fact strive to keep their vocal tract configuration constant during playing and had been taught to do so. Figure 5 shows several Z_{Mouth} measured for an amateur playing towards the upper limit of his range. These spectra exhibit modest peaks of magnitude 1 to 2 MPa.s.m^{-3} and consistent vocal tract resonances at about 240, 700 and 1130 Hz, demonstrating the absence of vocal tract adjustment by this player.

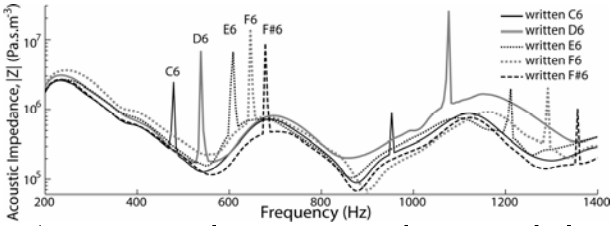


Figure 5. Z_{Mouth} of an amateur saxophonist towards the upper limit of his playing range, playing written notes C6, D6, E6, F6 and F#6 (sounding A#4, C5, D5, D#5 and E5) and indicated by narrow peaks at 479, 538, 608, 646 and 678 Hz respectively. Broad peaks about 1 to 2 MPa.s.m^{-3} at about 240, 700 and 1130 Hz indicate consistent and modest vocal tract resonances and configurations are used.

Our measurement show that across the standard range, no particular relationship is observed for the impedance magnitude of amateur's vocal tract resonances, varying widely from 0.4 to 6 MPa.s.m^{-3}. In contrast, a tendency is observed for the impedance magnitude of expert's vocal tract resonances to increase with rising pitch here. It starts from about 1 MPa.s.m^{-3} over the first saxophone register and grows steadily tenfold over the second register to ~10 MPa.s.m^{-3}, approaching the impedance magnitudes of bore resonances at the upper limit of the second register. (Chen, 2009)

Despite these differences, both experts and amateurs had no difficulty playing across the standard range. Moving to the altissimo range, however, amateurs were no longer able to sound the notes desired, whether on the experimental setup or on a normal saxophone, despite using appropriate fingerings. (At best, they could sound the first few notes of the altissimo range, but inconsistently and with great difficulty.)

On the other hand, the expert saxophonists faced no such trouble. Consistent with behaviour first observed in the bottom graph of Figure 4, these players show tight tuning of a strong vocal tract resonance near to the note played, typically not more than 100 Hz apart, as they enter the altissimo range (Figure 10, below). Indeed, towards the upper standard range, expert players already exhibit some systematic (albeit looser) adjustment of their vocal tract resonance. Expert saxophonists perform this tract tuning almost intuitively: some players explained that they must first 'hear' the intended altissimo note 'in the head' (Raschèr, 1941) and the desired vocal tract configuration is then produced without conscious effort, suggesting that procedural memory from extensive practice is used in the altissimo range and during pitch bending.

At the same time, impedances of tract resonances measured in the experts here are typically an order of magnitude greater than those used across the standard range, ranging between 10 to 40 MPa.s.m^{-3}: vocal tract resonances are now comparable in magnitude with operating resonances in the saxophone bore, and in some cases even exceed it. A strong vocal tract resonance is consistent with a narrow glottis in the player (Mukai, 1992; Fritz and Wolfe, 2005).

When saxophonists adjust their vocal tract resonance near to the note sounded in the altissimo range, its tuning need not be exact because the bore resonances are narrow and its impedance varies rapidly with frequency while tract resonances are broad and its impedance varies moderately with frequency (*cf.* Figure 4). Consequently, when vocal tract coupling is required by the player to influence the series impedance (Z_{Tract} + Z_{Bore}), a strong vocal tract resonance adjusted near the appropriate frequency is sufficient to facilitate altissimo playing. Furthermore, although vocal tract resonances measured are dispersed over a range of values when playing over the standard range but follow the tuning line over the altissimo range (grey diagonal, Figure 10), these resonances measured for both experts or amateurs tend to fall on, or higher than, that of the note sounded, rather than below. While this observation is not critical to the current discussion, possible reasons for such behaviour are discussed later.

