Saxophonists tune vocal tract resonances in advanced performance techniques

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The acoustical impedance spectrum was measured in the mouths of saxophonists while they played. During bugling and while playing in the very high or altissimo range, experienced players tune a strong, but relatively broad, peak in the tract impedance to select which peak in the bore impedance will determine the note. Less experienced players are unable to produce resonances with impedance peaks comparable in magnitude to those of the bore and consequently are unable to play these notes. Experienced players can also tune their tracts to select which combinations of notes are played simultaneously in multiphonics or chords, and to produce pitch bending, a technique in which notes are produced at frequencies far from those of the peak of impedance of the instrument bore. However, in normal playing in the standard range, there is no consistent tuning of the tract resonances. The playing frequency, in all cases, lies close to the peak in the impedance of the reed in parallel with the series combination of the impedances measured in the mouth and the instrument bore on either side of the reed $(Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}) \parallel Z_{\mathrm{Reed}}$.
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I. INTRODUCTION

The saxophone has a single reed, like that of the clarinet, but differs in having a predominantly conical bore with a greater angle than other common woodwinds. Saxophonists report using different vocal tract configurations to play notes in the highest or altissimo range and also for some other advanced techniques discussed below. In a simple model, the acoustical impedance of the bore, downstream from the reed, and that of the vocal tract, upstream from the reed, act in series. The vibration of the reed occurs at a frequency near that of a maximum in this series impedance.

Acoustical opinions on the possible acoustical effects of the vocal tract on performance on clarinets and saxophones have differed over the last few decades: Clinch *et al*. (1982) wrote that "vocal tract resonance must match the frequency of the required notes" while Backus (1985) said that "resonances in the vocal tract are so unpronounced and the impedances so low that their effects appear to be negligible." More recently, the influence of the vocal tract has been confirmed in various advanced playing techniques (Chen *et al*., 2008; Scavone *et al*., 2008). In this study, we measured the impedance spectrum inside the mouths of saxophonists while they performed normal and advanced techniques. These were then combined with the measured impedance spectra of the saxophone bore and the effective compliance of the reed to determine the acoustic load on the reed generator. We compare peaks in the magnitude of this load with the operating frequency.

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A. Acoustic input impedance of the saxophone

While more than half of the bore of the clarinet is approximately cylindrical, most of the bore of the saxophone is conical with a relatively large half angle (1.7° and 1.5° for the soprano and tenor saxophone, respectively, compared with 0.7° and 0.4° for oboe and bassoon, respectively). Partly because of this relatively wide cone, the saxophone is louder than the clarinet (Dalmont and Nederveen, 1997); indeed this was one of the objectives of Sax in inventing the instrument.

The wide-angle conical bore has acoustical consequences that affect the range of the saxophone (Benade and Lutgen, 1988). First, the amplitudes of peaks in the acoustical impedance spectrum of the saxophone decrease more rapidly with frequency than do those of the clarinet, as shown in Fig. 1. A second effect involves the cut-off frequency, f_c, above which waves in the bore propagate past an array of open tone holes. The typical cut-off frequency for the tenor saxophone occurs around 760 ± 250 Hz (Chen *et al*., 2009b), and 1340 ± 240 Hz for the soprano, which is less than three octaves above the frequency of the lowest note (sounding G#2 and G#3 at 104 and 208 Hz, respectively). On the clarinet, it falls around 1500 Hz (Dickens *et al*., 2007a), three octaves and a third above the lowest note (sounding D3 at 147 Hz).

As a result of these two effects, there are no strong peaks in the impedance spectrum of the saxophone bore at frequencies of about three octaves or more above the lowest fundamental frequency of the saxophone, whereas the clarinet bore impedance has strong peaks, more than four octaves above the fundamental of its lowest note. The relative frequency spacing of the impedance peaks is also different between the two instruments: For low notes, the first three resonances of the saxophone have ratios of approximately 1:2:3 while those of the clarinet have approximately 1:3:5.

In both the saxophone and clarinet, the fundamental of notes in the first register corresponds to the first mode of

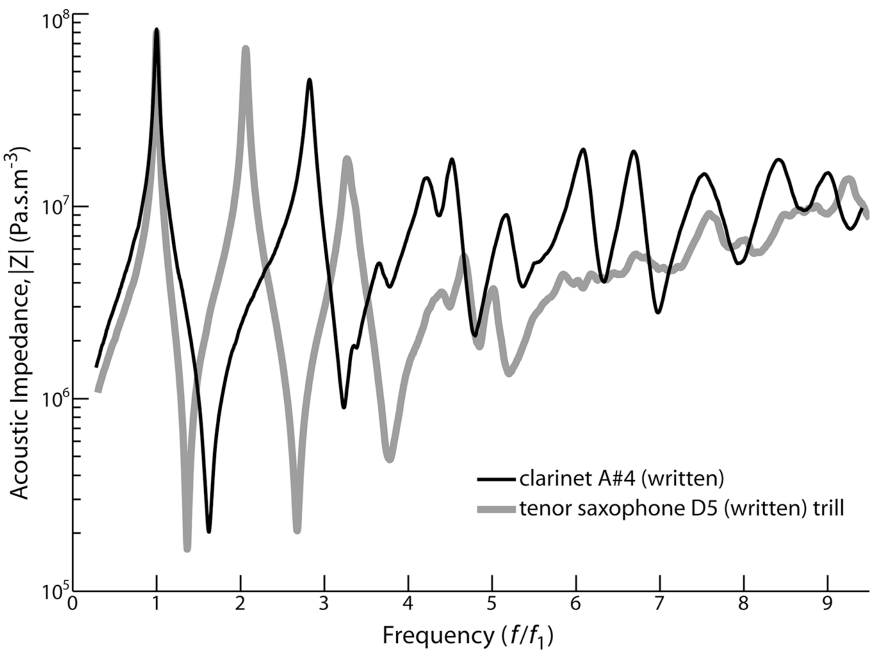

FIG. 1. The magnitude of the acoustic impedance, on log scale, of the clarinet and tenor saxophone (Z_{Bore}), shown for fingerings producing the highest notes of the first register for the clarinet (written A#4, 415 Hz, 16 semitones above the lowest note) and tenor saxophone (written D5, trill fingering, 262 Hz, 14 semitones above the lowest note). To facilitate comparison, the frequencies are scaled to f_1, the sounding frequency in each case.

standing waves in the bore and the first impedance peak, using successive openings of keys along the bore. In the second register, register keys are used to weaken the first impedance peak, and the instruments use the second mode and second impedance peak to play notes in this register. In both instruments, the first two registers cover a range of 2.7 octaves. (The saxophone compensates for its narrower gap between registers by having extra keys to extend the second register up and the first register down.)

These two registers comprise what is usually considered as the standard range of the saxophone, and a great majority of the written repertoire for the instrument respects this limit. The pitch range above the standard range is called the *altissimo* range, but playing in this range usually requires extensive training and is usually impossible for beginners and even some experienced players—see later. In contrast, the third register of the clarinet is relatively easy to play and is included in fingering guides for beginners.

B. Playing (sounding) frequency of the saxophone

In a simple model, stable reed oscillation on the saxophone (at the sounding frequency f_1) occurs very close to the frequency of one of the maxima in the acoustic impedance Z_{Load} that loads the reed generator, which, along with the pressure difference between the bore and mouthpiece, determines the airflow into the instrument (Fletcher, 1993). In this simple model, the pitch depends weakly on the natural frequency of the reed (and hence on the bite force applied by the jaw and the position at which it is applied) and weakly also on the blowing pressure. So, by changing the force exerted on the reed and pushing it against the curved surface on which it is mounted, players can change the effective length, stiffness, and mass of the reed, and thus its characteristic frequency, and its effective compliance, both of which affect pitch. The variation due to bite force and pressure, although musically important, is modest and these parameters were not studied here.

