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The acoustics of wind instruments – and of the musicians who play them

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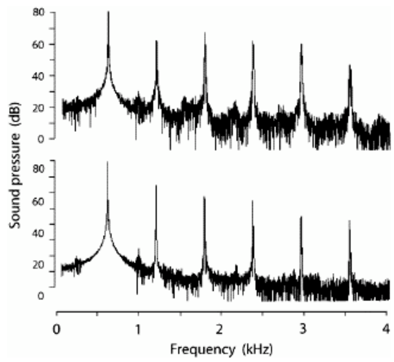
ABSTRACT

In many wind instruments, a non-linear element (the reed or the player's lips) is loaded by a downstream duct – the bore of the instrument – and an upstream one – the player's vocal tract. Both behave nearly linearly. In a simple model due to Arthur Benade, the bore and tract are in series and this combination is in parallel with the impedance associated with vibration of the reed or player's lips. A recent theme for our research team has been measuring the impedance in the mouth during performance. This is an interesting challenge, because the sound level inside the mouth is tens of dB larger than the broad band signal used to measure the tract impedance. We have investigated the regimes where all three impedances have important roles in determining the playing frequency or the sound spectrum. This talk, illustrated with demonstrations, presents some highlights of that work, looking at several different instruments. First order models of the bore of flutes, clarinets and oboes – the Physics 101 picture – are well known and used as metaphors beyond acoustics. Of course, they are not simple cylinders and cones, so we briefly review some of the more interesting features of more realistic models before relating performance features and instrument quality to features of the input impedance spectrum. Acousticians and sometimes musicians have debated whether the upstream duct, the vocal tract, is important. Setting aside flute-like instruments, the bore resonances near which instruments usually operate have high impedance (tens of MPa.s.m^{-3} or more) so the first order model of the tract is a short circuit that has no effect on the series combination. In this country, that model is quickly discarded: In the didjeridu, rhythmically varying formants in the output sound, produced by changing geometries in the mouth, are a dominant musical feature. Here, the impedance peaks in the tract inhibit flow through the lips. Each produces a minimum in the radiated spectrum, so the formants we hear are the spectral bands falling between the impedance peaks. Heterodyne tones produced by simultaneous vibration of lips and vocal folds are another interesting feature. In other wind instruments, vocal tract effects are sometimes musically important: as well as affecting tone quality, the vocal tract can sometimes dominate the series combination and select the operating frequency, a situation used in various wind instruments. In brass instruments, it may be important in determining pitch and timbre. Saxophonists need it to play the altissimo register, and clarinettists use it to achieve the glissandi and pitch bending in, for example, *Rhapsody in Blue* or klezmer playing.

Now, how to play the flute. Well you blow in one end and move your fingers up and down the outside. – Monty Python.

In a simple model of a musical wind instrument, the bore is a cylindrical or conical pipe, either open-open (flute family) or closed-open (most others). This acts as a resonator, which loads a nonlinear element (air jet, reed or player's lips) that converts DC air flow at higher pressure into AC. Together, the system oscillates at a fundamental frequency near one of the lower resonances of the bore and its higher harmonics are impedance matched to the radiation field by the higher resonances. In this model, the role of the player is to vary the length of the resonator (using keys, valves or slide), to supply the air at high pressure and to control some parameters of the nonlinear elements.

Of course this is not enough, as Figure 1 demonstrates. In this paper, we shall look at just a few of the reasons why. We begin with a quick look at the pressure-flow behaviour of one simple nonlinear generator. Next we review Benade's argument about how the ducts load the generator. Next we look at some of the subtleties and complications of the ducts that are real musical instruments, including one that explains the puzzle in Figure 1.



Source: Dickens *et al.* (2007a)

Figure 1. A sound spectrum of the same note played by a flute (open-open pipe) and a clarinet (closed-open). But which is which?

One complication is that the reeds of woodwinds or the lips of a brass player are acoustically loaded by two ducts: the instrument bore is located downstream; the player's vocal tract, upstream. We look here at some examples where the tract resonances have dominant musical roles.

Separating the two ducts is the autonomous (self-sustaining) oscillator, the nonlinear element mentioned above. A clarinet or oboe reed tends to close when the upstream pressure increases, whereas the lips of a brass player tend to open into the mouthpiece, or to move sideways. A model of all three types is given by Fletcher (1993). As an example, we look first at a clarinet reed.

A reed generator

The reed is thin and elastic and has its own natural frequency, known to clarinetists as a squeak, which is usually higher than the range of notes played on the instrument. It is attached to the mouthpiece so that small deflections make big changes to the aperture through which air enters, as shown in Figure 2. The graphs on that figure how steady air flow into the bore as a function of the pressure in the mouth minus that in the mouthpiece. (Acoustic waves in the mouthpiece were damped.)