Altissimo on the clarinet

As discussed earlier, the clarinet's largely cylindrical geometry mean that bore resonances are significant well into the third and fourth octave; its standard range – written E3 to C#7 (sounding D3 to B6, 147 to 1976 Hz) – is significantly broader than that of the saxophone. Over the clarinet's altissimo range (written C#6, sounding 988 Hz, and above), resonance peaks are fairly strong and well defined (typically ~40 MPa.s.m^{-3}, Figure 3), so the clarinet is able to support stable reed oscillations on its own at high frequencies without additional coupling from the player's vocal tract.

Bugling and multiphonic playing

Figure 6 shows measurements of an expert clarinettist bugling successive overtones while maintaining the fingering for written E3 (sounding D3, 147 Hz), the lowest note on the clarinet. It utilises the full acoustic length of the bore such that the clarinet roughly resembles a cylinder stopped on one end, so resonances in the bore approximate odd-numbered harmonics of the fundamental note. Therefore, unlike bugling on the saxophone, only notes roughly approximating odd-numbered multiples of the fundamental frequency are available for bugling on the clarinet. Figure 6 show these bore resonances, where the clarinet impedance is plotted with the reed compliance in parallel ($Z_{\text{Bore}} \parallel Z_{\text{Reed}}$). Regularly spaced impedance peaks are seen, and its frequencies approximate the odd-numbered harmonics of the lowest peak. Because of the bell and a slight flare in the bore leading to it, these clarinet resonances are flatter in frequency than those of a pure cylinder.

Figure 6 further shows impedances measured in the player's mouth (Z_{Mouth}) when bugling the first six overtones. In each case, sharp narrow peaks are seen, indicating harmonics of the note sounded. The lowest of each of these are matched closely in frequency to that of the bore resonance operating. A strong and broad impedance peak (indicating a vocal tract resonance) is again observed to be adjusted near it. This behaviour is similar to the strategy employed by expert saxophonists to facilitate altissimo playing: by adjusting a strong vocal tract resonance frequency near to that of a bore resonance, expert players can manipulate the reed to operate preferentially at the bore resonance desired.

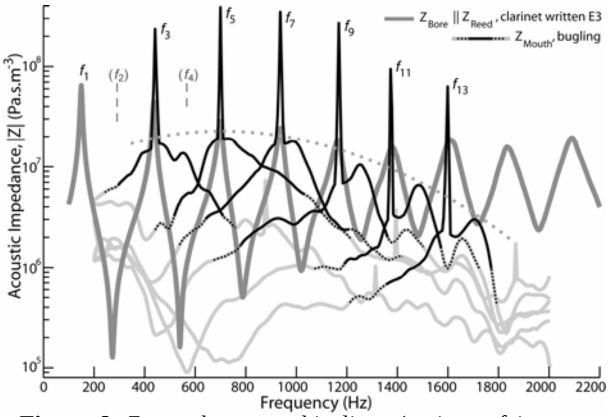


Figure 6. Z_{Mouth} shown as thin lines (regions of interest highlighted in black, while remaining portions are greyed) when bugling the first six overtones on the clarinet for the note written E3 (147 Hz). Bore impedance for this note is shown with the reed compliance in parallel, $Z_{\text{Bore}} \parallel Z_{\text{Reed}}$ (thick pale line). Sharp peaks in Z_{Mouth} at 441, 700, 937, 1168, 1373 and 1599 Hz indicate the frequency of the note sounded, falling at nominally odd-numbered multiples of the frequency of the lowest note or 'fundamental' f_1 (148 Hz). The dotted line indicates the envelope of Z_{Mouth} resonances, while vertical dashes indicate missing even-numbered multiples of f_1.

The envelope of vocal tract impedance peaks over the notes bugled (indicated by the gently sloping dotted line) for this player shows a decline in vocal tract impedance peak with increasing frequency, falling from 20 to 3 MPa.s.m^{-3} over 400 to 1800 Hz, while bore impedance peaks decrease from 45 to 18 MPa.s.m^{-3} over the same frequency range. Here, the vocal tract impedance envelope decreases faster with frequency than that of the clarinet bore. This suggests that, at sufficiently high frequencies (possibly above about 2000 Hz), the influence of the player's vocal tract over bore resonances becomes limited, because it becomes impossible to adjust this vocal tract resonance above these frequencies and still maintain a strong impedance peak.

