Pitch bending and *glissandi* on the clarinet: Roles of the vocal tract and partial tone hole closure

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(Received 9 March 2009; revised 15 June 2009; accepted 17 June 2009)

Clarinettists combine non-standard fingerings with particular vocal tract configurations to achieve pitch bending, i.e., sounding pitches that can deviate substantially from those of standard fingerings. Impedance spectra were measured in the mouth of expert clarinettists while they played normally and during pitch bending, using a measurement head incorporated within a functioning clarinet mouthpiece. These were compared with the input impedance spectra of the clarinet for the fingerings used. Partially uncovering a tone hole by sliding a finger raises the frequency of clarinet impedance peaks, thereby allowing smooth increases in sounding pitch over some of the range. To bend notes in the second register and higher, however, clarinettists produce vocal tract resonances whose impedance maxima have magnitudes comparable with those of the bore resonance, which then may influence or determine the sounding frequency. It is much easier to bend notes down than up because of the phase relations of the bore and tract resonances, and the compliance of the reed. Expert clarinettists performed the *glissando* opening of Gershwin's *Rhapsody in Blue*. Here, players coordinate the two effects: They slide their fingers gradually over open tone holes, while simultaneously adjusting a strong vocal tract resonance to the desired pitch.
 [DOI: 10.1121/1.3177269]

PACS number(s): 43.75.Pq, 43.75.St [NHF] Pages: 1511–1520

I. BACKGROUND

A. Pitch bending and *glissandi*

Pitch bending refers to adjusting the musical pitch of a note. Usually it means a smooth variation in pitch and can include *portamento* and *glissando*, which refer to continuous variation of pitch from one note to the next. The pitch of some instruments can be varied continuously over a wide range by adjusting the position of the hands and fingers, e.g., the slide trombone or members of the violin family. The pitch of some fretted string instruments, e.g., the guitar and sitar, can also be varied smoothly over a restricted range by moving the finger that stops the string on the fingerboard, thereby changing the string tension. The pitch of lip-valve instruments can be altered via changes in lip tension (lipping). In woodwind instruments, each particular configuration of open and closed tone holes is called a fingering, and each fingering is associated with one or more discrete notes. Woodwinds are, however, capable of pitch bending, either by partially opening/closing tone holes or by playing techniques that involve the player's mouth, vocal tract, breath, and in the case of some air-jet woodwinds such as the flute and shakuhachi, adjusting the extent of baffling with the face.

On the clarinet, partially covering a tone hole can be used to achieve pitch bending when a transition between notes uses a tone hole covered directly by a finger rather than by a pad. Seven tone holes are covered directly by the fingers, allowing bending by this method over the range G3 (175 Hz) to G4 (349 Hz) and from D5 (523 Hz) upwards. (The clarinet is a transposing instrument; clarinet written pitch is used in this paper—one musical tone above sounding pitch.) Substantial pitch bending using the vocal tract, however, is usually possible only over the upper range of the instrument (Pay, 1995), typically above about D5 (523 Hz), 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 (Rehfeldt, 1977). Similar observations apply to saxophones, whose reed and mouthpiece are somewhat similar to those of clarinets.

Pitch bending on the clarinet is used in several musical styles including jazz and *klezmer*. In concert music, the most famous example is in the opening bar of Gershwin's *Rhapsody in Blue* (Fig. 1), which features a clarinet playing a musical scale over two and half octaves. At the composition's first rehearsal, the clarinettist replaced the last several notes in the scale with a *glissando* (Schwartz, 1979). This delighted the composer and started a performance tradition. Figure 1 shows the spectrogram of a performance in this style, in which the *glissando* spans an octave from C5 (466 Hz) to C6 (932 Hz) at the end of the run. It is explained in Sec. III B why the *glissando* usually replaces only the last several notes, as shown in Fig. 1.

This solo in Rhapsody in Blue (including the performance tradition) is such a standard part of the clarinet repertoire that it is well known to most professional clarinettists. It is therefore used as the context for part of this study into the roles that a player's vocal tract and partial covering of tone holes can play in pitch bending. For the rest of the study, an artificial exercise was used: Players were simply asked to bend down the pitch of standard notes on the clari-

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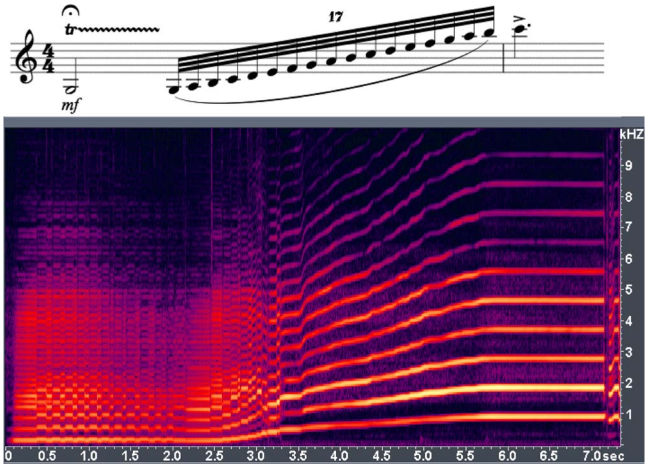

FIG. 1. (Color online) The opening of Gershwin's Rhapsody in Blue. The upper figure shows the 2.5 octave run as it is written—but not as it is usually played. In traditional performance, the last several notes of the scale are replaced with a smooth *glissando*. The lower figure is a spectrogram of such a performance. The opening trill on G3 (written, 174 Hz) is executed from 0 to 2 s and followed by a scale-like run at 2.5–3.5 s that becomes smooth pitch rise from C5 (466 Hz) to C6 (932 Hz) at 3.5–5.7 s.

net, using only their vocal tracts. Acoustic impedance spectra of the clarinet bore were measured using techniques reported previously (Dickens *et al.*, 2007a, 2007b), while impedance spectra inside the player's mouth were measured using an impedance head built into the mouthpiece of the clarinet so that the player could perform with very little perturbation.

B. The sounding frequency of the clarinet

The sounding frequency f_0 of the clarinet is determined by several interacting effects and thus depends on a number of parameters. Some of these effects are modest (such as lip damping, bite configuration, jaw force, and blowing pressure) and, in this study, the aim was to hold them constant rather than to examine them in detail. For example, f_0 depends on the natural frequency of the reed. For a given reed, this can be adjusted by the player during performance by applying greater or lesser force with the lower jaw, thereby varying its effective length and vibrating mass and thus influencing the sounding pitch slightly.