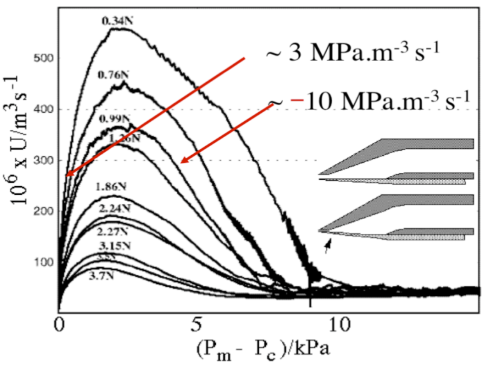


Figure 2. Air flow U *vs* the difference between pressures P_m in the mouth and P_c in the mouthpiece. Different experimental curves (Dalmont and Frappé, 2007) show different force applied by the lip to the reed. The inset shows a cross-section of a clarinet mouthpiece and reed. When the pressure in the mouth increases, the reed bends (black arrow) and reduces the opening through which air enters the bore. The red arrows indicate regions of positive and negative AC resistance (the reciprocal of the slope).

At low mouth pressure (reed not bent significantly), the flow increases with increasing pressure. (Assuming that the kinetic energy of the high-speed air in the narrow aperture is all lost in turbulence downstream, we should expect the pressure difference to be proportional to the square of the flow). At high mouth pressure, however, the reed closes with increasing pressure, so the flow decreases with increasing mouth pressure, and of course it closes completely at sufficiently high pressure, that pressure being reduced if the force applied by the lips is increased.

If we consider the AC behaviour implied by these curves, we see that, at low mouth pressure, a small change in flow ΔU and the associated change in pressure ΔP imply a positive resistance for AC signals. Over a range of higher mouth pressures, however, the AC resistance (the reciprocal of the slope) is negative. This region is of course the region in which the reed converts DC power to AC power: its negative resistance will offset the positive resistance due to visco-thermal losses in the bore and sound radiation, both of which take AC power out of the system. (The radiation by far the smaller term.) Note that the negative resistances are of the order of 10 MPa.s.m^{-3}, or 10 MΩ.

The Benade model for two ducts

The DC flow is asymmetrical: from tract to bore. The nonlinear generator also: a clarinet or oboe reed tends to close when the upstream pressure increases, whereas the lips of a brass player tend to open into the mouthpiece. For acoustic waves, however, the two are symmetrical. Both ducts have resonances that fall in the acoustic range: after all, we use our tract resonances for speech. In both cases, the resonance frequencies can be varied.

Benade (1985) made the following argument for the loading of the reed or lip generator. Figure 3 shows a schematic in which a reed or lip separates two ducts. First, continuity of flow requires that the flow into the mouth and that into the bore satisfy $U_{mouth} = -U_{bore}$. The force that acts across the reed or lip is $\Delta P = P_{mouth} - P_{bore}$. From the definition of the impedance of each duct, looking into the ducts: $\Delta P = U_{mouth}Z_{mouth} - U_{bore}Z_{bore}$. Combining these equations gives

$$\Delta P = U_{mouth}\,(Z_{mouth} + Z_{bore}).$$

So the tract (measured at the mouth) and the bore act in series.

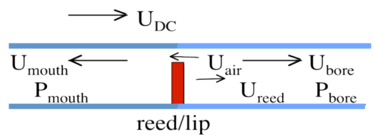


Figure 3. A schematic of the reed or lip that lies between the tract (left) and instrument bore (right).

Consider the flow U_{reed}, that due directly to the motion of the reed or lip, here assumed to have the same value on both sides. Consider also U_{air}, that passing through the aperture left by the reed or lip. If the generator operates to produce U_{air} and pressure difference ΔP, then the impedance loading that generator is

$$\frac{\Delta P}{U_{air}} = \frac{\Delta P}{U_{mouth} + U_{reed}} = \frac{\Delta P}{U_{mouth} + \dfrac{\Delta P}{Z_{reed}}}$$

Substitution for ΔP from the previous equation gives

$$\frac{\Delta P}{U_{air}} = \frac{Z_{reed}\,(Z_{mouth} + Z_{bore})}{Z_{reed} + Z_{mouth} + Z_{bore}}$$

$$= Z_{reed} \,||\, (Z_{mouth} + Z_{bore}) \qquad (1),$$

where the last equation indicates that the reed is in parallel with the series combination of the mouth and the bore. We shall look at these three impedances in turn.

Impedance measurements

Measuring the impedance spectra of instrument bores requires precision and dynamic range: musicians are sensitive to even small changes and sometimes pay large sums for instruments whose physical properties differ only a little from those of much cheaper models. Measuring the impedance spectra in the mouth, during playing, requires measuring a small probe signal in the presence of the much louder signal radiated inside the mouth. We have found two techniques very helpful: The first is adjusting the spectral envelope of the probe signal to compensate for the gain of the measurement system (Smith *et al.*, 1997) and for the noise spectrum (Dickens *et al.*, 2007b). The second is using only nonresonant loads for calibration (Smith *et al.*, 1997). Aspects of this system are described elsewhere in this volume (Dickens *et al.*, 2010).

Impedance spectra of the bore

Let's begin with simple geometry. Figure 4 shows the measured input impedance spectrum of a cylindrical pipe, 15 mm in diameter, 600 mm long and open to the air at the far end. It shows the expected regularly spaced maxima and minima whose magnitudes decrease with increasing frequency because of visco-thermal losses at the wall. The length and inner diameter of this pipe correspond approximately to both a flute and a clarinet, both of which are largely cylindrical. So which is it?