Similarly, by making subtle but deliberate vocal tract adjustments, expert players can determine which tones in a multiphonic fingering are sounded and how prominently. These require players to adjust their vocal tracts to interact with the instrument in addition to the complex exchanges arising from the combinations of bore resonances, nonlinearity in the system and amplitude of vibrations already at play in the multiphonic fingering. In this way, different tones may be sounded individually or in simultaneous combinations all while using the same multiphonic fingering (Chen, 2009).

PITCH BENDING

On the clarinet, when a transition between notes uses one of the seven tone-holes which are covered directly by a finger (rather than by a pad), pitch bending can be achieved by carefully partially covering or uncovering a tone-hole with one's fingers, thereby incrementally adjusting the bore's effective acoustical length. However, pitch bending without adjusting the fingers but solely controlled by the vocal tract is also possible on the clarinet, typically above about written D5 (sounding C5, 523 Hz). Pitch bending here can be substantial, sometimes varying over several semitones while maintaining the same fingering, although the actual range depends on the player. Further, this bending is asymmetric: although expert players can use their vocal tract and embouchure to lower the pitch by as much as several semitones, they can only raise the pitch slightly (Scavone *et al.*, 2008; Chen *et al.*, 2009b).

Similar observations apply to the saxophone, whose reed and mouthpiece is similar to that of the clarinets.

Figure 7 shows the measured impedance of the clarinet bore (shown with || Z_{Reed}), and that of a typical impedance measured in the mouth (Z_{Mouth}) during normal playing (top) and a typical Z_{Mouth} of a player performing a pitch bend (bottom), both while holding the fingering for written A5 (sounding G5, 784 Hz). Z_{Mouth} is added in series with Z_{Bore}, and the effective Z_{Reed} added in parallel to obtain an estimate of the effective acoustic impedance Z_{Load} loading the reed generator.

In normal clarinet playing (Figure 7, top), the magnitude of the peak in Z_{Mouth} (20 MPa.s.m^{-3} in this example) is less than half that of the operating peak in Z_{Bore} (44 MPa.s.m^{-3}, with Z_{Reed} in parallel). Consequently, according to the simple Benade (1985) model, the combined acoustic impedance for normal playing yields a resulting maximum determined largely by the maximum in Z_{Bore}: the reed vibrates at a frequency (781 Hz) matching the strongest peak in Z_{Bore} || Z_{Reed}.

During the pitch bend, however, the maximum impedance measured in the mouth is typically comparable in magnitude with that of the maximum of the bore impedance. The bottom graph in Figure 7 shows that, because here the peak in Z_{Mouth} is no longer negligible in comparison with Z_{Bore}, the peak in (Z_{Mouth} + Z_{Bore}) || Z_{Reed} is no longer determined solely by a peak in Z_{Bore}. The Z_{Mouth} peak (32 MPa.s.m^{-3}) centred at 705 Hz is more comparable in magnitude with the corresponding Z_{Bore} || Z_{Reed} maximum (44 MPa.s.m^{-3}). The sounding frequency of the pitch bend (indicated by a sharp peak) is about 76 Hz (190 cents or about one whole tone) lower than that produced for normal playing, and nearer to the peak calculated in (Z_{Mouth} + Z_{Bore}) || Z_{Reed} at 662 Hz, than the peak in Z_{Bore} || Z_{Reed} alone (781 Hz). (This discrepancy may be due to the simplicity of Benade's (1985) model. Also, a smaller Z_{Reed} value would result in a higher frequency for the peak predicted in (Z_{Mouth} + Z_{Bore}) || Z_{Reed}, so the difference here can also be explained if the compliance of the reed in this situation were higher than the normal playing conditions from which it was estimated, *e.g.* by biting harder on the reed.)

Figure 8 shows similarly the measured impedance of the tenor saxophone bore (shown with Z_{Reed} in parallel), and that of a typical result for Z_{Mouth} during normal playing (top) and a typical measurement of the acoustic impedance in the mouth of an expert saxophonist performing a pitch bend (bottom), both holding the fingering for written D#6 (sounding C#5, 554 Hz). Likewise, an estimate of the effective acoustic impedance loading the reed generator, Z_{Load} = (Z_{Mouth} + Z_{Bore}) || Z_{Reed} in both cases is plotted in the respective graphs.