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

In this simple model, Z_{Tract} and Z_{Bore} are in series, and their sum is in parallel with Z_{Reed}. Consequently, under conditions in which the vocal tract impedance is small compared to the bore impedance, Z_{Load} depends only on Z_{Bore} and Z_{Reed}. 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.

The interaction of bore, reed, and airflow is inherently non-linear and the subject of a number of analyses and experimental studies (e.g., Backus, 1963; Wilson and Beavers, 1974; Benade, 1985; Grand *et al.*, 1996; Fletcher and Rossing, 1998; Silva *et al.*, 2008). Although the non-linear effects must be considered to understand the threshold pressure for blowing and features of the waveform and spectrum, the playing frequency can be explained to reasonable precision simply in terms of the linear acoustics of the bore, vocal tract, and reed, using Benade's (1985) model.

Figure 2 compares the magnitudes of the measured acoustic input impedance for operating bore resonances in the clarinet, soprano saxophone, and tenor saxophone across their respective sounding ranges. The first, second, and altissimo registers are demarcated for these instruments. In this and subsequent plots, the measured bore impedance is plotted in parallel with a typical value of the reed compliance. The data are from Chen *et al.* (2009b) for the saxophones and Dickens *et al.* (2007a) for the clarinet.

The acoustic differences mentioned above are apparent here: The magnitudes of the peaks in impedance of the clarinet vary much less with frequency than do those of either saxophone. For the tenor saxophone, not only are the

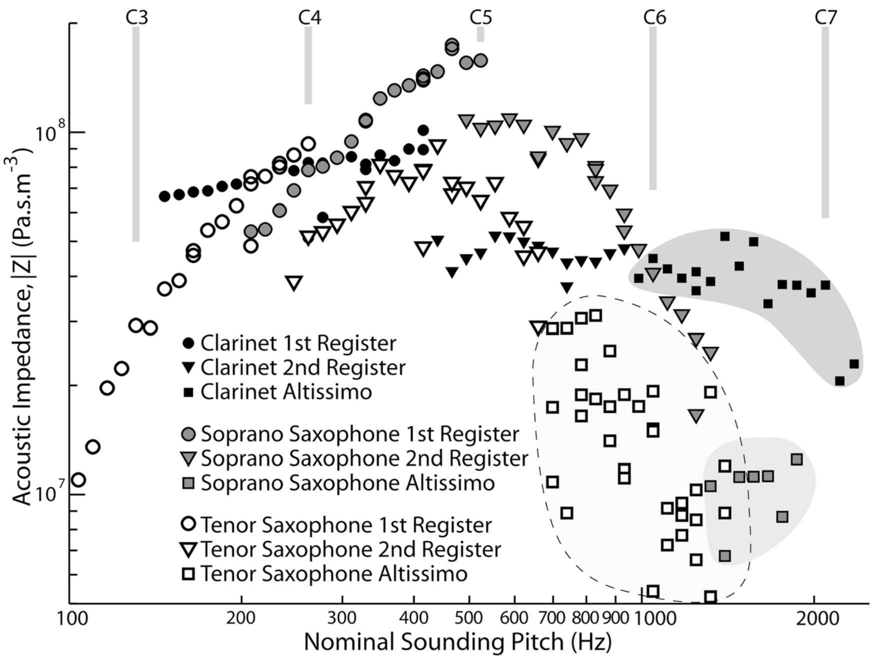

FIG. 2. A log–log graph comparing the magnitudes of the peaks in the acoustic impedance of the parallel combination of bore and reed, the latter treated as a pure compliance. The magnitudes of impedance peaks for the clarinet (dark symbols), soprano saxophone (gray symbols), and tenor saxophone (open symbols) are plotted against the nominal sounding frequency. Circles indicate operating resonances used in the instrument's first register, triangles for the second register, while squares indicate resonances used when playing in the altissimo range (shaded regions). Gray vertical bars indicate the sounding pitch in musical notation.

altissimo resonances weak, but the very lowest notes also have rather small impedance peaks, consistent with the observation by players that these notes are difficult to play softly (i.e., to play with relatively weak higher harmonics).

C. Advanced playing techniques

1. Altissimo

Playing the altissimo register on the saxophone usually requires extensive training; consequently playing in this range is usually impossible for beginners and even some experienced players. Players often report that, for different notes in this range, different configurations of the vocal tract, including different tongue positions and/or different imagined vowels, must be used.

2. Bugling

Bugling is a common teaching exercise for the saxophone (and a less common one for the clarinet). In this exercise, players maintain a constant fingering on the instrument and adjust their breath, lips, tongue, and throat to produce additional notes without using the register key. By holding the fingering for the lowest note on the saxophone—written A#3 (sounding G#2, 104 Hz on the tenor saxophone)—experienced saxophonists may produce a series of tones falling close to the harmonic series, similar to that produced on a trumpet or bugle.

This technique is commonly used on the saxophone as an exercise that prepares the student for playing the altissimo range. Several of the lower notes in the series can be sounded by suitable adjustment of the lips, jaw, and blowing pressure. However, beginners find it hard to sound notes above the standard range, and experts acknowledge the use of the vocal tract.

3. Multiphonic playing

Multiphonic playing is the technique of sounding two or more pitches simultaneously on woodwind instruments by using special fingerings and careful adjustment of playing parameters, including, in some cases, the vocal tract (Bartolozzi, 1967). Depending on how adjustments are made by the player, the same fingering may produce one or more different pitches simultaneously (Rehfeldt, 1977).

Certain woodwind fingerings give rise to two or more impedance maxima (or minima, for the flute) that allow the player to produce standing waves in superposition whose frequencies are not in harmonic ratios. Multiphonics involve reed (or jet) oscillations that depend on two or more inharmonic bore resonance frequencies as well as the resulting intermodulation components. In the linear approximation, somewhat independent oscillations at these bore resonance frequencies arise (Backus, 1978), thereby allowing the reed (or air jet) generator to drive these resonances simultaneously (Fletcher and Rossing, 1998). At sufficiently small amplitude oscillations, quasi-linear superposition might be expected. However, because of the non-linearity of the generator, the resulting sound spectrum for such a fingering contains not only simple harmonics of the operating bore resonances but also heterodyne components arising from the non-linear behavior of the reed (Benade, 1976). Multiphonics involve bore resonances that are sufficiently inharmonic to prevent mode locking via the non-linear generator. Mode locking is more likely to occur at high amplitudes, and so many multiphonic fingerings can only be played softly (Fletcher, 1978).

Some multiphonic fingerings produce two or more notes relatively easily and do not require particular embouchure or vocal tract adjustments on the part of the player. Others, however, are more complicated and perhaps more interesting musically: By making subtle adjustments, experienced players can determine which tones in the multiphonic fingering are sounded and how prominently. These require players to adjust control parameters, including the configuration of the vocal tract.

4. Pitch bending

Pitch bending refers to a continuous variation of pitch and is a technique used widely in jazz and rock, as well as folk music traditions such as *klezmer*. The pitch sounded on the clarinet and saxophone can be altered by playing techniques that involve the player's breath, bite, and, for substantial variation, the vocal tract (Rehfeldt, 1977). 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*., 2009a). This asymmetry arises because, although the impedance of the reed is always compliant, the impedance of the instrument bore is inertive at frequencies below an impedance peak and compliant above it (Chen *et al*., 2009a).

D. The influence of the player's vocal tract

Various pedagogical studies (e.g., Raschèr, 1994; Rehfeldt, 1977; Pay, 1995) support musicians' opinions that the vocal tract influences the note sounded during musical performance, as do empirical studies (Watkins, 2002) and numerical modeling (Johnston *et al*., 1986; Sommerfeldt and Strong, 1988; Scavone, 2003; Guillemain, 2007).