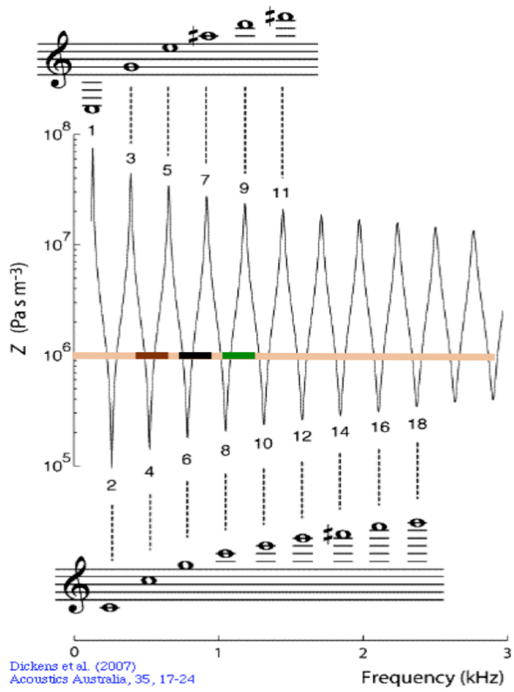


Figure 4. The measured impedance of a cylindrical pipe, 600 mm long and 15 mm in diameter, and open at the far end. the frequencies of maxima and minima are indicated as pitches (Dickens *et al.*, 2007a). A 1 MΩ line is drawn on this and subsequent curves for reference.

At the embouchure, a flute is open to the radiation field. It is driven by a jet that must flow easily into and out of the bore, so it operates near the minima of impedance. A flute, with all tone holes closed, will indeed play the first eight or so of the minima shown in Figure 4, if the player provides an air jet with appropriate speed.

A clarinet, in contrast, has the mouthpiece we've seen above: it requires a large acoustic pressure to move the reed, so one might expect it to operate near the maxima of impedance shown in the figure. This simple, cylindrical model approximately predicts the first two notes played on a clarinet with all tone holes closed.

This section on idealised bore geometries has omitted the cone, for the obvious reason that a complete cone does not have an input impedance: if it were complete, there would be no aperture for air flow. In practice, the oboe, bassoon and saxophone approximate truncated cones with, at the input, a volume approximately equal to that lost by the truncation.

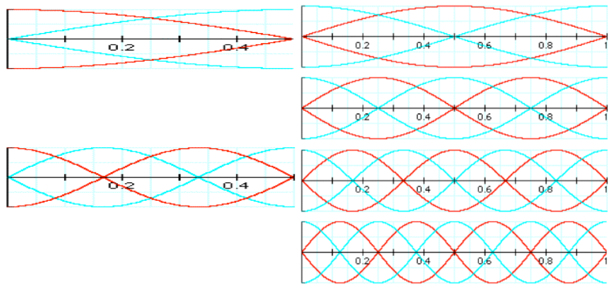


Figure 5. Standing waves in a cylinder. For the open-closed pipe (left) the pressure (red) has an antinode at the closed end (left) and a node at the open end. The open-open pipe has pressure nodes at both ends. These waves correspond (left) to the first two maxima in Figure 4, and (right) to the first four minima.

For a complete conical bore, solutions to the wave equation are written in terms of spherical harmonics rather than sine and cosine functions. The lowest frequency solution has a wavelength twice the length of the radius of the sphere or the length of the conical tube. Consequently, the lowest note on the nearly conical instruments has a wavelength twice the length of the instrument. So the oboe, which is also approximately the same length as the flute and clarinet, has a lowest note similar to that of the flute, while the clarinet plays nearly an octave lower.

Real instruments

Figure 6 shows five measured impedances: three real instruments and two simple geometries. One is a cylinder, as in Fig 4 but for a shorter length. Another is a truncated cone, where the truncation is replaced by a cylindrical section having the same volume as the truncated section.

The real instruments in Figure 6 show a number of interesting features. The flute shows very little variation in Z above about 3 kHz. This is due to a Helmholtz resonance, at about 4 kHz, in parallel with the bore and that shorts it out at the frequency of resonance. The mass of this oscillator is located in the embouchure riser, a very short flaring duct at right angles to the main bore. The 'spring' is that of the air enclosed upstream from the mass: a small volume between the riser and the cork. The purpose of this parallel impedance is to improve the intonation of the high registers. However, by shorting out the bore resonances, it also has the effect of imposing an upper limit to the playing range (about G7).

Z for the clarinet shows the effect of the cut-off frequency. The tone holes in the lower half of the instrument are open for this note. At low frequencies, each tone hole acts as a short circuit to the outside radiation field, so the most upstream tone hole determines the effective length. At higher frequencies, the picture is more complicated.

In each tone hole is a mass of air with a finite inertance: although the tone hole provides an open pathway from the bore to the outside, to produce flow through this hole requires a pressure difference. At higher frequencies (larger accelerations of the mass), larger pressure differences are required.