In normal playing (Figure 8, top), the magnitudes of the peak in Z_{Mouth} (3 MPa.s.m^{-3} in this example) are much smaller than the operating peak in Z_{Bore} (72 MPa.s.m^{-3}, with Z_{Reed} in parallel). Consequently, the combined acoustic impedance for normal playing yields a resulting maximum determined largely by the maximum in Z_{Bore}: the reed vibrates at a frequency (552 Hz), matching the strongest peak in Z_{Bore} || Z_{Reed} (550 Hz); this peak is in turn determined by the peak in Z_{Bore}.

For the saxophone pitch bend (Figure 8, bottom), the maximum impedance measured in the mouth is now increased almost sixfold to approach that of the maximum of the bore impedance. Similar to the behaviour observed earlier in Figure 7 for clarinet pitch bending, during pitch bending on the saxophone the peak in Z_{Mouth} is no longer negligible in comparison with Z_{Bore} and the peak in (Z_{Mouth} + Z_{Bore}) || Z_{Reed} is likewise no longer determined solely by a peak in Z_{Bore}. In this example, the Z_{Mouth} peak (17 MPa.s.m^{-3}) centred at 472 Hz is now a quarter of the corresponding Z_{Bore} || Z_{Reed} maximum (72 MPa.s.m^{-3}). The sounding frequency (indicated by a sharp peak) during the pitch bend here is 80 Hz (270 cents or about a musical minor third) lower than that produced for normal playing, while the peak in (Z_{Mouth} + Z_{Bore}) || Z_{Reed} now falls at 474 Hz, 78 Hz lower than the peak in Z_{Bore} || Z_{Reed} (552 Hz). This is consistent with behaviour observed earlier for pitch bending in clarinet, and similar to the average maximum downward pitch bend of 330 cents found by Scavone *et al*. (2008) for the alto saxophone.

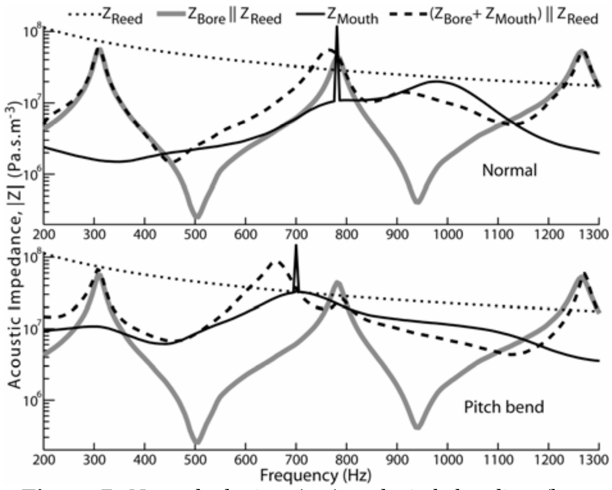


Figure 7. Normal playing (top) and pitch bending (bottom) on the clarinet while holding the fingering for written A5 (sounding G5, 784 Hz). Measured impedance of the clarinet bore, Z_{Bore}, is shown here with the reed compliance in parallel, Z_{Bore} || Z_{Reed} (pale line), along with the impedance measured in the mouth, Z_{Mouth} (dark line) and the impedance of the reed, Z_{Reed} (dotted line). Sharp peaks in Z_{Mouth} indicate the frequency f_1 of the note sounded. At this stage of the pitch bend, the sounding frequency is 76 Hz (190 cents, almost a whole tone) below that produced for normal playing.