The clarinet has a range of rather more than three octaves and, to first order, stable reed oscillation (at the sounding frequency f_0) occurs near one of the maxima in the acoustic impedance Z_{load} that loads the reed generator, which, along with the pressure difference between mouthpiece and bore, determines the airflow into the instrument (Fletcher and Rossing, 1998). The acoustic pressure difference across the reed is $\Delta p = p_{\text{tract}} - p_{\text{bore}}$ where p_{tract} and p_{bore} are, respectively, the acoustic pressures in the mouth near the reed (upstream) and in the clarinet mouthpiece near the reed (downstream). If U is the acoustic flow passing through the aperture between the reed and the mouthpiece, then $Z_{\text{load}} = \Delta p / U$. Benade (1985) offered a considerable simplification of processes at the reed junction, applied continuity of volume flow, and assumed that p_{tract} and p_{bore} both act on equal areas of the reed. He then showed that the impedance loading the reed generator is given by

$$Z_{\text{load}} = \frac{Z_{\text{reed}}(Z_{\text{bore}} + Z_{\text{tract}})}{Z_{\text{reed}} + Z_{\text{bore}} + Z_{\text{tract}}} = (Z_{\text{bore}} + Z_{\text{tract}}) \parallel Z_{\text{reed}}. \tag{1}$$

This impedance includes contributions from the bore of the instrument (Z_{bore}) and the player's vocal tract (Z_{tract}) where both are measured near the reed. It also includes the effective impedance of the clarinet reed (Z_{reed}) itself: Δp divided by the volume flow due to reed vibration. The second expression in Eq. (1) is included to show explicitly that, in this rudimentary 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} alone—indeed, the maximum in measured impedance of the clarinet bore in parallel with the reed corresponds closely to the pitch in normal playing (Benade, 1985). 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 significantly influence, or even determine, the sounding frequency of the player-instrument system.

The interaction of bore, reed, and airflow is inherently nonlinear 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 nonlinear effects must be considered to understand the threshold pressure for blowing and features of the waveform and spectrum, there is agreement that the playing frequency can be explained to reasonable precision in terms of the linear acoustics of the bore, vocal tract, and reed, using Benade's (1985) model. Specifically, the operating frequency lies close to the frequency at which the imaginary part of the acoustical load is zero, which in turn is very near or at a maximum in the magnitude of the impedance. The present experimental paper considers only the linear acoustics of the bore, the vocal tract and the compliance of the reed.

C. Influence of the player's vocal tract

Some pedagogical studies on the role of the player's vocal tract in woodwind performance report musicians' opinions that the tract affects the pitch (Pay, 1995; Rehfeldt, 1977). Scientific investigations to date include numerical methods, modeling the tract as a one-peak resonator (Johnston *et al.*, 1986), electro-acoustic analog simulations in the time domain (Sommerfeldt and Strong, 1988), and digital waveguide modeling (Scavone, 2003). Clinch *et al.* (1982) used x-ray fluoroscopy to study directly performing clarinettists and saxophonists and concluded that "vocal tract resonance frequencies must match the frequency of the required notes" played. Backus (1985) later observed that the player's vocal tract impedance maxima must be similar or greater in magnitude than the instrument bore impedance in order to influence performance, but concluded that "resonances in the vocal tract are so unpronounced and the impedances so low that their effects appear to be negligible." On the other hand, Wilson (1996) while investigating pitch bending concluded that the upstream vocal tract impedance at the fundamental frequency in pitch bending must be large and comparable to the downstream bore impedance, but did not report details on the vocal tract resonance frequency or the magnitude of its impedance. Watkins (2002) summarized several empirical studies of the use of the vocal tract and its reported or measured geometry in saxophone performance.

The environment in the clarinettist's mouth when playing poses challenges for direct measurements of vocal tract properties during performance. The vibrating reed generates high sound pressure levels in the mouth: Backus (1961) and Boutillon and Gibiat (1996) reported sound levels of 166 dB and exceeding 170 dB inside the mouthpiece of a clarinet and saxophone, respectively, when artificially blown. The static pressure and humidity in the mouth complicate measurements. To avoid these difficulties, some previous measurements of the musician's vocal tract (Wilson, 1996) were made under conditions that were somewhat different from normal performance. Fritz and Wolfe (2005) made acoustic impedance measurements inside the mouth by having the musician mime with the instrument for various musical gestures, including pitch bending. The peaks in impedance measured in the mouth were as high as a few tens of MPa s m^{-3} and so comparable with those of the clarinet bore, but no simple relation between the frequencies of the peak and the note played was reported.

More recently, Scavone *et al.* (2008) developed a method to provide a real-time measurement of vocal tract influence on saxophones while the player performs a variety of musical effects. This method, developed from Wilson's (1996) indirect technique, uses microphones in the mouthpiece, one on the tract side and one on the bore side. It uses the played note and its harmonics as the measurement signal, and so measures impedance ratios of the upstream vocal tract to downstream saxophone bore at harmonics of the sounding reed. This has the advantage of simplicity, a strong signal, and is fast enough to provide real-time feedback to players. However, it does not measure vocal tract resonance frequency or the magnitude of impedance at the tract resonance. Using this method, they found that during pitch bending on the alto saxophone, the pressure component at the playing frequency was larger in the player's mouth than in the bore, from which it may be surmised that a strong vocal tract resonance influences behavior of the reed.

At the same time, the authors (Chen *et al.*, 2008) reported direct impedance spectra measurements made inside the mouth during performance and described how expert tenor saxophonists can produce maxima in Z_{tract} and tune them to produce notes in the very high (*altissimo*) range of that instrument. Several amateur saxophonists, on the other hand, were found not to exhibit tuning, and consequently were unable to play in the altissimo range. The saxophone has a single reed mouthpiece, somewhat similar to that of a clarinet. A major difference, however, is that the saxophone's bore is nearly conical, while that of the clarinet is largely cylindrical. This difference has the result that, for high notes, the maxima in Z_{bore} on the saxophone (Chen *et al.*, 2009) are rather smaller than those in the clarinet (Backus, 1974; Dickens *et al.*, 2007b), so saxophone players can achieve the condition $Z_{\text{tract}} \approx Z_{\text{bore}}$ discussed above with weaker resonances of the vocal tract.

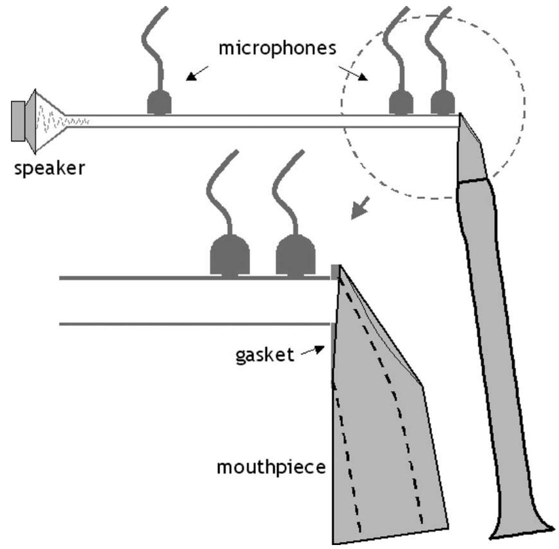

FIG. 2. Schematic of the 3M2C technique used to measure the acoustic impedance of the clarinet bore. The loudspeaker provides a stimulus synthesized as the sum of 2900 sine waves, while three microphones at known spacings record the response from the clarinet being measured. Not to scale.