At sufficiently high frequencies, therefore, the inertia of the air in the tone holes effectively seals the bore from the outside so, above about 1.5 kHz, we note that the peaks in Z for the clarinet appear at frequency spacings about half that of low frequencies. Thus, for low frequencies, the bore is effectively terminated by the first open tone hole, about half way along. In contrast, high frequencies don't 'see' the open tone holes and travel the whole length of the bore before reflecting to make standing waves. (In the case of the flute, the cu-off frequency cannot be seen in the frequency range plotted, because of the Helmholtz shunt discussed above. See also Wolfe and Smith, 2007.)

The cut-off frequency can be estimated by treating the bore-tone hole array as a continuous transmission line (Benade, 1960) or as an infinite array of finite elements (Wolfe and Smith, 2007). For the clarinet, this is about 1.5 kHz, for the flute, about 2 kHz. (This resolves the riddle posed by Figure 1: the higher harmonics produced by the vibrating reed of the clarinet fall above the cutt-off frequency, so there is no systematic difference between odd and even harmonics. As to which is which: the jet of the flute produces some broad band sound, which is part of its characteristic timbre. In the concert music tradition, the clarinet, alone among the woodwinds, is played without vibrato, and so its spectrum usually has narrower harmonic peaks.)

For the simple cone-cylinder, the extrema in Z become weaker more rapidly with increasing frequency than for the cylinder. This is one effect that deprives the saxophone of strong, high frequency resonances. We'll see later that this has important consequences for performance technique.

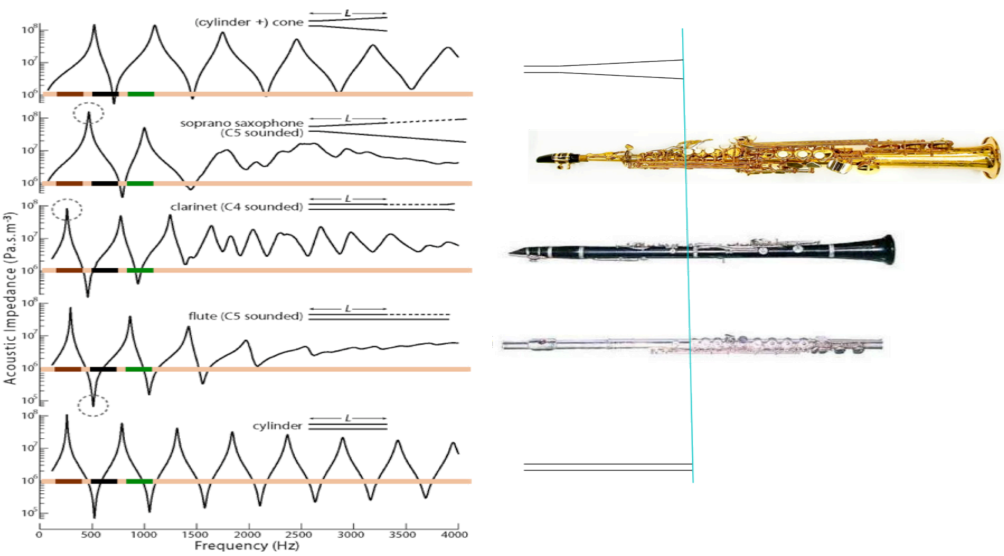


Figure 6. Measured input acoustical impedance spectra (Chen *el al.*, 2009a). From the bottom, they are a cylinder, a flute, a clarinet, a soprano saxophone and a cone-cylinder combination, where the volume of the cylindrical section equals that of the truncation of the cone. The flute and saxophone have the fingering that plays C5, the clarinet C4. The length of the cylinder was chosen so that its first maximum is at C4 and its first minimum at about C5. The length of the cone gives a first maximum at C5. Thus these pipes could all be said to have the same acoustical length, as indicated by the vertical line at right. For comparison, the 1 MΩ bar is included on each.