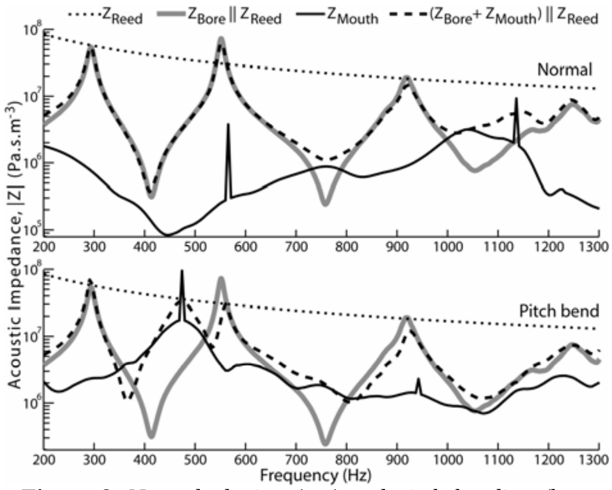


Figure 8. Normal playing (top) and pitch bending (bottom) on the tenor saxophone while holding the fingering for written D#6 (sounding C#5, 554 Hz). Measured impedance of the clarinet bore, Z_{Bore}, is shown here with the reed compliance in parallel, Z_{Bore} || Z_{Reed} (pale line), along with the impedance measured in the mouth, Z_{Mouth} (dark line) and the impedance of the reed, Z_{Reed} (dotted line). Sharp peaks in Z_{Mouth} indicate the frequency f_1 of the note sounded. At this stage of the pitch bend, the sounding frequency is 91 Hz (300 cents, a minor third) below that produced for normal playing.

Figures 7 and 8 show that for both the clarinet and saxophone, if the upstream resonance in the player's vocal tract is deliberately adjusted to produce a sufficiently high impedance peak at the appropriate frequency, this vocal tract resonance can compete with or dominate the bore resonance to determine the reed's sounding frequency, resulting in a playing pitch which deviates from that of the standard fingering.

Vocal tract resonance frequency, its corresponding impedance magnitude and frequency of the note played are extracted from 488 measurements from five expert clarinettists for both normal playing and pitch bending in the range between written G4 and G6 (sounding 349 to 1397 Hz), and plotted in Figure 9. This plot shows the extent of vocal tract tuning in clarinet pitch bending: if the players tuned a resonance of the vocal tract to the note played, then the data would lie close to the tuning line y = x (grey line). If players maintained a constant vocal tract configuration with a weak resonance and the sounding pitch determined solely by (Z_{Bore} || Z_{Reed}), the data would form a horizontal line. The magnitude of the impedance peak is indicated on this graph by the size of the symbol used, binned in half decades.

In Figure 9, the data for pitch bending (black circles) show clear tuning from above about 600 Hz (written E5): the sounding frequency f_1 is always close to that of an impedance peak measured in the player's mouth. Below this frequency, the examples where the peaks in Z_{Mouth} are large (indicated by large circles) also follow the tuning line. In the range below 600 Hz, examples of (intended) pitch bending with relatively small peaks (small black circles) sometimes deviate from the tuning line: in these cases, the player has not succeeded in having the instrument play at the frequency determined by a resonance in the mouth. The legend shows, for comparison, the magnitude of the peaks in Z_{Bore} for fingerings in the first and second register of the clarinet. Comparison with the size of the peaks in the bore and the tract impedance gives one reason why pitch bending is easier in the second register and higher, where peaks in Z_{Bore} are smaller.

In contrast to the results for normal playing, the measurements made during pitch bending show tight tuning of the sounding pitch to the vocal tract resonance, the difference in frequency being typically less than 30 Hz. Here, a strong resonance measured in the mouth (Z_{Mouth} ~20 MPa.s.m^{-3}) is generated by the player and competes with the clarinet bore resonance. This changes (Z_{Mouth} + Z_{Bore}) || Z_{Reed} and, as predicted by Benade's (1985) simple model, the resonance frequency of the player's vocal tract begins to influence the sounding frequency of the reed (normally determined by the bore resonance). This can be observed for sounding notes above 600 Hz, in agreement with Rehfeldt (1977) who suggests the lower limit to large pitch bending on the clarinet lies about written D5 (sounding 587 Hz).

Below about 600 Hz (near written E5), there is less strict tuning of vocal tract resonance. This might be because it is difficult to produce a vocal tract resonance with a sufficiently large impedance peak at frequencies below this range. (Scavone *et al*. (2008) place the lower limit for adjusting the relevant vocal tract influence at about 520 Hz) Further, clarinet bore resonances in this lower playing range are rather stronger (Figure 3). Although the extent of pitch bending using the vocal tract resonance is limited in this range, other strategies are used, including partially uncovering tone-holes and techniques that are not studied here, such as changing the bite force on the reed and adjusting lip damping.