II. MATERIALS AND METHODS

A. Measurements of bore impedance

Measurements of the acoustic impedance of the clarinet bore for the fingering positions employed in pitch bending were made on a B-flat soprano clarinet, the most common member of the clarinet family (Yamaha model CX). Z_{bore} was measured using the three-microphone-two-calibration (3M2C) method with two non-resonant loads for calibration (Dickens *et al.*, 2007a): one was an open circuit (nearly infinite impedance) and the other an acoustically infinite waveguide (purely resistive impedance). This method allows the measurement plane to be located near the reed tip "looking into" the clarinet bore (Fig. 2) without the involvement of a player. Clarinet bore impedances were then measured for standard fingering positions, as well as for some with partial uncovering of the tone holes. The excitation signal for these measurements was synthesized as the sum of sine waves from 100 to 4000 Hz with a spacing of 1.35 Hz. The measurements of standard fingerings gave results similar to those reported previously (Dickens *et al.*, 2007b). A professional clarinettist was engaged for measurements involving partial uncovering of tone holes. Fingering gestures that would be typical when executing the *glissando* in Rhapsody in Blue were used, involving the gradual and consecutive sliding of one's fingertips off the keys in order to uncover smoothly the open finger holes of the clarinet, starting from the lowest. Acoustic impedance spectra of the clarinet bore were measured at varying stages of the finger slide while the clarinettist temporarily halted the slide for several seconds.

B. Measurements of effective reed compliance

Representative values for the effective compliance of the clarinet reed during playing were measured using Benade's (1976) technique: measuring the sounding frequency produced by a clarinet mouthpiece (with reed) that is attached to

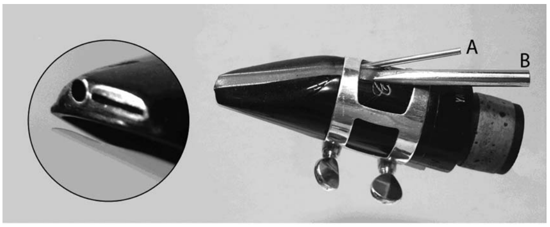

FIG. 3. Photograph of the modified mouthpiece used to measure the acoustic impedance of the player's vocal tract during performance. Tube A is attached to the microphone whereas tube B is attached to the calibrated source of acoustic current. The circular inset to the left shows a magnified view of the mouthpiece tip. The circular end of tube A and the rectangular cross section of tube B are visible just above the reed.

various lengths of pipe and played *mezzoforte* in a "normal" style, i.e., without using the vocal tract to adjust the pitch. Comparing the lengths of pipe for each tone with the calculated lengths of simple tubes (closed at one end) having a natural frequency matching the played one, the equivalent compliance and volume of the mouthpiece under playing conditions for a wide range of frequencies can be calculated by reducing the mouthpiece volume (having the tubes as deep as possible), then treating the calculated compliance as the sum of the compliance of the remaining mouthpiece volume and the compliance of the reed. Here, Benade's (1976) technique relies on the assumption that the impedance of the air in the gap between reed and mouthpiece does not contribute to the end effect. The magnitude of the ac component of the flow resistance is discussed in Sec. III B.

Three Légère synthetic reeds of varying hardness ($1\frac{3}{4}$, $2\frac{1}{2}$, and 3) were used in combination with cylindrical metal pipes with internal diameter of 14.2 mm and external diameter of 15.9 mm, and lengths of 99, 202, 299, and 398 mm. The reed compliance thus calculated was consistent for all pipe lengths listed. A reed of hardness 3 played with a tight embouchure, typical for normal playing, yielded an average equivalent volume of 1.1 ml, which equals the value given by Nederveen (1998). This value, treated as a pure compliance, is used for Z_{reed} in calculations here, i.e., reed losses are neglected. (The effect of different reeds and of the lip force applied to them was not studied in detail here. However, it is worth nothing that a reed of hardness 3 played with a relaxed embouchure yielded an equivalent volume of 1.7 ml, and that the softest reed (hardness $1\frac{3}{4}$) played with a relaxed embouchure gave 2.7 ml. Clarinettists are well aware that one can play flat with a relaxed embouchure, and especially with a soft reed.)

C. Measurements of vocal tract impedance

The acoustic impedance of the player's vocal tract was measured directly during performance using an adaptation of a technique reported previously (Tarnopolsky *et al.*, 2006; Chen *et al.*, 2008) and based on the capillary method [methods reviewed by Benade and Ibisi (1987) and Dickens *et al.* (2007a)]. An acoustic current is injected into the mouth via a narrow tube incorporated into a standard clarinet mouthpiece (Yamaha 4C)—see Fig. 3. The internal cross section of this narrow tube is approximately rectangular with an area of 2 mm^2, giving a characteristic source impedance around 200 MPa s m^{-3}. The sound pressure inside the mouth is measured via an adjacent tube embedded into the mouthpiece. This cylindrical tube (internal diameter of 1.2 mm) is connected to a microphone (Brüel & Kjær 4944A) located just outside the mouthpiece to form a probe microphone. The system thus measures the impedance looking into the vocal tract from a location inside the mouth just past the vibrating reed. It is calibrated by connecting the modified mouthpiece to the quasi-infinite tube used as a standard (Smith *et al.*, 1997), which has an internal diameter of 26.2 mm (comparable in size with the vocal tract) and length 197 m. To minimize the perturbations to the players, they used their own clarinet and a reed of their choice with the experimental mouthpiece. They reported only moderate perturbation to their playing—presumably because the mouthpiece geometry remains almost unchanged, except for an increase in thickness of about 1.5 mm at the bite point. (Indeed, some players routinely add a pad of up to 0.8 mm thickness at this point.)

The acoustic impedance spectrum for each particular vocal tract configuration was measured by injecting a calibrated acoustic current (synthesized as the sum of 336 sine waves from 200 to 2000 Hz with a spacing of 5.38 Hz) during playing. Each configuration was measured for 3.3 s to improve the signal-to-noise ratio. Because measurements are made during playing, the signal measured by the microphone will necessarily include the pressure spectrum of the reed sounding in the mouth. This produces clearly recognizable harmonics of the note played in the raw impedance spectrum with amplitudes much higher than those of the vocal tract itself, and allows the sounding frequency f_0 to be determined. To determine the $Z(f)$ measured in the mouth, these broadly spaced, narrow peaks are removed and replaced with interpolation. There are also high levels of broad band noise produced in the mouth. For this reason, the spectrum is then smoothed using a third order Savitsky–Golay filter typically over 11 points ($\pm$30 Hz) for magnitude values and 15 points ($\pm$40 Hz) for phase values. An example is shown in Fig. 4.