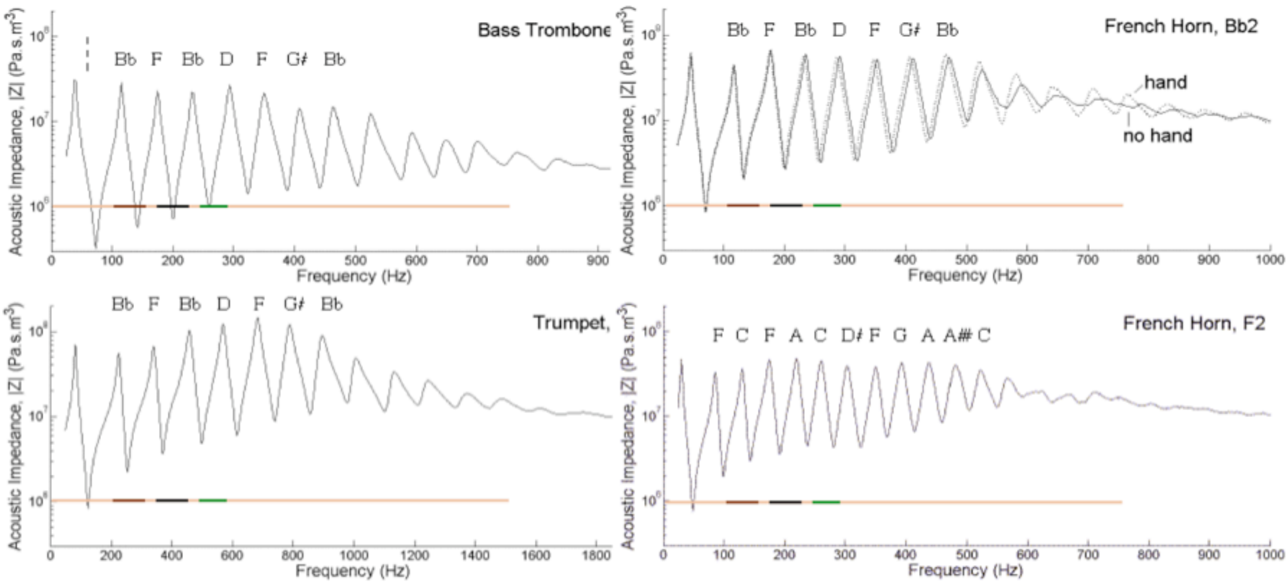


Figure 7. Measured acoustical impedances for brass instruments: a Bb bass trombone (first position, valve not depressed), a Bb trumpet (no valves depressed) and a horn in the open Bb and F configurations (no finger valves depressed) (Chen, 2009; Wolfe, 2005). The frequency scale for the trumpet is twice that of all the others, which shows that the trumpet is rather like a one-half scale model of the trombone: in Italian, *tromba* means trumpet and *trombone* means big trumpet.

Impedance spectra of brass instruments

Unlike earlier relatives such as the serpent and the keyed bugle, modern brass instruments have no tone holes: their lengths are varied by valves or slides. Figure 7 shows that they also have a cut-off frequency however: for sufficiently small wavelengths, the bell radiates efficiently, so the reflection coefficient is low at high frequencies, so there are no strong standing waves and no strong impedance peaks. In Figure 7, we see that the player's hand in the bell of the horn increases reflections. This not only increases the number of playable resonances, but also affects the tuning.

These instruments all have substantial cylindrical sections, which include the valves and slides. They also have a flare and a bell at one end, and a cup- or cone-shaped mouthpiece at the other, linked to the cylindrical section by an approximately conical section. The net result of this geometry is that the second and higher impedance maxima fall close to the harmonic series, i.e. at frequencies $2f_0$, $3f_0$, $4f_0$ etc. The first, however, falls well below f_0, and is not played. Players can, however, play what they call a pedal note at approximately f_0. While there is no resonance at this frequency, there are resonances at several of its harmonics. The seventh resonance (here and in Figure 4) does not fall on a note in common Western scales, hence the half-sharp symbols. (The resonances are discussed in more detail by Backus, 1976 and Wolfe, 2005.)

Impedance spectra of the vocal tract

The shape of the vocal tract is complicated, Further, it varies with time as we move tongue, jaw, lips, palate and glottis. We shall see some measurements later but, for the moment, let's ask what features we might expect in Z(f).

There are two simplifications: To play a wind instrument, one doesn't want a short circuit through the nose, so the palate seals the nasal tract from the bucal tract. Further, the jaw and lip positions are almost fixed so as to make an air-tight seal at the mouth.

The glottis is the name of the aperture at the larynx. Even with the glottis open, there is still a considerable constriction at the glottis so, at high frequencies, one would expect a strong reflection. Further, Mukai (1992) reports that experienced wind players tend to keep their glottis aperture rather small. The respiratory tract below the glottis branches many times before terminating in the alveoli: its resonances at acoustic frequencies are thought to be weak.

So, as our first approximation, let's picture the wind player's tract as a cylinder, nearly closed at the glottis. The 'nearly' is very important. If the glottis were closed (easy enough to do, but one can't play a wind instrument for very long with no air supply), Z would be infinite for DC. The small glottal aperture, however, makes the impedance low at low frequencies. Where is the first maximum?

For round numbers, let's consider a tract of length 0.17 m from mouth to glottis. If the glottis were completely closed, then we should expect maxima in Z at zero frequency, and also at $f = nc/2L = 0$, 1000, 2000, 3000 Hz etc. If ideally open, maxima at $c(2n+1)/4L = 500$, 1500, 2500 Hz etc.

Of course it's neither ideally open, nor even very open. At sufficiently low frequencies, with $\lambda >> L$, it might operate as a Helmholtz resonator, with mass of air in the glottis supported on the spring of the air in the tract. At the Helmholtz resonance, there would be a maximum in impedance. For the higher resonances, with higher reactances at the glottis, the peaks in Z (for a cylindrical tract) would be closer to 1000, 2000 Hz etc.

The tract is not cylindrical, of course: if the player constricts the tract at any point, e.g. with the tongue, then that lowers the frequency of modes having displacement antinodes near that point. Usually, changes due to changes in tongue position are less important for the first Z maximum, because its wavelength is rather longer than the tract.

During performance on a range of instruments, we have observed a maximum in the mouth impedance somewhere around 200 Hz for nearly all players and conditions, and another whose frequency can be varied with different articulations between about 400 and 1800 Hz. We shall see some of these in the figures to come. However, many of our measurements do not include frequencies below 200 Hz. The reason is the difficulty of making measurements of impedance spectra in the mouth during wind instrument performance: in the presence of a very large signal produced in the mouth by reed or lips, one must limit the frequency range of the probe signal so as to concentrate sufficient power in the frequencies to be measured. Fritz and Wolfe (2005) give some comparisons between measurements and models. The measurements, however, were made while subjects mimed.