The range of frequencies over which the vocal tract is used for pitch bending in the second register of the clarinet (well within the normal range of the instrument) is comparable with the range for which Scavone *et al*. (2008) report vocal tract effects for the alto saxophone (520 to 1500 Hz). This range is also comparable with that reported for vocal tract tuning on tenor saxophones to play in the altissimo range (Figure 10): expert saxophonists tune their vocal tract resonance, but they do not do so in the normal range. However, the tenor saxophone is a tenor instrument and its altissimo range – above written F#6 (sounding E5, 659 Hz) – corresponds approximately with the upper second and third register on the clarinet and to the range over which we show tract tuning (Figures 9 and 10).

Why is it easier to bend pitch down rather than up?

In the simple model of Benade (1985), the reed is treated as a pure compliance; at bore or tract resonances, however, their impedances are inertive at frequencies just below the Z peak (a positive Z slope) but compliant at frequencies just above the Z peak (a negative Z slope). Here, the sounding frequency occurs near the maximum in the acoustic impedance loading the reed generator $Z_{Load} = (Z_{Tract} + Z_{Bore}) \parallel Z_{Reed}$ when the total reactance (*i.e.* the imaginary part) is zero (Fletcher and Rossing, 1998). Because it is taken as a pure compliance, the reed's reactance is always negative, and moderately large (about -20 MPa.s.m^{-3} at 1 kHz for a clarinet reed). For sustained reed oscillation to occur, the net series reactance of the tract and bore must therefore be positive and equally large.

In normal playing, Z_{Tract} is generally small in comparison with the maxima in Z_{Bore}, so the sounding frequency f_1 must lie on the low frequency (inertive) side of the resonance peak in Z_{Bore}. A softer reed (and hence a larger compliance) decreases its reactance, and consequently lowers f_1.

Now, if a player establishes a significant tract resonance comparable in magnitude to the bore resonance and at the same resonance frequency as the bore, both the reactance of the tract and bore are positive at frequencies below their resonances, so the sum of their reactances increases. Accordingly, the sounding frequency f_1 now falls to where the sum reactances of the tract and bore match the reed's compliance.

If the player then lowers the resonance frequency of the tract, the sum reactance of the tract and bore at around f_1 will increase further, and so the sounding frequency f_1 again falls to match the reed's compliance. (However, lowering f_1 by continuing to reduce the tract resonance frequency becomes increasingly difficult, because the bore reactance diminishes as f_1 moves away from the peak in Z_{Bore}. Eventually, the player will be unable to compensate by increasing Z_{Tract} sufficiently to match the reed compliance at lower frequencies, so further downward pitch bending becomes impossible.)

The situation is quite different, however, if a player wishes to bend the pitch upwards. Again, we imagine a vocal tract resonance that is comparable in magnitude to that in the bore and with initially the same resonance frequency as the bore. If the resonant frequency of the tract is now raised, the sum reactances of the tract and bore in the frequency range where this sum is inertive will decrease, and consequently f_1 rises. However, once f_1 exceeds the resonance frequency of the bore, the reactance of the bore now suddenly becomes compliant (a negative Z slope), so the sum reactances of the tract and bore will fall dramatically, much smaller than the reed compliance. Players are unlikely to be able to increase the magnitude of Z_{Tract} sufficiently in order to raise f_1 past this point. Thus in most situations, the maximum increase in sounding frequency will be of the same order in magnitude as the decrease in resonance frequency of the bore due to the compliance of the reed, possibly not more than 50 cents.

NORMAL PLAYING

In the clarinet and the saxophone, modest vocal tract resonances observed in all players during normal or standard playing for both instruments (Figures 9 and 10, respectively). These resonances are weak when compared with the operating bore resonance, so they contribute little to the series combination and are expected to have only a small effect on the sounding frequency of the reed; here the instrument bore resonance dominates as expected.

In the standard saxophone range played by both expert and amateur players (Figure 10), a wide range of vocal tract resonance frequencies can be observed (bounded with a dashed box), with horizontal bands of data points at about 650 and 1100 Hz showing little adjustment in tract resonance to the note played. Similarly, at frequencies below about 600 Hz on the clarinet (Figure 9), the results are approximately as expected for a tract configuration which did not vary with pitch. Here, the resonances of the bore are strong and unintended pitch bending is less of a danger. In this range, players may keep the tract resonance at a constant frequency (near 600 Hz for these players).