An important experimental advance was that of Wilson (1996), who studied the ratio of the acoustic pressure measured in the player's mouth to that in the instrument near the reed, during playing. This technique uses the reed as the sound source, and so only yields data at harmonics of the fundamental frequency (or, in multiphonic playing, frequencies) present. Thus it cannot indicate the presence, center frequency, magnitude, and width of resonances in the tract. However, when the pressure components in the mouth and bore are comparable at the fundamental playing frequency, this indicates that the acoustic impedances are comparable, too, at that frequency. Wilson investigated playing techniques including pitch bending, playing second register notes without using the register key (cf., bugling), and multiphonic playing. She was thus able to surmise that vocal tract resonances are increased and adjusted in frequency when performing such techniques.

More recently, Fritz and Wolfe (2005) made broadband, acoustic impedance measurements inside the mouth by having the clarinettist mime with the instrument for various musical gestures. They concluded 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 megapascals per second per cubicmeter, comparable with those of the clarinet bore, but no simple relation between the frequencies of the peak and the note played was reported.

Scavone *et al*. (2008) used Wilson's method to investigate pitch bending, bugling, altissimo, and multiphonic playing on the alto saxophone. They too reported that, in these techniques (particularly pitch bending), the pressure component at harmonics of the playing frequency may be greater in the player's mouth than in the bore, supporting Wilson's conclusion that the tract impedance could be comparable with or greater than that of the bore.

At the same time, the present authors made direct measurements of acoustic impedance spectra inside the player's mouth during altissimo performance on the tenor saxophone (Chen *et al*., 2008), using a broadband signal and an impedance head built into the mouthpiece. The same authors also studied pitch bending on the clarinet (Chen *et al*., 2009a). In both instances, expert players were observed both to produce a strong vocal resonance, with a maximum in $|Z_{\text{Mouth}}|$ that was comparable with that in $|Z_{\text{Bore}}|$. Further, they were observed to shift its resonance frequency near the intended pitch and thus to control the frequency at which the reed vibrates.

These recent experimental studies all indicate that the player's vocal tract is involved acoustically in order to execute these advanced performance techniques. The present study uses an impedance head built into the mouthpiece of a tenor saxophone to examine in detail the impedance spectra in the player's mouth, during both normal playing, and for the advanced techniques mentioned above. Some of the altissimo data presented in Fig. 7 have been briefly reported elsewhere (Chen *et al*., 2008).

II. MATERIALS AND METHODS

A. Measurements of bore impedance and effective reed compliance

The acoustic impedance spectra of the saxophone bore (Z_{Bore}) were measured on a Yamaha Custom EX tenor saxophone using the three-microphone-two-calibration (3M2C) method calibrated with two non-resonant loads (Dickens *et al*., 2007b): 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. A database containing many of these data is available (Chen *et al*., 2009b).

Representative values for the effective compliance of the tenor saxophone reed during playing conditions were measured using Benade's technique (1976), in which the reed is considered as a pure compliance terminating a bore. For this study, synthetic saxophone reeds from Légère Reeds Ltd. (Canada) were used, as the physical properties of synthetic reeds remain constant whether wet or dry, and are stable over time. Tenor saxophone reeds of hardness 2½, 3, 3½, and 4 were used in combination with cylindrical metal pipes (internal diameter 14.2 mm and external diameter 15.9 mm) of lengths 99, 202, 299, and 398 mm. The average compliance of all reeds corresponds to an equivalent volume of 3.2 ± 0.5 ml of air. This (pure) compliance is used as the value of Z_{Reed} in this study.

B. Measurements of vocal tract impedance

The acoustic impedance of the player's vocal tract was measured directly during performance using a technique based on the capillary method [reviewed by Benade and Ibisi (1987) and Dickens *et al*. (2007b)] and adapted previously for measurements made during playing of the didjeridu (Tarnopolsky *et al*., 2006), tenor saxophone (Chen *et al*., 2008), and clarinet (Chen *et al*., 2009a). A narrow tube with

FIG. 3. (Color online) Right: Photograph of the tenor saxophone mouthpiece modified to measure the acoustic impedance in the player's mouth during performance. Tube A is attached to the microphone while tube B is attached to the calibrated acoustic current source. Left: The circular inset shows a close-up of the mouthpiece tip, where the circular end of tube A and the rectangular cross section of tube B are visible just above the reed.

approximately rectangular internal cross section area of 2 mm^2 incorporated into a standard tenor saxophone mouthpiece (Yamaha 5C) allows an acoustic current of characteristic source impedance ~200 MPa s m^{-3} to be injected into the player's mouth during performance. The resulting sound pressure in the mouth is measured via an adjacent narrow tube (internal diameter 1.2 mm) embedded similarly in the mouthpiece and connected to a microphone (Brüel & Kjær 4944A) located just outside the mouthpiece (see Fig. 3) to form a probe microphone, thereby measuring the impedance "looking into" in the player's vocal tract from a location in the mouth within a few millimeters of the vibrating reed. This system is calibrated by attaching the modified mouthpiece to a reference load consisting of a quasi-infinite tube of length 197 m and internal diameter 26.2 mm (comparable in cross section with the vocal tract) (Smith *et al.*, 1997). The modifications made to the mouthpiece result in an increase in thickness of about 1.5 mm at the bite point. However, players report only moderate perturbation to their playing because the mouthpiece geometry remains otherwise largely unchanged.

The raw acoustic impedance measured in the player's mouth is then analyzed and smoothed in a manner reported earlier (Chen *et al.*, 2009a) 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 artifact that appears as sharp narrow peaks in the raw impedance spectra at harmonic frequencies of the note sounded. Although this artifact is removed and interpolated for the treated Z_{Mouth} spectra used in calculations in this paper, 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 artifact is deliberately retained for treated Z_{Mouth} spectra shown in this paper (e.g., Fig. 4).

C. Players and protocols

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. While sustaining each note for several seconds, a measurement of the acoustic impedance in their mouth was made. The following advanced performance techniques were studied.

(1) Bugling: The player was asked to sound successively each possible overtone while maintaining the fingering for the lowest note, written A#3 (sounding G#2, 104 Hz).

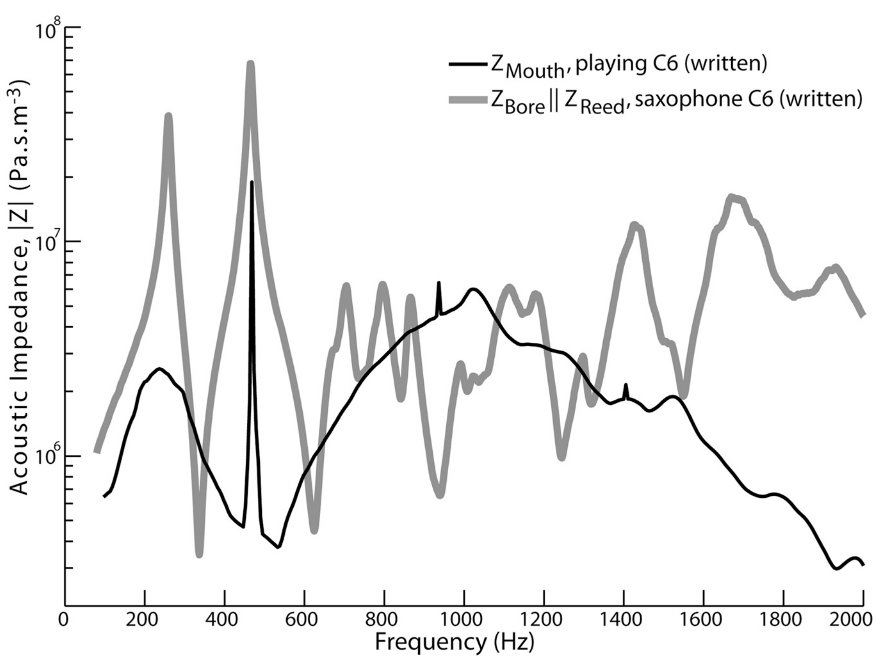

FIG. 4. Impedance measured in a saxophonist's mouth, Z_{Mouth} (dark line), while playing the written note C6 (sounding A#4, 466 Hz) and the input impedance of the tenor saxophone, Z_{Bore}, shown with the reed in parallel, Z_{Bore} $\|$ Z_{Reed} (pale line) for that fingering. Sharp peaks in Z_{Mouth} at 468, 937, and 1405 Hz indicate harmonics of the sounded note emitted into the player's mouth.