Once we could measure impedance spectra during performance, our first target was the didjeridu. One reason was that the instrument is iconically Australian. More importantly, it is clear from listening to the instrument that vocal tract effects are not only involved, but are of the greatest musical interest.

The vocal tract and the didjeridu

The didjeridu is made from the trunk or sometimes the branch of a eucalypt tree that has been hollowed out by termites, leaving an irregular duct. The ends are trimmed and a ring of wax is usually applied to the narrower mouth end, to achieve an airtight seal around the mouth and to improve player comfort (Fletcher, 1996).

Figure 8. Ben Lange, of the Mara people of Northern Australia, worked on the didjeridu project while studying engineering at UNSW.

The instrument is typically 1.4 m long, and roughly approximates a truncated cone with a small angle, that varies among instruments. The lowest resonance is typically at about 60 to 80 Hz (about B1 to E2) and the next about 2.5 to 2.8 times (a tenth or eleventh) higher. The instrument is blown somewhat like a tuba, with three obvious differences: First, it usually plays only one note, near the first resonance, with the second used only occasionally as a brief contrast. Second, the musical interest is in the rhythmic changes in timbre rather than in variations in pitch. Third, the player does not stop playing in order to breathe.

The instrument is called the yidaki by the Yolngu people of Northern Australia, one of the many peoples to whom the instrument is culturally significant. The English name didjeridu is thought to be onomatopoeic, the rhythmic succession of vowels in the name resembling the rhythmic variation in timbre that is idiomatic to performance.

The long, continuous note is achieved by an unusual breathing technique, misleadingly called 'circular breathing'. While blowing into the instrument in a manner similar to that used for brass instruments, the player fills his cheeks with air. (Traditionally, the player is a man.) He then seals the mouth from the respiratory and nasal tracts by lowering the velum or soft palate, which allows him to expel the air from his cheeks into the instrument, while simultaneously inhaling air through the nose to fill the lungs.

While the mouth is thus sealed by the velum, its acoustic properties are rather different from those it has when connected to the vocal tract. Consequently, the timbre changes abruptly.

Like the tuba, which plays in a similar pitch range, the instrument requires a substantial air flow, so the player regularly interrupts the normal tone with one or a few short timbral contrasts that accompany the inhalation. This provides the regular rhythmic ground. The player can then introduce a range of different timbres during the more sustained normal exhalation and thus create extended, varied musical patterns.

We conducted a series of experiments in which we measured the impedance spectrum inside the mouth (Figure 9) while performers played using different articulations.

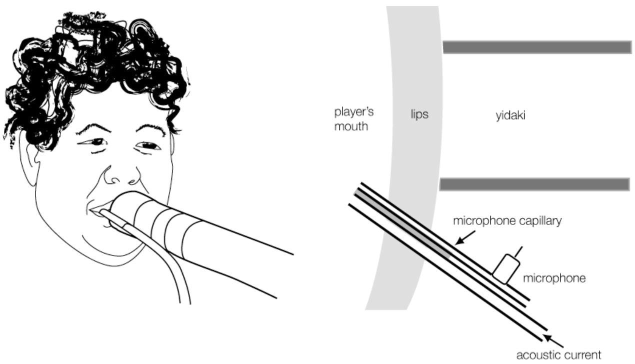


Figure 9. An impedance head inside the mouth of a player. The microphone capillary makes an inertance divider that reduces the magnitude of the signal to the microphone (Tarnopolsky *et al.*, 2006).

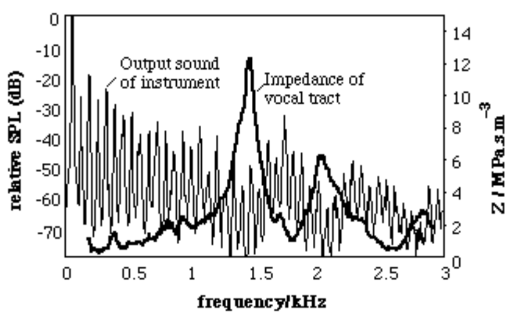


Figure 10. Sound pressure spectrum radiated by the instrument (fine lines) and impedance spectrum inside the mouth (thick lines) measured simultaneously (Tarnopolsky *et al.*, 2005).

The sound and impedance spectra in Figure 10 are for an articulation in which the tongue is raised close to the roof of the mouth, in a gesture described by some players as the 'ee' position. This produces what they called a high drone. Two strong peaks in Z are seen and, at the same frequencies the harmonics of the radiated sound are suppressed. At these frequencies, the high impedance in the mouth prevents flow between mouth and lips.

At about 1.8 kHz, a strong formant is seen in the sound spectrum and heard in the radiated sound. This formant is produced by the harmonics lying between the two strong impedance peaks, which are therefore not suppressed. Similar comparisons for different players and articulations showed that formants (peaks in the spectral envelope of the sound) coincided closely with local minima in the impedance measured in the mouth and that minima in the sound spectra coincided with the impedance peaks (Tarnopolsky *et al.*, 2006).