D. Players and protocols

Five expert clarinettists (four professional players and 1 advanced student) were engaged for the measurements on the players' vocal tract. They used the modified mouthpiece on their own clarinet and performed the following tasks.

(i) They played the opening bar of George Gershwin's Rhapsody in Blue (Fig. 1), first normally, then later pausing for a few seconds at various points in the *glissando* while their vocal tract impedance was measured.

(ii) They were asked to play chromatic notes in the range G4 (349 Hz) to G6 (1397 Hz) using standard fingerings and their normal embouchure and tract configuration, and to hold each note while the impedance in their mouth was measured.

(iii) They used standard fingerings for chromatic notes in the range G4 (349 Hz) to G6 (1397 Hz) and were asked to bend each sounding pitch progressively

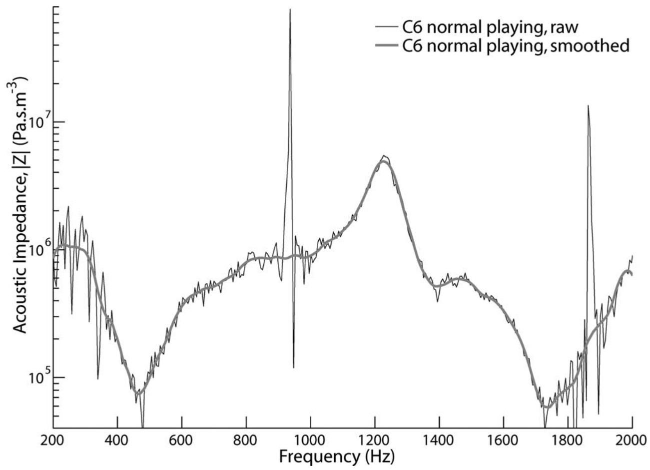

FIG. 4. The magnitude of the acoustic impedance spectrum measured in the mouth for a normal vocal tract configuration (and embouchure) playing the written pitch C6 (932 Hz) with standard fingering. Because measurements (thin line) are made during playing, harmonics of the note sounded appear added to the impedance spectrum—at 935 and 1870 Hz in this case. These are removed and replaced with interpolation, and the data then smoothed (thick line) to produce the vocal tract impedance spectra used in this paper. Here, the measured resonance is at 1225 ± 25 Hz.

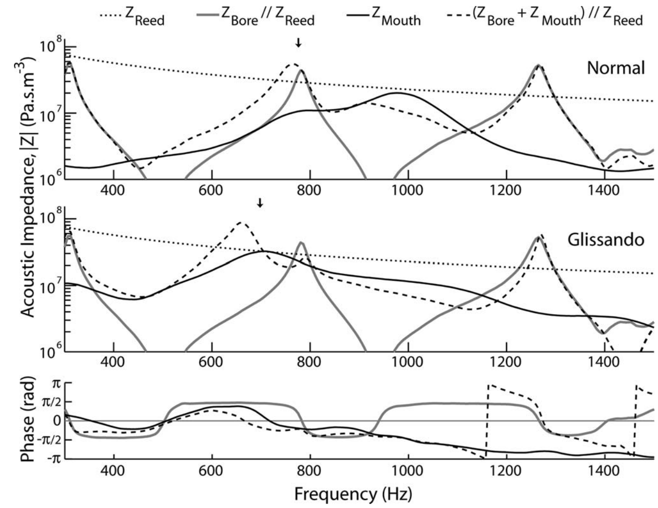

FIG. 6. Measured input impedance of the clarinet, Z_{bore}, shown here with the reed compliance in parallel, $Z_{\text{bore}} \| Z_{\text{reed}}$ (pale line), and the impedance measured in the mouth, Z_{mouth} (dark line). The impedance of the reed, Z_{reed} (dotted line), was calculated from the measured reed compliance. $Z_{\text{load}} = (Z_{\text{mouth}} + Z_{\text{bore}}) \| Z_{\text{reed}}$ is plotted as a dashed line. In both cases the fingering is for the note written A5 (784 Hz). Arrows indicate the frequency f_0 of the sounded note. The top graph shows the impedance magnitude for the note played normally. The middle graph shows that for the same fingering, as played in the *glissando* exercise. At this stage of the *glissando*, the sounding frequency is 76 Hz (190 cents, almost a whole tone) below that of the normal fingering. The bottom graph shows the phases of the impedances whose magnitudes are shown in the middle graph.

down from its standard pitch and to hold it steady while the impedance in their mouth was measured.

III. RESULTS AND DISCUSSION

A. Effects of partial tone hole closure on the clarinet bore impedance

Acoustic impedance measurements of the clarinet bore (Z_{bore}) for standard fingerings show the expected, well-spaced maxima indicating the bore resonances near which the clarinet reed operates in normal playing (Fig. 5). This same figure also shows measurements using a fingering with one tone hole partly uncovered, to different extents, by a finger slide. These fingerings with different extents of hole uncovering show impedance maxima at frequencies intermediate between those used for notes on the diatonic scale. The peaks, however, are lower than those for standard fingerings, particularly when the hole is nearly closed: The difference can be as large as tens of percent (Fig. 5). Thus the finger slide allows sounding pitch to increase smoothly by gradually raising the bore resonance, instead of moving in discrete steps as in a normal musical scale. Over part of the clarinet's range, this technique alone, with no vocal tract or embouchure adjustments, could contribute to the smoothly varying sounding pitch. However, musicians report that this is only one of the effects used to produce a *glissando*.

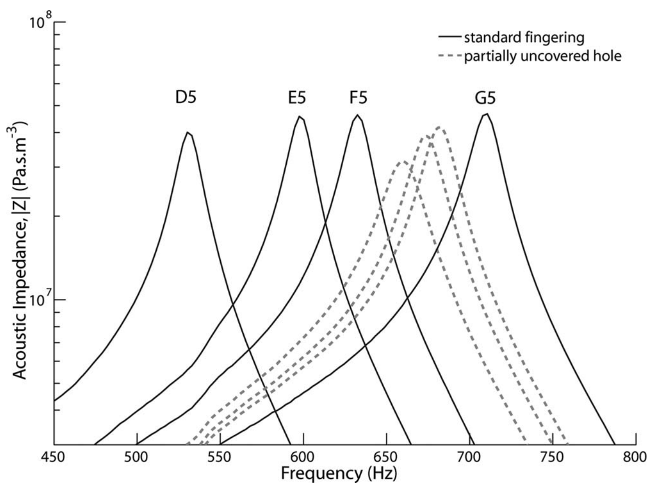

FIG. 5. The measured acoustic impedance at the mouthpiece of the clarinet (Z_{bore}) for different fingerings. The second maxima only shown here. Solid lines indicate the standard fingerings for the written pitches D5 (523 Hz), E5 (587 Hz), F5 (622 Hz), and G5 (698 Hz), and show maxima spaced at discrete frequencies corresponding to those notes. Dashed lines indicate a sequence of fingerings that use partial covering of the hole that is opened to change from F5 to G5.