(2) Altissimo register: Players performed the C Major scale (written) starting from C4 (sounding A#2, 117 Hz) and ascended diatonically through the standard range (ending at written F#6—sounding E5, 659 Hz), using standard fingerings. They then continued the scale as far as possible through the altissimo range from written G6 (sounding F5, 698 Hz) to G7 (sounding F6, 1397 Hz) using altissimo fingerings of their preference.
(3) Multiphonics: Two fingerings (DK 5/6 and DK 104/105) from a multiphonic instruction book (Kientzy, 1982) were chosen. Each fingering is known to generate two different sets of multiphonics (hence the slashed fingering numbering system), and players were asked to produce them selectively.
(4) Pitch bending: Players were asked to finger written D#6 (sounding C#5, 554 Hz), a standard note on the tenor saxophone, and to bend its sounding pitch down from the standard pitch, then to hold it steady while the impedance in their mouth was measured.

III. RESULTS AND DISCUSSION

A. Vocal tract resonances measured in the mouth

Figure 4 shows the bore impedance of the tenor saxophone combined with the reed compliance in parallel ($Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$) for the fingering that plays the note written C6 (sounding A#4, $f_1 = 466$ Hz). Figure 4 also shows the impedance measured in the mouth (Z_{Mouth}) of a saxophonist playing that note. The narrow peaks in Z_{Mouth} are the useful artifact mentioned above: They show the harmonics of the note sounded during measurement, which are 468, 937, and 1405 Hz in this example. Impedance peaks in Z_{Mouth} occur at 240 and 1020 Hz with relatively modest amplitudes, 2.5 MPa s m^{-3} and 6.0 MPa s m^{-3}, respectively. In this example, there is no apparent relation between the peaks in Z_{Mouth} and the note played.

The example shown in Fig. 4 is for a note played softly. The sound level produced in the mouth by the vibrating reed is high and is concentrated on the harmonics of the note played, while the power of the injected acoustic current is spread over all of the frequencies measured. There are also high levels of low frequency noise in the mouth during playing. Thus measurements with high signal–noise ratio and over a wide frequency range can only be made when the saxophonist plays softly. Many of the subsequent measurements reported here were made at louder playing levels. Consequently, the lower limit of the measured frequency range for these measurements was increased from 100 to 200 Hz. In all measurements made spanning the range 100–2000 Hz, a modest peak in Z_{Mouth} (of not more than several MPa s m^{-3}) was consistently observed around 150–250 Hz. In measurements made from 200 to 2000 Hz, such a peak was either observed or was suggested by a shoulder just above 200 Hz. Henceforth, this peak is called the first resonance and the next peak in impedance, which typically occurs around 1 kHz, is called the second resonance and is of primary interest in this study.

While making the measurements of soft playing, the vocal tract resonances were also measured during what saxophonists describe as subtone playing: A technique that produces a tone that is both low in sound level and dark in timbre. No significant tuning of the vocal tract resonances was observed.

B. Bugling

Figure 5 shows the bore impedance of the tenor saxophone combined with the reed compliance in parallel ($Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$) for the fingering that plays the lowest note: Written A#3 (sounding G#2, $f_1 = 104$ Hz). Successive peaks lie approximately at integral multiples nf_1. The first two peaks are weaker than the third and fourth. The lowest note (f_1) is difficult to play softly.

All three amateur saxophonists studied could bugle notes at the first four or five peaks. We conclude that they could not proceed further because of the weak bore impedance peaks above about 500 Hz, with magnitudes less than 10 MPa s m^{-3}.

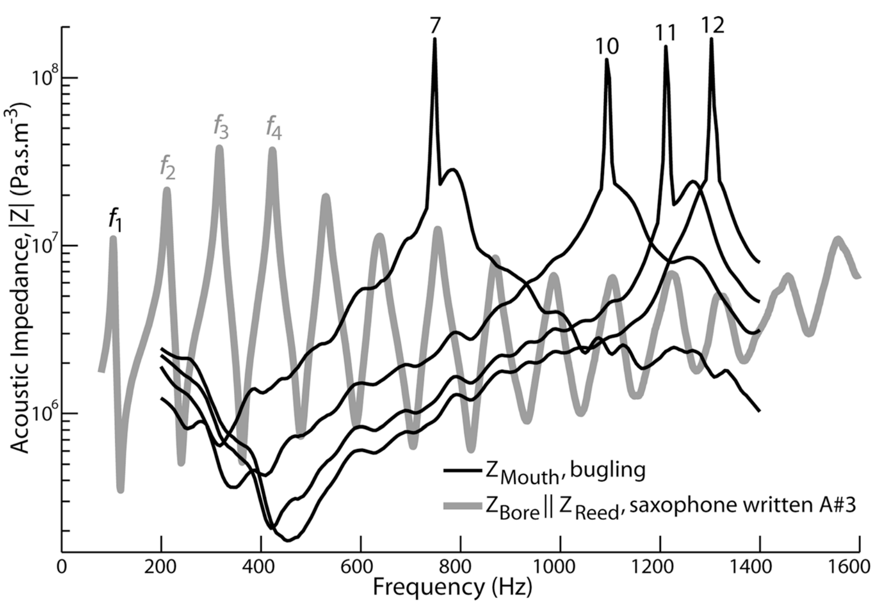

FIG. 5. Impedance measured in an expert saxophonist's mouth, Z_{Mouth} (dark lines), while bugling the 7th, 10th, 11th, and 12th impedance peaks on the tenor saxophone for the fingered note written A#3 (104 Hz). The input impedance of the tenor saxophone, Z_{Bore}, shown with the reed in parallel, $Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$ (pale line), for that fingering. Sharp peaks in Z_{Mouth} at 748, 1093, 1211, and 1303 Hz indicate the frequency of the sounded note, labeled as a multiple of the fundamental frequency f_1 (104 Hz).

In contrast, all five professional players were able to bugle successively at peaks up to the 12th overtone, reportedly by changing their vocal tract configuration. Although changes in bite (and hence the effective stiffness and compliance of the reed) are possibly also involved, the expert players in this study report being unable to bugle without adjusting the tract configuration.

Figure 5 also shows the impedance measured in the mouth (Z_{Mouth}) of an expert player bugling notes at the 7th, 10th, 11th, and 12th peaks. (To preserve clarity, the spectra for other notes are not shown.) For each measurement, the broad peaks with magnitudes about 22–28 MPa s m^{-3} are resonances which lie close to the 7th, 10th, 11th, and 12th peak in Z_{Bore} when sounding each of the notes whose fundamental appears as a sharp peak superimposed on Z_{Mouth}.

Thus players systematically adjust a strong vocal tract resonance to select which impedance peak will drive the reed. This behavior explains the observations of Scavone *et al.* (2008), who reported sound pressure levels higher in the player's mouth than in the instrument when bugling on the alto saxophone above the third overtone: The presence of a strong vocal tract resonance adjusted close to the note played will generate stronger sound pressure signals in the player's mouth at the frequency of the note than would be measured without a resonance, especially when Z_{Bore} is small.

C. The altissimo range

Figure 6 plots the magnitude and phase of the acoustic impedance spectra measured in the player's mouth (Z_{Mouth}) and in the saxophone bore (Z_{Bore}) for two notes, one in the standard and one in the altissimo range, played by the same expert player. The series combination $Z_{\mathrm{Bore}} + Z_{\mathrm{Mouth}}$ is also shown.