Interference tones on the didjeridu

Another method of varying the timbre of the didjeridu is called vocalisation. In traditional performance, this can simulate animal or bird sounds; in contemporary performance it has a range of roles. While playing at note at the drone frequency f, a player 'sings' into the instrument at frequency g. So, two different periodic vibrations (vocal folds and lips) modulate the flow of air into the instrument. The radiated sound has not only the harmonics of f and g, but also the heterodyne components g–f, f+g, etc, as shown in Figure 11.

In this experiment (Wolfe and Smith, 2008), one of us (JW) played a simple cylindrical pipe in the manner of a didjeridu. Electroglottograph electrodes were attached both in the normal position (across the neck at the level of the vocal folds) and either side of the lips. The MHz electrical admittance of the two signals is also shown for lips and vocal folds. (Sound files and more examples are given at www.phys.unsw.edu.au/jw/yidakididjeridu.html)

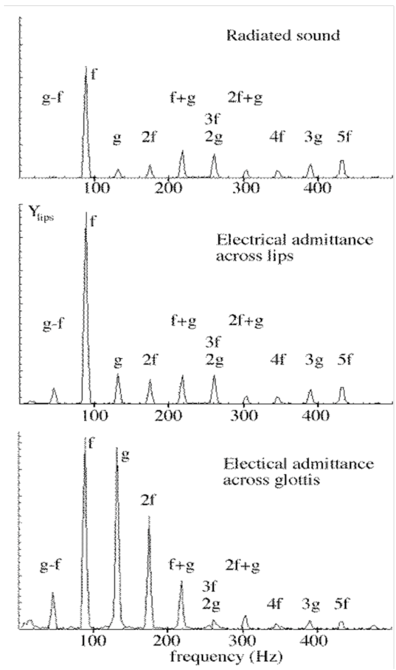


Figure 11. The spectrum of the radiated sound of a didjeridu vocalisation. The middle trace shows the MHz electrical admittance across the player's lips, the lower that across the neck at the level of the vocal folds (Wolfe and Smith, 2008).

The vocal tract and other lip valve instruments

The brass family (trumpet, horn, trombone, tuba and others) are modern lip valve instruments. Compared with the didjeridu, they have a narrow bore near the mouthpiece, and the mouthpiece itself has a narrow constriction. This gives these instruments resonances whose impedance peaks are somewhat greater than those of the didjeridu: The didjeridu impedance curves shown by Smith *et al.* (2007) have peaks of typically about 10 to 30 MΩ at low frequencies whereas the instruments in Figure 7 have peaks of 30 to 100 MΩ. However, the magnitudes of peaks in Z for the didjeridu decrease more rapidly with increasing frequency for the didjeridu than for the brass.

This has the consequence that the effect on timbre of similar articulation changes in the mouth are less striking on the brass than they are on the didjeridu. However, they are still significant enough for composers to include these effects in works for trombone (Berio, 1966; Erickson, 1969).

Small changes in articulation have acoustical effects that can change the pitch in two ways. First, a change in the contribution of Z_{mouth} to the series impedance $Z_{mouth} + Z_{bore}$ can change the frequency of the impedance peak at which the mouth-lip-bore system operates. More dramatically, it can change which peak in Z_{bore} determines the playing frequency.

Both of these effects are shown in Figure 12. An artificial trombone playing system used highly simplified models of lip, vocal tract and glottis (Wolfe *et al.*, 2003). To simulate the relatively non-resonant lower tract, an acoustically infinite duct was used (Dickens *et al.*, 2010). The model vocal tract representing the high tongue configuration played sharper than the low tongue model when they operated on the same impedance peak of the bore. As the slide was extended, there was also a range over which the high tongue model played on a higher resonance. Experienced players reported the same effect: when they lowered the tongue while playing a sustained note, and while holding all else constant, sometimes the pitch fell slightly, while sometimes it dropped to the next lower register.

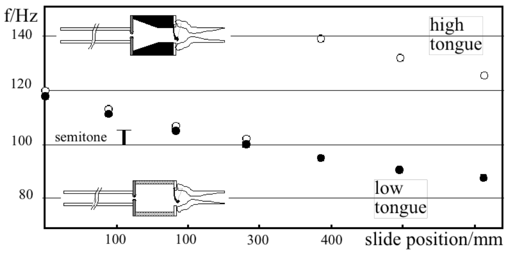


Figure 12. The playing frequency of an artificial trombone playing system as the slide is extended from the closed position (0 mm). The open filled circles refer to geometrically simplified 'vocal tracts' represented by the sketches for 'high tongue' (top) and 'low tongue' (bottom). From (Wolfe *et al.*, 2003).

In the simple models of lip valve instruments (e.g. Fletcher, 1993), the playing frequency lies reasonably close to the natural frequency of vibration of the non-linear oscillator. Players of brass instruments have considerable control over this frequency and are adept at choosing one of several impedance peaks of the bore (see Figure 7).

Can the players select resonances by lip control alone, or do they need to adjust the resonances of the vocal tract? Figure 13 shows measurements of the impedance spectrum measured inside the mouth of a trumpet player using an appraratus similar to that shown in Figure 9, though a probe microphone replacing the inertance divider.