Above about 600 Hz to at least 1400 Hz, however, expert clarinettists demonstrate that tract resonances are now adjusted at frequencies about 150 Hz higher (on average) than the sounding frequency (bounded with a dashed box). (This playing range is comparable to that reported for vocal tract tuning on the tenor saxophone: the tenor saxophone is a tenor instrument and its altissimo range corresponds approximately with the upper second and third register of the clarinet, where we observe tract tuning in the clarinet.) The magnitudes of these vocal tract resonances formed during normal playing are modest (Z_{Mouth} about 9 MPa.s.m^{-3} on average) when compared with those of the operating clarinet impedance peak (~40 to 90 MPa.s.m^{-3}). Similar observations can be seen in Figure 10 for saxophonists playing in the standard range.

Even though the players are not tuning their vocal tract to the note produced, they are adjusting it as a function of the note produced. Why might this be?

First we note that, in normal playing, a strong resonance of the vocal tract is not needed, to first order, to determine the sounding frequency: here the player can usually allow the clarinet bore resonance to determine, at least approximately, the appropriate sounding pitch. Indeed, calculations show that the magnitude and frequencies of these vocal tract impedance peaks change $(Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}) \parallel Z_{\mathrm{Reed}}$ by only several hertz at most. (While even a few hertz difference is important in accurate intonation, a raise in pitch over the whole range can be achieved by adjusting the mouthpiece on the barrel.)

One possibility is that, in this range, expert players learn, presumably implicitly, to keep their vocal tract resonance *away* from the sounding pitch to prevent it form interfering with the bore resonance during normal playing. Also, as it is easier to bend a note down than up (explained earlier), maintaining a tract resonance above that of the bore, but ‘nearby’ (~100 to 200 Hz away) makes for a good performance strategy: fine tuning assistance from the vocal tract can be quickly and easily engaged by adjusting the resonance frequency and strength appropriately, should the need arise. Also, having a resonance slightly below the played note is just too dangerous, because of the potential effects on the playing pitch.

This strategy of keeping the tract resonance at a frequency somewhat above that of the bore resonance during normal playing may explain the results of Clinch *et al*. (1982), who observed a gradual variation of vocal tract shape with increasing pitch over the range of notes studied. These researchers used x-ray fluoroscopy to study the vocal tract during playing and concluded that players were tuning the tract resonance to match the note played. However, as this technique can only give qualitative information about the tract resonance, it is possible that the subject of their study was also keeping the tract resonance frequency somewhat above that of the note played.

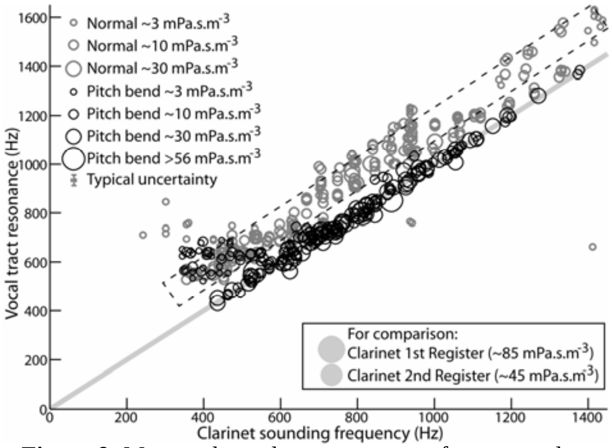


Figure 9. Measured vocal tract resonance frequency plotted against sounding frequency for both normal playing (pale circles) and pitch bending (dark circles) by expert clarinettists, in the range between written G4 and G6 (sounding F4 to F6, 349 to 1397 Hz). The size of each circle represents the magnitude of the acoustic impedance for that measurement, binned in half decade bands. For comparison two circles at bottom right show typical magnitudes of Z_{Bore} for fingerings in the first and second register of the clarinet. The diagonal line shows the relationship: tract resonance frequency = pitch frequency. The dashed box approximates the regime for normal clarinet playing.