For the note in the standard range (written D6), Z_{Mouth} shows a broad impedance peak with magnitude 9.2 MPa s m^{-3} near 1350 Hz. This has no relation to the harmonics of the note sounded, seen at 522 and 1044 Hz. The magnitude of this peak in Z_{Mouth} is more than seven times smaller than the peak in Z_{Bore} at 549 Hz (67 MPa s m^{-3}). For much of the standard range of the saxophone, peaks in Z_{Bore} are much greater than that found in Z_{Mouth}, and therefore peaks in Z_{Bore} dominate the series combination ($Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}$) at low frequencies, as indicated by the top graph in Fig. 6.

For the note in the altissimo range (written C7, sounding A#5), the middle graph of Fig. 6 shows a strong peak in Z_{Mouth} at 980 Hz with magnitude 33 MPa s m^{-3}, more than three times the magnitude of the peak in Z_{Bore} (9.8 MPa s m^{-3} at 949 Hz). The sharp spike at 921 Hz is the note sounded, 60 Hz below the maximum of the broad peak in Z_{Mouth}. The high frequency peaks in Z_{Bore} are weak (Fig. 6, graphs are representative) and therefore unable to support stable reed oscillations on their own. However, when the player adjusts a strong peak in Z_{Mouth} at these frequencies, the resonance in Z_{Mouth} dominates the series combination ($Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}$). Consequently, the sounding frequency falls near the maximum in ($Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}$), as indicated in the middle graph of Fig. 6. Thus, in the altissimo range, a weak resonance in Z_{Bore} is selected when the player tunes a relatively broad tract resonance in Z_{Mouth} to a frequency near that of the desired resonance.

Figure 6 also shows, for playing in both standard and altissimo ranges, another vocal tract impedance peak at lower frequencies (253 Hz and 242 Hz respectively) with smaller magnitudes (3.3 MPa s m^{-3} and 2.9 MPa s m^{-3}, respectively). This impedance peak, described earlier, is not tuned in the playing conditions investigated here.

D. Strategies in altissimo playing

1. Tuning of vocal tract resonances

Figure 7 plots the frequency of the second vocal tract impedance peak against that of the note played, using 650 measurements made on both amateur and expert saxophonists

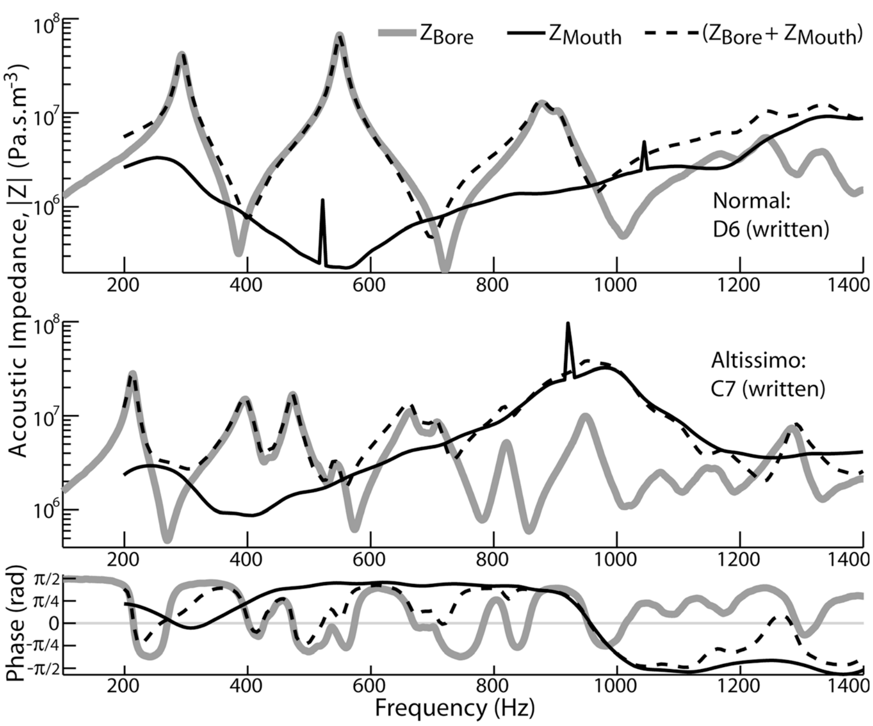

FIG. 6. Representative acoustic impedances Z_{Mouth} (dark line) measured in the vocal tract of an expert saxophonist playing (top) the written note D6 (523 Hz, sounding C5) in the standard range and (middle) the written note C7 (932 Hz, sounding A#5) in the altissimo range of the tenor saxophone (the bottom graph shows its phase). Narrow peaks in Z_{Mouth} (dark line) indicate harmonics of the note sounded, while broad peaks indicate resonances in the mouth. The bore impedances Z_{Bore} for the two fingerings used are shown with a broad, pale line, while the combined acoustic impedance of the player and instrument bore ($Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}$) is shown using a dashed line. The phase is shown only for the altissimo note.

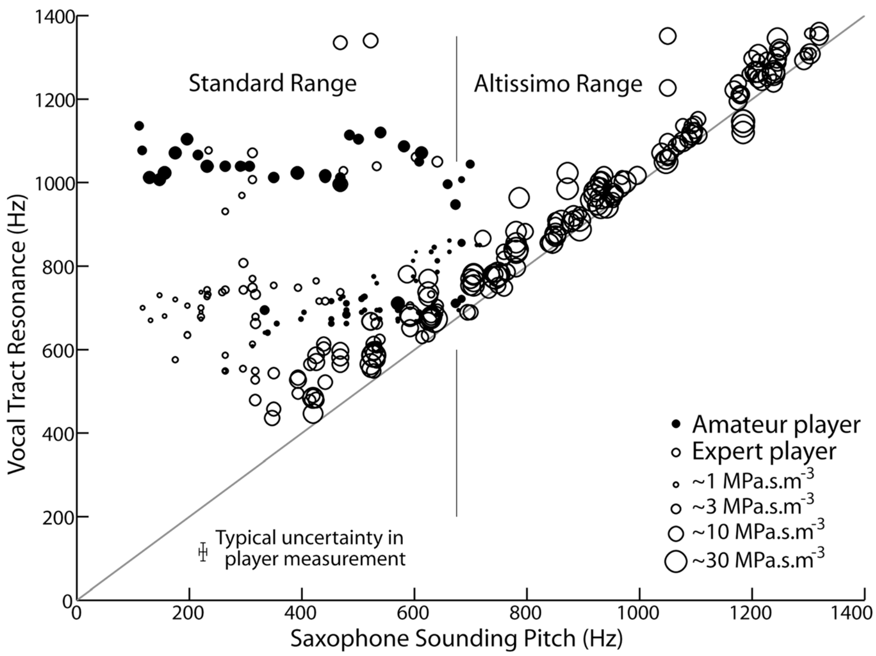

FIG. 7. Frequencies of the second vocal tract resonance plotted against the frequency of the note sounded, for 650 measurements from eight saxophonists (five expert, three amateurs); dark dots are measured for amateurs while open circles indicate experts. The size of each circle represents the magnitude of the acoustic impedance for the measurement (indicative magnitudes are shown in the legend, binned in half decade bands). The vertical line indicates the transition from standard to altissimo range (written F#6 to G6, sounding 659–698 Hz). The diagonal line shows the relationship: Tract resonance frequency = pitch frequency.

playing the standard range and the first octave of the altissimo range (where possible).

Over the standard playing range, Fig. 7 shows a wide variation in vocal tract resonance frequencies, from about 500 to 1100 Hz, for both expert and amateur players; no simple relationship to the note sounded is observed, as discussed earlier and typified by the top graph of Fig. 6. While experts displayed broadly distributed vocal tract resonances, particularly over the lower standard range, tract resonances of amateur players remain fairly static: Tract resonance data lie within two horizontal bands at about 650 and 1100 Hz over most of the standard range. Despite these differences, both experts and amateurs had no difficulty playing across the standard range.