B. Vocal tract resonance and *glissandi*

Figure 6 shows the measured impedance of the clarinet bore (shown here with Z_{reed} in parallel), and that of a typical result for the impedance measured in the mouth (Z_{mouth}) during normal playing (top). For comparison, it also shows a typical measurement of the acoustic impedance in the mouth of a player performing a *glissando* (middle and bottom). This measured impedance in each case is simply added in series with the clarinet bore impedance, and then the effective reed impedance added in parallel to obtain an estimate of the effective acoustic impedance of the tract-reed-bore system according to the simple model represented by Eq. (1). In both cases, the player's fingers were fixed at the fingering used for A5.

In some cases, the impedance measured in the mouth Z_{mouth} is expected to be a good approximation to that of the vocal tract Z_{tract}. It is complicated, however, by the presence in the mouth of the reed and the acoustic component of volume flow past the reed. In the simple Benade (1985) model, the measured impedance would be Z_{tract} in parallel with $(Z_{bore}+Z_c)$, where Z_c is the combined impedance of the reed and the intermittent air gap beside it. The impedance of the reed, assumed largely compliant, is discussed above, and has a magnitude of a few tens of $MPa\ s\ m^{-3}$ in the range of interest. The impedance through the intermittent gap includes both the inertance of the air in the gap and the flow resistance across it. For a typical blowing pressure of a few kilopascal and a cross section of about 10 mm^2, and considering only the Bernoulli losses, this is also some tens of $MPa\ s\ m^{-3}$. Despite their geometry, the two components are not simply in parallel, because when the reed's motion produces a volume flow into the bore, it also tends to reduce the aperture, and conversely.

Because Z_{mouth} is the parallel combination of Z_{tract} and (Z_c+Z_{bore}), it may sometimes be an underestimate of Z_{tract}, especially when Z_{tract} is large. An estimate of the lower bound for Z_c can be gained from the magnitude of Z_{mouth} measured when Z_{bore} is small. In Fig. 6, for example, Z_{mouth} is 17 $MPa\ s\ m^{-3}$ at 942 Hz, when Z_{bore} is a minimum at 0.4 $MPa\ s\ m^{-3}$, over 40 times smaller. In the cases of pitch bending, Z_{mouth} is measured as high as 60 $MPa\ s\ m^{-3}$ at frequencies when Z_{bore} is a few $MPa\ s\ m^{-3}$. Hence Z_{mouth} is likely to be a significant underestimate of Z_{tract} only when the latter is several tens of $MPa\ s\ m^{-3}$. For this reason, Z_{mouth} is simply shown in Fig. 6 as an estimate of Z_{tract} and is used in estimating Benade's (1985) effective impedance $Z_{load} \cong (Z_{mouth}+Z_{bore}) \| Z_{reed}$.

In normal playing (top graph in Fig. 6), the magnitudes of the peak in Z_{mouth} (20 $MPa\ s\ m^{-3}$ in this example) is about half that of the peaks of Z_{bore} (41 $MPa\ s\ m^{-3}$ here), smaller than the effective impedance of the reed ($\sim$25 $MPa\ s\ m^{-3}$ at these frequencies), and also smaller than those of the peak in $Z_{bore} \| Z_{reed}$ (44 $MPa\ s\ m^{-3}$ here).[1] Consequently, according to the simple Benade (1985) model expressed in Eq. (1), 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 $Z_{bore} \| Z_{reed}$ (which is close to the peak in Z_{bore}).

In the *glissando* exercise, however, the maximum impedance measured in the mouth is consistently comparable in magnitude with that of the maximum of the bore impedance and the effective impedance of the reed. The middle graph in Fig. 6 shows that, because here the peak in Z_{mouth} is no longer small compared with Z_{bore}, the peak in $(Z_{mouth}+Z_{bore}) \| Z_{reed}$ is no longer determined solely by a peak in Z_{bore}. In this example, the Z_{mouth} maximum (32 $MPa\ s\ m^{-3}$) centered at 705 Hz is more comparable in magnitude with the corresponding $Z_{bore} \| Z_{reed}$ maximum (44 $MPa\ s\ m^{-3}$). Here, the sounding frequency during the *glissando* (indicated by an arrow) is about 76 Hz (190 cents or about one whole tone) lower than that produced for normal playing, while the peak in $(Z_{mouth}+Z_{bore}) \| Z_{reed}$ is calculated to fall at 662 Hz, 119 Hz lower than the peak in $Z_{bore} \| Z_{reed}$ (781 Hz). In most of the *glissando* examples studied, sounding frequency f_0 did not coincide with the peak in $Z_{bore} \| Z_{reed}$ but instead occurred closer to the peak in $(Z_{mouth}+Z_{bore}) \| Z_{reed}$. However, f_0 was usually about 10–40 Hz above the peak in $(Z_{mouth}+Z_{bore}) \| Z_{reed}$. This difference might be due to the simplicity of the model used to derive Eq. (1). Also, a smaller value of Z_{reed} would give rise to a higher frequency for the peak in $(Z_{mouth}+Z_{bore}) \| Z_{reed}$, so the difference might also be explained if the compliance of the reed in this situation were higher than in normal playing condition from which it was estimated. (The compliance of the reed could, in principle, be reduced by biting harder on the reed. However, players report no changes in the lip force during this exercise. Unfortunately, it would be difficult to determine independently the value of the reed compliance for the pitch bending playing condition, because Benade's (1976) technique assumes a non-negligible vocal tract impedance.)

As explained above, the clarinet's resonance dominates in normal playing and the player's tract has only a minor effect, as shown in the top part of Fig. 6. However, the region of the *glissando* in Rhapsody in Blue (from C5 to C6, written—i.e., 466–932 Hz) lies in the clarinet's second register, a range where the clarinet resonances have somewhat weaker impedance peaks than those in the lower register. In this range, experienced players can produce a resonance in the vocal tract whose measured impedance peak is comparable with or sometimes even larger in magnitude than those of the clarinet. Consequently, by tuning a strong resonance of the vocal tract and skillfully adjusting the fingering simultaneously, expert clarinettists can perform a *glissando* and smoothly control the sounding pitch continuously over a large pitch range. In performing this *glissando*, the sounding pitch here need only deviate from that of the fingered note by a semitone or so. However, greater deviations are possible. To study this, a simple pitch bending exercise was used.