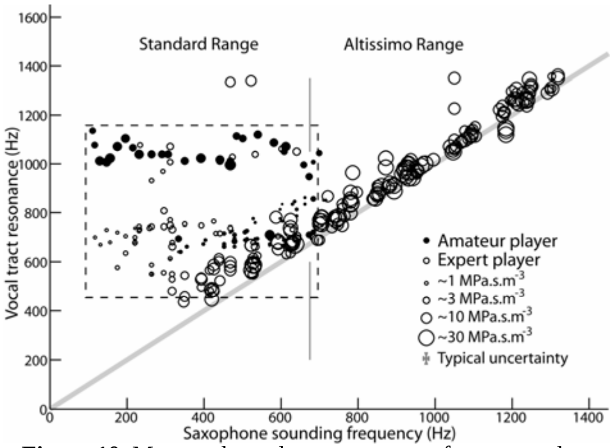


Figure 10. Measured vocal tract resonance frequency plotted against sounding frequency for both playing in the standard range and the altissimo range; dark dots are measured for amateurs while open circles indicate experts. The size of each circle represents the magnitude of the acoustic impedance for the measurement (indicative magnitudes are shown, binned in half decade bands). The vertical line indicates the transition from standard to altissimo range (written F#6 to G6, sounding 659 to 698 Hz). The diagonal line shows the relationship: tract resonance frequency = pitch frequency. The dashed box approximates the regime for saxophone playing in the standard range.

CONCLUSION

During altissimo playing, bugling and some multiphonic performance on the saxophone, a relatively weak bore resonance (with an impedance magnitude typically below 30 MPa.s.m^{-3} and at a frequency higher than the lower, strongest peak) must cooperate to drive the reed generator. To enable playing at these weaker bore resonances, expert saxophonists are observed to create a strong resonance in their vocal tracts with impedance maxima ranging from 10 to 40 MPa.s.m^{-3}, comparable in magnitude with that of the bore, and to adjust its frequency close to the frequency of the desired bore resonance. The vocal tract impedance upstream is seen to be coupled with the bore impedance downstream in series (Benade, 1985). This increases the effective combined impedance loading the reed generator at the desired frequency, and consequently enables the reed to operate at a frequency near that of the weak bore resonance.

Less experienced players were found not to make these vocal tract adjustments, and thus could not execute these advanced techniques. However, expert players are able to execute these adjustments and perform in the altissimo range, to determine the notes produced during bugling, and to selectively produce multiphonic and single tones while maintaining certain multiphonic fingerings, despite the disadvantage of weak operating bore resonances in that frequency range.

To facilitate pitch bending on the saxophone and clarinet, expert players were similarly observed to adjust systematically a strong vocal tract resonance. In this case however, the vocal tract is not merely used to ‘select’ the bore resonance to be sounded – indeed, the operating bore resonance here is sufficiently strong and will drive the reed on its own – but now the vocal tract significantly influences the sounding pitch, and in some cases determines it with relatively little influence from the bore resonance. By carefully adjusting the frequency of a strong vocal tract resonance, players have been shown to ‘pull down’ the sounding pitch by several semitones below the standard pitch expected for that fingering. During pitch bending on the clarinet, players have been shown to generate strong vocal tract resonances with magnitudes of up to 60 $MPa.s.m^{-3}$, comparable with those found in the clarinet bore in this range (40 to 50 $MPa.s.m^{-3}$).

In contrast, during normal playing on the clarinet and saxophone, only bore resonances – which are strong – are required to establish the operating frequency of the reed. Here, impedance peaks of the vocal tract have a much smaller magnitude (ranging typically no more than one to two tenths) than those of the bore. However, expert clarinettists playing the second or clarino register were observed to adjust a vocal tract systematically to typically 150 Hz above that of the relevant bore resonances. The reason for this behaviour is not yet known, but perhaps it is simply a case of keeping the tract resonance above that of the bore, so that it will not produce a small but undesired reduction in the pitch sounded.

ACKNOWLEDGEMENTS

We thank the Australian Research Council for support of this project and Neville Fletcher for many helpful discussions. We thank Yamaha for the saxophones and clarinet, Légère for the synthetic reeds, and our volunteer players.

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