Over the altissimo range, however, the amateur players in this sample—none of whom were observed to adjust their vocal tract resonance—were no longer able to sound the notes desired, whether on the experimental instrument or on a normal saxophone, despite using the 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, expert players faced no such trouble (sound files are given by Music Acoustics, 2010). As with the example in Fig. 6 (middle graph), Fig. 7 shows that, in the altissimo range, experienced players tune a strong vocal tract resonance near to the note played, typically not more than 100 Hz apart. Toward the upper standard range, expert players already also exhibit some systematic adjustment of the tract resonance.

The tract resonance frequencies measured for both experts or amateurs tend to fall on or above that of the note sounded, rather than below—very few points in Fig. 7 lie below the tuning line. Similar behavior has been reported previously for the clarinet (Chen *et al.*, 2009a), with suggestions given for its utility.

2. Operating saxophone resonances

Figure 8 uses the same measurements as Fig. 7 to plot the magnitude of the vocal tract impedance peaks against the sounding pitch performed for that particular vocal tract configuration used (indicated by circles). The magnitudes of the bore impedance peaks in the first, second, and altissimo registers are also plotted. As before, the reed impedance is added in parallel for all standard and some non-standard fingerings over the complete standard range (beginning with written A#3) and the first octave of the altissimo range (written G6 to G7).

The peak at lowest frequency, at written A#3 (104 Hz), has a magnitude of 11 MPa s m^{-3}. Over the first register, the magnitudes climb to 93 MPa s m^{-3} at written D5 (262 Hz). In the second register, Z_{Bore} peaks vary from about 50 to 80 MPa s m^{-3}, decreasing in magnitude from above written C6 (sounding 466 Hz) toward the upper limit of the standard range at written F#6 (sounding 659 Hz). One of two register keys weakens and detunes the first peak in Z_{Bore}, to play in this register, allowing the saxophone to operate at the second peak in Z_{Bore}. (The overlap between registers involves alternative fingerings.)

In the altissimo range starting from written G6 (sounding F5, 698 Hz), Z_{Bore} peaks are considerably weaker than those in the standard range and decrease with increasing sounding frequency because visco-thermal losses near the walls and radiation at the bell increase with frequency and also because of complications introduced by cross fingering (Wolfe and Smith, 2003). These notes operate at the third or higher Z_{Bore} maximum, 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). Weak Z_{Bore} peaks in this range explain why these resonances do not easily support notes without "help" from the tract.

3. Impedance magnitude of vocal tract resonances

When amateurs play the standard range, no simple relationship is observed for the magnitudes of tract impedances, which vary from about 0.4 to 6 MPa s m^{-3}. In contrast, for experts, as the pitch increases over this standard range, the

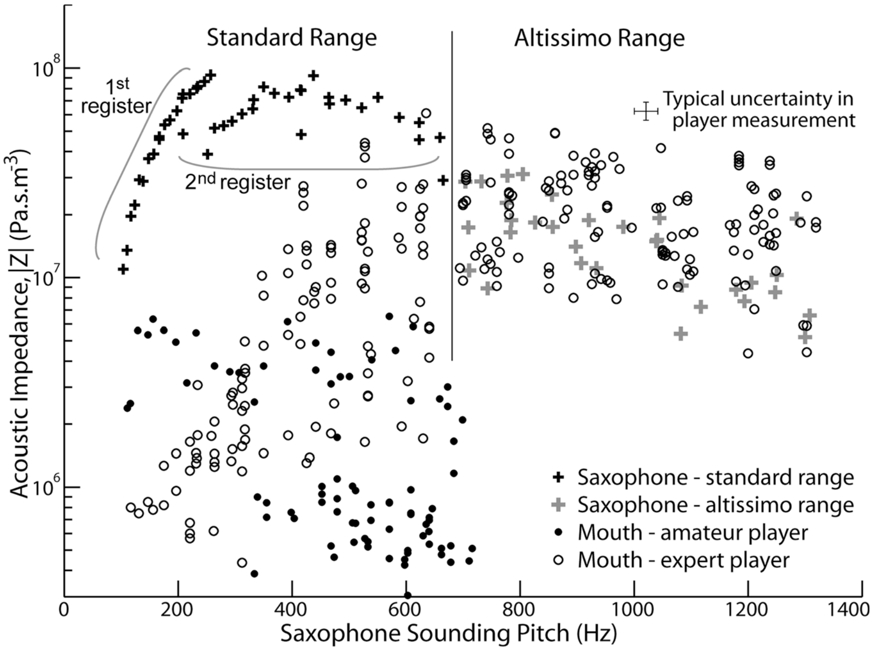

FIG. 8. Magnitudes of the peaks in acoustic impedance of the tenor saxophone resonance (plotted with reed compliance added in parallel) vs frequency. Dark crosses indicate resonances used in the standard playing range (written A#3 to F#6; 104–659 Hz) with brackets indicating first and second registers. Pale crosses indicate peaks used in the altissimo range (written G6 and above—a vertical line indicates the transition). The magnitudes of impedance peaks measured in the mouth are plotted against sounding pitch; dark dots indicate amateurs and open circles indicate experts.

magnitude tends to rise from about 1 MPa s m^{-3} to about 10 MPa s m^{-3} where, near the top of the second register, they approach the magnitudes of the peaks in the bore impedance. Above 600 Hz, a clear difference in the magnitudes can be observed between expert and amateur players. However, this difference does not have a very obvious effect on ability to play the standard range.

So, across the standard range, saxophone bore resonances are strong, and tract resonances generally are not strong and the former dominate the series impedance. In the altissimo range, however, impedances of tract resonance measured are typically an order of magnitude *greater* than those used across the standard range: Tract resonances select or dominate bore resonances. This agrees with the measurements of Scavone *et al.* (2008), who found the ratio of the acoustic pressure in the mouth to that in the mouthpiece, measured at the playing frequency, increased abruptly when players entered the altissimo range.

The tract tuning need not always be exact however, because the bore resonances are narrow while those of the tract are broad (*e.g.* Fig. 6). Thus the tract peak can often determine which peak in the series impedance ($Z_{Mouth} + Z_{Bore}$) and thus which peak in $Z_{Load} = (Z_{Mouth} + Z_{Bore}) \parallel Z_{Reed}$ is greatest. Nevertheless, because the peak in Z_{Bore} is narrow, the frequency of the operating peak in Z_{Load} still falls close to that of $Z_{Bore} \parallel Z_{Reed}$: In this situation, the tract "selects" which bore resonance operates but the exact sounding frequency is largely determined by the bore and the reed.

A strong vocal tract resonance is consistent with a narrow glottis: Expert wind players are reported to play with their glottis almost closed (Mukai, 1992), and an almost closed glottis vocal tract produces resonances with high impedance maxima (Fritz and Wolfe, 2005).

E. Multiphonics

Figures 9 and 10 show the measured vocal tract and saxophone bore impedance for two multiphonic fingerings, listed by Kientzy (1982) as DK 5/6 and 104/105, respectively, when played by an expert using two different vocal tract configurations.

The fingering for DK 5/6 produces an impedance spectrum for the saxophone bore with three pairs of maxima at close and non-harmonically related frequencies; they occur at about 187 and 214 Hz, 380 and 428 Hz, and 581 and 641 Hz—see Fig. 9. Although the peak at 380 Hz is the strongest, no multiphonic operates at that bore resonance for either tract configuration.

For tract configuration 1 (Fig. 9, top graph), bore resonances at 187 (sounding F#3 +19 cents) and 214 Hz (sounding A3 −48 cents), denoted by f and g, respectively, both drive reed oscillation. The resulting frequencies in the sound (visible as narrow peaks superposed over Z_{Mouth}) include not only the harmonics of frequencies f and g (183 and 205 Hz) but also the sum-and-difference components. This tract configuration thus yields additional frequency components, including 366, 388, 414, and 576 Hz. Within the measurement accuracy of ±5 Hz, these equal, respectively, $2f$, $f + g$, $2g$, and $2f + g$. In this tract configuration, the low frequency peak in Z_{Mouth} around 200 Hz has the largest value in Z_{Mouth} at 8 MPa s m^{-3}. This peak in Z_{Mouth} is usually present and has been discussed previously in Sec. III A.