C. Vocal tract resonance in normal playing and pitch bending

Figure 7 shows the resonance frequency measured in the mouth for the five test subjects as they played. It is plotted against the sounding pitch for both normal playing and pitch bending in the range between G4 (349 Hz) and G6 (1397 Hz). This plot shows the extent of vocal tract tuning: If the players tuned a resonance of the vocal tract to the note played, then the data would lie close to the tuning line $y=x$, which is shown as a gray line. If players maintained a constant vocal tract configuration with a weak resonance and the sounding pitch were 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 as indicated by the legend.

Above about 600 Hz (written E5), the data for pitch bending (black circles) show clear tuning: The sounding frequency f_0 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

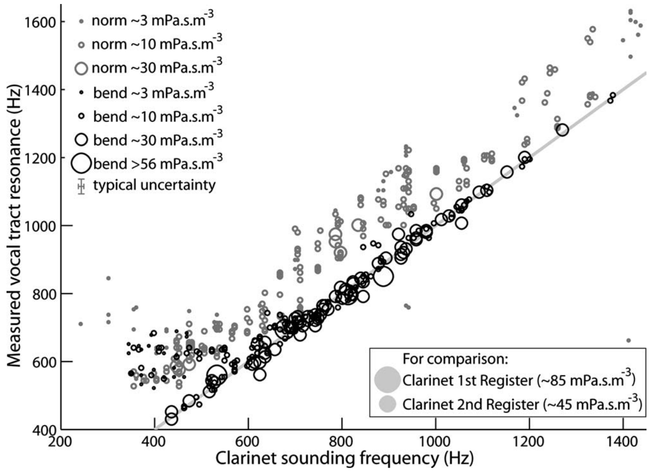

FIG. 7. Measured vocal tract resonance frequency plotted against clarinet sounding frequency. Data from the five players include both normal playing (pale circles) and pitch bending together with the *glissando* exercise (dark circles) in the range between written G4 (349 Hz) and G6 (1397 Hz). The size 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 registers of the clarinet. The gray line indicates the hypothetical relationship (frequency of vocal tract resonance)=(frequency of note played).

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 registers of the clarinet. [For the purposes of this discussion, the second register can be defined to be the notes played using the second peak in impedance. Loosely speaking, these are the notes that use the second mode of the bore. Thus the second register goes from written B4 (440 Hz) to C6 (932 Hz).] 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.

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) reported vocal tract effects for the alto saxophone (520–1500 Hz). This range is also comparable with that reported for vocal tract tuning in a study on tenor saxophones: To play in the very high (*altissimo*) range, saxophonists tune their vocal tract resonance (Chen *et al.*, 2008), 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 to the upper second and third registers on the clarinet and to the range over which tract tuning is shown in Fig. 7.

The results for normal playing (gray symbols in Fig. 7) are more complicated. First playing at low frequencies (which were not the principal object of this study) is discussed. At frequencies below about 600 Hz, the results are approximately as expected for a configuration of the tract, which did not vary with pitch. Above about 600 Hz, however, and in normal playing, the resonance measured in the player's mouth occurs at frequencies about 150 Hz higher (on average) than the sounding pitch. 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 ($\sim$40–90 MPa s m^{-3}), so they contribute little to the series combination and thus are expected to have only a small effect on the sounding frequency of the reed; here the clarinet bore resonance dominates as expected (Nederveen, 1998; Dickens *et al.*, 2007b). Nevertheless, 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 it is noted that, in normal playing, a strong resonance of the vocal tract is not needed, to first order, to determine the sounding frequency f_0: 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 $(Z_{mouth}+Z_{bore})\|Z_{reed}$ 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, experienced players learn, presumably implicitly, to keep their vocal tract resonance *away* from the sounding pitch to prevent it from interfering with the bore resonance during normal playing.

For f_0 below about 450 Hz, the resonances of the bore are stronger and unintended 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). For the range 450 Hz to at least 1400 Hz, they raise the frequency of their tract resonance to keep it substantially above that of the bore. As will be discussed below, it is easier to bend a note down than up on the clarinet. Perhaps having a tract resonance "nearby" (100–200 Hz away) makes for a good performance strategy: Tuning assistance from the vocal tract can be quickly and easily engaged by adjusting the resonance frequency and strength appropriately, should the need arise. And perhaps having a resonance slightly below the played note is just too dangerous, because of the potential effects on the pitch, which will be discussed later. This strategy of keeping the tract resonance at a frequency somewhat above that of the bore resonance for 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.

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 (average $|Z_{mouth}|$ $\sim$20 MPa s m^{-3}) is generated by the player and competes with the clarinet bore resonance. This changes (Z_{mouth}

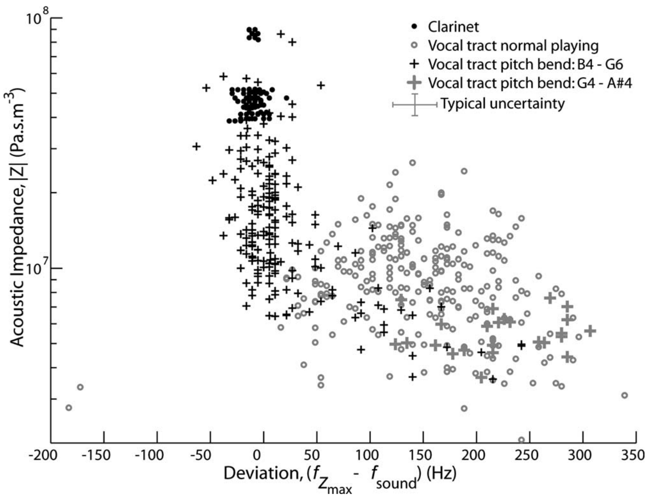

FIG. 8. The magnitudes of the maxima in acoustic impedance of $Z_{bore}\|Z_{reed}$, the clarinet bore in parallel with the reed (dark dots) and of that measured in the player's mouth, Z_{mouth}, are plotted as a function of the difference between the frequency of the relevant maximum and that of the pitch played: In other words as a function of the deviation of resonance frequency from the sounding pitch. Crosses indicate pitch bending together with the *glissando* exercise; open circles indicate normal playing.

$+Z_{bore})\|Z_{reed}$ and, as predicted by the 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 suggested that the lower limit to large pitch bending on the clarinet lies about D5 (587 Hz). This would also explain why the *glissando* is usually only played over the last several notes of the scale in Rhapsody in Blue.

Below written E5 (~600 Hz), 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) placed 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. However, although the extent of pitch bending using the vocal tract resonance is limited in this range, other strategies are used, including partial uncovering of tone holes and techniques that are not studied here, such as changing the bite force on the reed and adjusting lip damping.