In contrast, Z_{Mouth} for vocal tract configuration 2 (Fig. 9, bottom graph) includes an additional broad, strong tract resonance at 727 Hz with an impedance of 30 MPa s m^{-3}. Consequently, the reed now operates at the bore resonance at 641 Hz (fundamental frequency h, sounding E5 −49 cents) rather than the resonances f and g, and the frequency components sounded are simple multiples of this resonance: 646 Hz (h), 1292 Hz ($2h$), and 1938 Hz ($3h$). These examples are interesting in that they show how the performer can avoid sounding a note at the frequency of the largest peak in Z_{Bore}, which for this fingering lies at 380 Hz, and instead select maxima at lower or higher frequencies by using appropriate tract configurations.

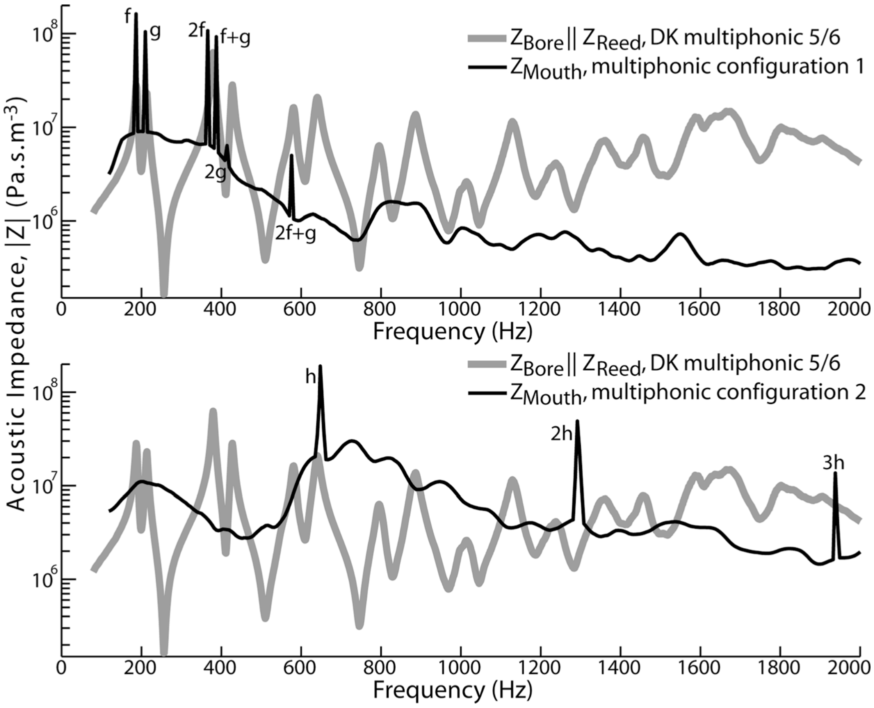

FIG. 9. Changes in vocal tract impedance control the presence of a multiphonic. Impedances measured in the player's mouth, Z_{Mouth}, for two vocal tract configurations (dark lines) are shown while playing Kientzy's multiphonic fingering DK 5/6. The impedance of the tenor saxophone bore for that fingering, Z_{Bore}, is shown with the reed compliance in parallel, $Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$ (pale line). Two prominent peaks of comparable magnitude are seen at 187 and 214 Hz (frequency components f and g); peak h is at 641 Hz. Sharp peaks in Z_{Mouth} are indicative of frequency components of the sounded note. In configuration 1 (top graph) components are present at 183 (f), 205 (g), 366 ($2f$), 388 ($f+g$), 414 ($2g$), and 576 ($2f+g$) Hz, while in configuration 2 (bottom graph) components are present at 646 (h), 1292 ($2h$), and 1938 ($3h$) Hz.

Figure 10 shows that the fingering for DK 105/106 produces a pair of maxima in the bore impedance at 238 and 291 Hz (frequencies f and g, sounding A#3 +36 cents and D4 −16 cents, respectively). Another peak of comparable strength is present at 520 Hz (frequency h, sounding C5 −11 cents). For the tract configuration 1 used with this fingering (top graph), a modest vocal tract resonance is observed at 1400 Hz (well above the strong resonances of the bore) with impedance maximum 4 MPa s m^{-3}: The vocal tract impedance here makes only a small contribution to the series impedance dominated by the bore resonances f and g. The sound produced with this tract configuration has frequency components including 237 (f), 291 (g), 528 ($f+g$), and 581 ($2g$) Hz.

However, for tract configuration 2 (Fig. 10, bottom graph), a strong and broad tract resonance is observed at 689 Hz with impedance maximum 15 MPa s m^{-3}. Here, a strong, broad vocal tract resonance is now only 170 Hz from the strong bore resonance (39 MPa s m^{-3}) at frequency h, so consequently the series impedance is large: The reed can now vibrate at this frequency, while also vibrating at frequencies f and g. The sound produced with this tract

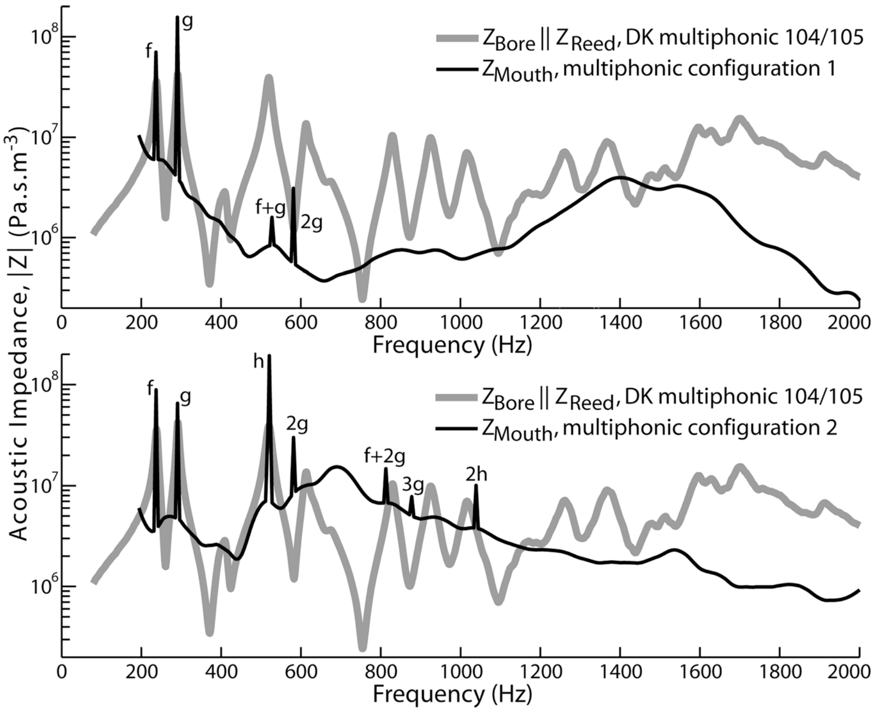

FIG. 10. Changes in vocal tract impedance control the combination of multiphonics sounded. Impedance measured in the player's mouth, Z_{Mouth}, for two vocal tract configurations (dark line) for playing Kientzy multiphonic fingering DK 104/105. The impedance of the tenor saxophone for that fingering, Z_{Bore}, is shown with the reed compliance in parallel, $Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$ (pale line); three prominent peaks of comparable magnitude are seen at 238, 291, and 520 Hz (frequency components f, g, and h). Sharp peaks in Z_{Mouth} are indicative of frequency components of the sounded note. In configuration 1 (top graph) components are observed at 237 (f), 291 (g), 528 ($f+g$), and 581 ($2g$) Hz, while in configuration 2 (bottom graph) components are observed at 237 (f), 291 (g), 520 (h), 581 ($2g$), 824 ($f+2g$), 878 ($3g$), and 1039 ($2h$) Hz.

configuration has frequency components due to combinations of all three superposed standing waves supported by three of the bore resonances f, g, and h: 237 (f), 291 (g), 520 (h), 581 ($2g$), 824 ($f+2g$), 878 ($3g$), and 1039 ($2h$) Hz.