Figure 8 plots the same data used for Fig. 7 to show the magnitude of Z_{mouth} and $Z_{bore}\|Z_{reed}$ explicitly. Here, these quantities are plotted as a function of the deviation of the impedance maximum from sounding frequency f_0. For $Z_{bore}\|Z_{reed}$ (black dots), two tight clusters of data are seen. One cluster is those of the bore resonances involved in producing notes in the clarinet's first register: These have magnitudes of about 90 MPa s m^{-3}, the other corresponds to the resonances that produce the clarinet's second register (about 40–50 MPa s m^{-3}). These bore resonances are of course centered on the normal sounding pitch.

For the vocal tract resonances, two contrasting regimes are seen in Fig. 8: For vocal tract resonances with impedance peaks above about 20–25 MPa s m^{-3}, the sounding frequency is tuned closely to the resonance frequency measured in the mouth, with typically less than 30 Hz deviation. Only measurements made during pitch bending fall into this region. For tract resonances with smaller magnitude, the sounding frequency is not necessarily tuned to the vocal tract resonance.

Normal playing (light circles) over this pitch range (G4–G6) shows a broad scattering of weak mouth resonances that deviate from the sounding frequency by typically 100–200 Hz. The asymmetry is striking: They are nearly always above the sounding frequency. These weak tract resonances ($|Z_{tract}| \ll |Z_{bore}|$) do not affect the correct sounding pitch. For pitch bending (crosses), however, a strong vocal tract resonance can influence the sounding frequency. When the peak in Z_{mouth} is large (for notes in the high range of Z: dark crosses), the tract resonance dominates and consequently there is little deviation from the sounding pitch. The pitch bending points in the right of the graph largely correspond to the lower range of the clarinet (below about 600 Hz—pale crosses) where bore resonances are very strong (dots, top left). It may be that it is difficult to produce a vocal tract resonance with a strong peak in this frequency range. Here, the tract resonances are weak and do not determine the sounding frequency directly.

D. Example: Pitch bending exercise on fingered C6

To elucidate the relative influence of bore, tract, and reed on combined impedance and sounding frequency, players were further asked to finger a standard note (written C6, 932 Hz) and to bend its sounding pitch progressively down from the standard pitch while their vocal tract impedance was measured. Players were able to bend the normal pitch C6 (932 Hz) smoothly down by as much as a major third to G#5, a deviation of 400 cents or a third of an octave. This is similar to the average maximum downward pitch bend of 330 cents found by Scavone *et al.* (2008) for the alto saxophone.

Figure 9 shows calculations of the combined impedance ($Z_{mouth}+Z_{bore}$) for bending a note down. A single measured clarinet impedance spectrum (for C6 fingering) is added in series to three different impedance spectra measured in a player's vocal tract for normal playing and two varying degrees of pitch bending, all using the same fingering. To increase pitch bending, the tract resonance moves to successively lower frequencies. It also has successively increased magnitude. The resulting decrease in frequency of the maximum in the series impedance correlates with successively lower sounding frequencies (indicated by the arrows).

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

On the clarinet and saxophone, it is possible to bend pitches down, whereas on the clarinet "only slight upward alterations are possible" (Rehfeldt, 1977) and similarly "significant upward frequency shifts… are not possible" on the alto saxophone (Scavone *et al.*, 2008). It can be shown here that, according to the simple model of Benade (1985), this is simply because although X_{reed} is always compliant, Z_{bore} can be either inertive or compliant.

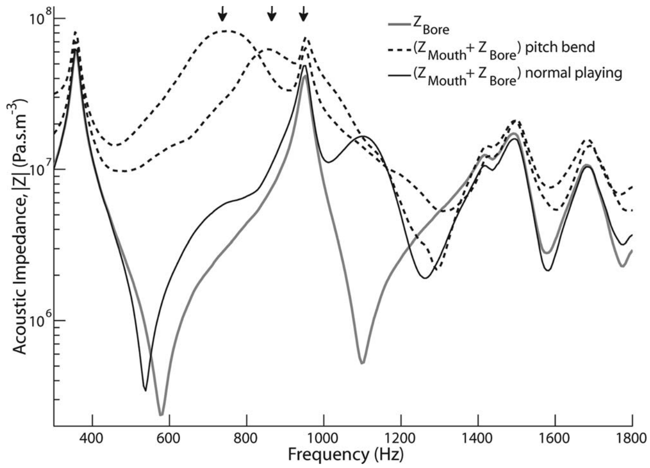

FIG. 9. The clarinet bore impedance (Z_{bore}) for the fingering C6 (gray line) is shown with the series impedance ($Z_{\mathrm{mouth}}+Z_{\mathrm{bore}}$) for normal playing (solid line) and increasing degrees of pitch bending (dashed lines), all while maintaining the same fingering for C6 (932 Hz). Vertical arrows indicate the sounding pitch for the three cases: The right-hand arrow shows a normal sounding pitch at C6+8 cents (937 Hz), while the left-hand arrow denotes the lowest pitch sounding at G#5+7 cents (743 Hz), a deviation of 400 cents or a major third.

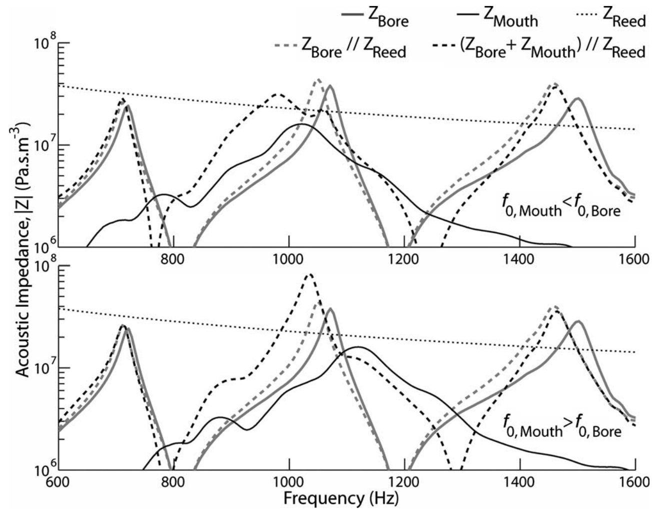

FIG. 10. To examine the effect of vocal tract resonances tuned above and below that of the bore, two hypothetical vocal tract values of equal magnitude (11 MPa s m^{-3}) are shown (dark lines), with resonance frequencies 1020 (shown above) and 1120 Hz (shown below), along with Z_{reed} (dotted line), Z_{bore} (peak at 1070 Hz, pale line), and $Z_{\mathrm{bore}}\|Z_{\mathrm{reed}}$ (peak at 1050 Hz, pale dashes). Total impedance of the tract-reed-bore system ($Z_{\mathrm{bore}}+Z_{\mathrm{mouth}})\|Z_{\mathrm{reed}}$ for both cases are shown (dark dashes), with respective maxima at 980 (above) and 1035 Hz (below).