The examples in Figs. 9 and 10 again show that, although a weak resonance peak in the bore impedance might not usually support reed oscillations on its own, experienced players are able to adjust a strong vocal tract resonance sufficiently near to such a peak in order to select that particular bore resonance in the series combination, thus allowing the saxophone to operate either solely at that frequency (Fig. 9, tract configuration 2) or in combination with other frequencies (Fig. 10, tract configuration 2). This selection presumably requires the deliberate, but subtle, control of the vocal tract of an expert, finely balancing the magnitude and frequency of their tract resonance, as well as other embouchure variables, to select the desired combination, often using auditory feedback.

F. Pitch bending

Figure 11 shows a typical measurement of the acoustic impedance in the mouth of a player performing a pitch bend. It also shows the measured impedance of the tenor saxophone bore for the fingering used (that of the note written D#6, sounding C#5, 554 Hz). For comparison, a tract measurement for normal playing using the same fingering is also shown. In each case, the series impedance $Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}$ is also plotted, and then the effective reed impedance is added in parallel to estimate the effective acoustic impedance of the tract-reed-bore system according to the Benade (1985) model.

In normal playing (Fig. 11, top graph), the magnitude of the peak in Z_{Mouth} (3 MPa s m^{-3} in this example) is much smaller than that of the operating peak of Z_{Bore} (62 MPa s m^{-3} here), smaller than the effective impedance of the reed ($\sim$32 MPa s m^{-3} at these frequencies), and also smaller than those of the peak in $Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$ (73 MPa s m^{-3} here). The frequency of the peak in Z_{Mouth} is 1039 Hz and has no obvious relation to that of the note sounded. Consequently, the combined acoustic impedance for normal playing according to the simple Benade (1985) model yields a resulting maximum determined very largely by the maximum in Z_{Bore} (as we saw earlier in Sec. III D 3). Here, the reed vibrates at a frequency (565 Hz) not far from that of the strongest peak in $Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$ (552 Hz), that frequency in turn depending weakly on the value of Z_{Reed} used.

In the pitch bending exercise, however, the magnitude of the maximum measured in Z_{Mouth} is increased almost sixfold and is no longer negligible in comparison with those of the maximum in Z_{Bore} and the effective impedance of the reed. The bottom graph in Fig. 11 shows that, during pitch bending, the peak in the calculated $(Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}) \parallel Z_{\mathrm{Reed}}$ is now 78 Hz lower than that in $Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$. The sounding frequency during the pitch bend is lower by 91 Hz (300 cents or a musical minor third) than that produced during normal playing with that fingering. In the pitch bending examples studied, sounding frequency f_1 did not coincide with the peak in $Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$ but instead occurred closer to the peak in $(Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}) \parallel Z_{\mathrm{Reed}}$. This behavior is consistent with that observed for pitch bending on the clarinet.

In Fig. 11, the peak in $(Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}) \parallel Z_{\mathrm{Reed}}$ that determines the playing frequency during pitch bending has the same height as a peak in $(Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}) \parallel Z_{\mathrm{Reed}}$ lying close to the peak in $Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$, the peak that would normally determine the pitch of a note whose pitch was not "bent." This was the maximum pitch bend that this player could achieve on this saxophone and reed. In the context of the clarinet, Chen *et al*. (2009a) give an explanation of how the phases of the impedances involved limits the extent of pitch bending possible and also explain why it is much easier to bend notes down than up in pitch.

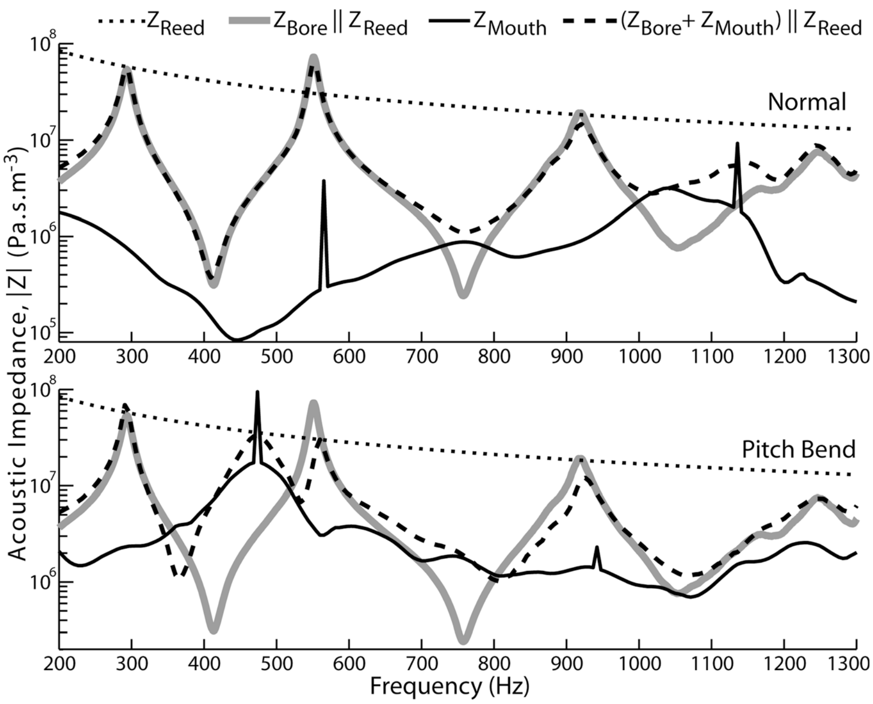

FIG. 11. The influence of vocal tract impedance on pitch bending. The measured input impedance of the tenor saxophone, Z_{Bore}, shown here with the reed compliance in parallel, $Z_{\mathrm{Bore}} \parallel Z_{\mathrm{Reed}}$ (pale line), and the impedance measured in the mouth, Z_{Mouth} (dark line). The impedance of the reed, Z_{Reed} (dotted line), was calculated from the reed compliance measured in another experiment. $Z_{\mathrm{Load}} = (Z_{\mathrm{Mouth}} + Z_{\mathrm{Bore}}) \parallel Z_{\mathrm{Reed}}$ is plotted as a dashed line. In both cases the fingering is for the note written D#6 (sounding C#5, 554 Hz). Sharp peaks in Z_{Mouth} indicate the frequency f_1 of the note sounded. The top graph shows the impedance magnitudes for the note played normally, while the bottom graph shows those played during pitch bending using the same fingering. At this stage of the pitch bend, the sounding frequency is 91 Hz (300 cents, a minor third) below that produced for normal playing.

IV. CONCLUSION

During bugling and altissimo playing on the saxophone, a relatively weak bore resonance (with acoustic impedance typically below 30 MPa s m^{-3} and at a frequency higher than that of lower, stronger impedance peaks) will not, without help from the vocal tract, determine the frequency of the reed generator. To play using these weaker bore resonances, experienced saxophonists create a strong resonance in their vocal tract with impedance maxima ranging from 10 to 40 MPa s m^{-3}, comparable in magnitude with that of the bore, and adjust its frequency close to the frequency of the desired bore resonance. The frequency of the note produced lies very close to the peak in $(Z_{\text{Mouth}} + Z_{\text{Bore}}) \parallel Z_{\text{Reed}}$. Less experienced players cannot make these vocal tract adjustments, and thus cannot execute these advanced techniques.

Experienced players also use tract resonances to select the relative contributions of the multiple possible notes that can sound together in certain multiphonic fingerings.

In pitch bending on the saxophone, as on the clarinet, the influence of the vocal tract is sufficiently strong that, even in the standard playing range, the peak in $(Z_{\text{Mouth}} + Z_{\text{Bore}}) \parallel Z_{\text{Reed}}$ may be substantially displaced from that of the bore resonance. Consequently, players can decrease the sounding pitch several semitones below the standard pitch for that fingering.

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