Nederveen (1998) and the experiments reported here give an effective clarinet reed compliance C (in a typical clarinet embouchure on a reed of hardness 3) as about 7×10^{-12} m^3 Pa^{-1} (equivalent to an air volume of 1.1 ml). At a frequency of 1 kHz, this gives a reactance X_{reed} ($=-1/2\pi fC$) of about -20 MPa s m^{-3}. Its dependence on frequency is weak compared with that of the tract and bore impedances near resonances. For the purposes of this simple model, and as argued above, the sounding frequency f_0 occurs near the maximum in $Z_{\mathrm{load}}=(Z_{\mathrm{tract}}+Z_{\mathrm{bore}})\|X_{\mathrm{reed}}$, where the reactance (i.e., the imaginary part) is zero, i.e., when

$$X_{\mathrm{tract}}(f)+X_{\mathrm{bore}}(f)=-X_{\mathrm{reed}}(f). \qquad (2)$$

Because X_{reed} is always negative and moderately large, the net sign of ($X_{\mathrm{tract}}+X_{\mathrm{bore}}$) must always be positive (and equally large) for resonance to occur.

In normal playing, Z_{tract} is generally small in comparison with the maxima in Z_{bore}, and initially, its effect can be neglected. The condition that $X_{\mathrm{bore}}(f)=-X_{\mathrm{reed}}(f)$ requires that X_{bore} be positive and so the sounding frequency f_0 must lie on the low frequency (inertive) side of the resonance peak in Z_{bore}. A soft reed or a more relaxed embouchure will produce a larger compliance C, a decrease in X_{reed}, and consequently a decrease in sounding frequency.

Now, consider the effect of including Z_{tract} with maxima of similar magnitude to that of Z_{bore} and, initially, at the same resonance frequency, which will be greater than f_0. If the resonant frequencies of Z_{tract} and Z_{bore} are similar, both $X_{\mathrm{tract}}(f)$ and $X_{\mathrm{bore}}(f)$ will be positive at frequencies below their resonances, including f_0. If the magnitude of the resonance in Z_{tract} is now increased, $X_{\mathrm{tract}}(f)$ will also increase and consequently the sum $X_{\mathrm{tract}}(f)+X_{\mathrm{bore}}(f)$ will increase and so the sounding frequency f_0 will decrease so that X_{reed} satisfies Eq. (2). If the player now decreases the resonance frequency of the tract, the value of $X_{\mathrm{tract}}(f)$ around f_0 will increase and so f_0 must again decrease to satisfy Eq. (2). However, decreasing f_0 by continuing to decrease the resonance frequency of the tract will become increasingly difficult. This is because the contribution of $X_{\mathrm{bore}}(f)$ to the sum $X_{\mathrm{tract}}(f)+X_{\mathrm{bore}}(f)$ will decrease as f_0 moves further away from the resonance frequency of Z_{bore} and yet $X_{\mathrm{tract}}(f)+X_{\mathrm{bore}}(f)$ must increase to match the increase in $X_{\mathrm{reed}}(f)$ as f_0 decreases. Eventually a player will be unable to increase $Z_{\mathrm{tract}}(f)$ sufficiently to match $X_{\mathrm{reed}}(f)$ and further downward pitch bending will not be possible.

The situation is quite different, however, if a player wishes to bend the pitch upwards. Again, imagine a vocal tract resonance, comparable in magnitude to that in the bore, and with initially the same resonance frequency as the bore, again above f_0. If the resonant frequency of the tract is then increased, the sum of $X_{\mathrm{tract}}(f)+X_{\mathrm{bore}}(f)$ in the frequency range where this sum is inertive will decrease and consequently f_0 will increase as predicted by Eq. (2). However, once f_0 exceeds the resonance frequency of the bore, $X_{\mathrm{bore}}(f)$ will suddenly change sign and the sum $X_{\mathrm{tract}}(f)+X_{\mathrm{bore}}(f)$ will decrease dramatically to a value much smaller than possible for $X_{\mathrm{reed}}(f)$. Players are probably unable to increase $Z_{\mathrm{tract}}(f)$ sufficiently to increase f_0 past this point, unless they can produce a peak in Z_{tract} that is significantly greater than that in Z_{bore}, which Fig. 8 shows is relatively rare. (In those rare cases where the player can produce such a peak in Z_{tract}, then f_0 is determined largely by the tract and depends less strongly on the bore, much as is the case in the altissimo region of the saxophone.) Thus, in normal 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.

What then are the effects of vocal tract resonances tuned above and below that of the bore? Figure 10 shows the impedance of Z_{bore} for the note written D6, with a peak at 1070

Hz, and that of $Z_{bore} \| Z_{reed}$, which has a peak at 1050 Hz (near the nominal frequency, 1047 Hz, for that note). A single measured vocal tract impedance spectrum Z_{mouth} was then numerically shifted in frequency so that the "same" tract impedance peak now lay at either 50 Hz above or 50 Hz below the peak in 1070 Hz. Then $(Z_{bore}+Z_{mouth}) \| Z_{reed}$ is plotted for the two cases. In both cases, the frequency of the peak $(Z_{bore}+Z_{mouth}) \| Z_{reed}$ lies below that of the peak in $Z_{bore} \| Z_{reed}$, but the downward pitch bend is larger for the lower frequency tract resonance. This figure also shows what happens when Z_{mouth} is much smaller than Z_{bore}, because this is the case for the other two bore resonances that occur in the frequency range shown. Finally, it is worth observing another peak in Z_{bore}, that at about 700 Hz. At this frequency, Z_{mouth} is small compared with Z_{bore}, and both are small compared with Z_{reed}; consequently, the peak in $(Z_{bore}+Z_{mouth}) \| Z_{reed}$ here nearly coincides with that in Z_{bore}.

IV. CONCLUSION

For normal clarinet playing, resonances in the clarinet bore (determined by the fingering used) dominate to drive the reed to oscillate at a frequency very close to that of the bore and reed in parallel. However, if the upstream resonance in the player's vocal tract is adjusted to have a sufficiently high impedance peak at the appropriate frequency, the vocal tract resonance competes with or dominates the clarinet resonance to determine the reed's sounding frequency.

By skillfully coordinating the fingers to smoothly uncover the clarinet finger holes and simultaneously tuning strong vocal tract resonances to the continuously changing pitch, expert players are able to facilitate a smooth trombone-like *glissando*, of which a famous example is the final octave of the run that opens Gershwin's Rhapsody in Blue.

ACKNOWLEDGMENTS

The authors thank the Australian Research Council for support of this project and Neville Fletcher for helpful discussions. They thank Yamaha for the clarinets, Légère for the synthetic reeds, and the volunteer clarinettists.

[1]The peak in $Z_{bore} \| Z_{reed}$ has a larger magnitude than that of either Z_{bore} or Z_{reed} because it is a parallel resonance between the reed compliance and the bore in its inertive range, i.e., at frequencies a little below the peak in Z_{bore}.

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