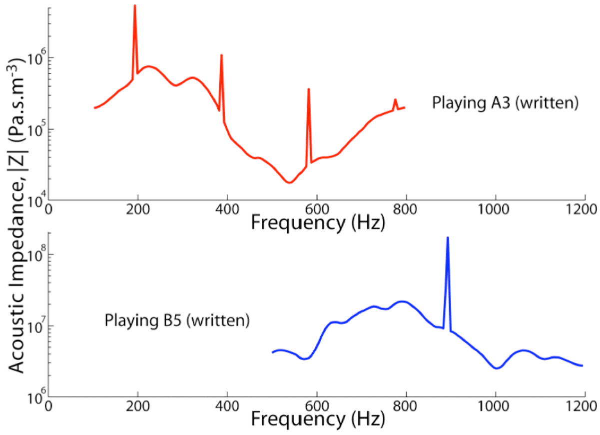


Figure 13. The impedance spectrum measured inside the mouth of a trumpeter. For the upper graph, he was playing written A3 (sounding G3), near the bottom of the instrument's range. For the lower, he was playing written B5 (A5), over two octaves higher. In each graph, the sharp peaks are (useful) artefacts: they are the harmonics of the notes being played (nominally 196 and 880 Hz respectively), which are, of course, strongly radiated inside the mouth. The broad peaks at about 200 and 800 Hz are due to resonances in the vocal tract. To improve signal:noise ratio, only part of the spectrum was measured for a given note, so only one tract resonance appears in each plot. From (Tusch, 2010).

In this case, the player does not tune the tract resonance to match the note being played. It is possible, of course, that he is using it for fine control of tuning (*cf* Figure 12), but he evidently has sufficient control of the lip oscillator not to need the assistance of vocal tract resonances over this range. Further, this player reports no deliberate changes in the position and shape of tongue or other articulators playing over the standard trumpet range.

The vocal tract and single reed instruments

In contrast with trumpetters, the players of reed instruments have relatively modest control of the natural frequency of the reed, although they can vary the stiffness and vibrating mass by the position and force with which they bite. How are their vocal tracts involved? We have been studying vocal tract and embouchure effects on single reed woodwind instruments (clarinet and saxophone) using measurements on both live players (Chen *et al.*, 2007-10) and artificial playing machines (Almeida *et al.*, 2010).

Concerning these instruments, acousticians and sometimes even musicians have debated whether the acoustic effects are important: while Clinch *et al.* (1982) stated that, for the clarinet, "vocal tract resonance must match the frequency of the required notes". Backus (1985) wrote that "resonances in the vocal tract are so unpronounced and the impedances so low that their effects appear to be negligible".

Direct measurements were difficult. Wilson (1996) used a microphone inside a clarinet mouthpiece and another in the player's mouth. The ratio of the two pressures is approximately proportional to that of the impedances of bore and tract. The problem is that data are only obtained at the playing frequency and harmonics. She deduced, however, that vocal tract effects are sometimes involved in pitch bending and in playing the second register without the register key. We made measurements in the mouths of players while they mimed (Fritz and Wolfe, 2005) but were unable to relate the frequency of impedance peaks to that of notes.

More recently, we were able to make impedance measurements in the mouth during playing, using an impedance head built into the mouthpiece of a tenor saxophone (Chen *et al.*, 2007, 2008). At the same time, Scavone and colleagues (2008) made measurements on the saxophone, using a technique similar to that of Wilson.

The saxophone offers a spectacular example of the use of vocal tract effects. Partly because of its largely conical bore, the third and higher modes of standing waves in the bore usually produce relatively weak impedance peaks, as shown in Figure 6 and www.phys.unsw.edu.au/music/saxophone/ Without using the vocal tract, players can play the first register, using the first impedance peak and the second register, using one of two register keys that weakens and detunes the first peak in Z. Not only beginners, but also some players with considerable experience, are therefore limited to about 2.6 octaves, the 'standard' range of the instrument. The altissimo register, using the third and higher peaks in Z, requires tuning the vocal tract.

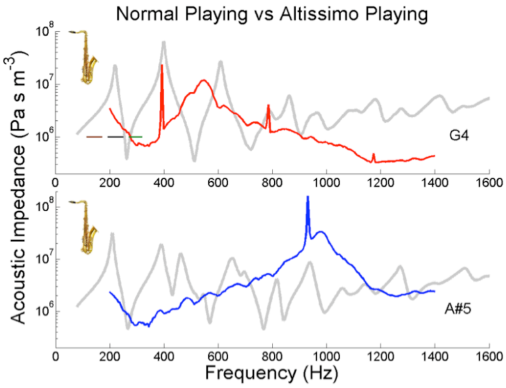


Figure 14. The broad, pale grey line shows the impedance of the bore for the fingerings that play G4 in the standard range of the tenor saxophone and A#5 in the altissimo range. (On this transposing instrument these notes are written A5 and C7.) The vocal tract impedance, measured while playing these notes is shown in red and blue respectively. The sharp peaks are harmonics of the note played; the broad peaks are resonances in the tract (Chen *et al.*, 2007).

Figure 14 shows the impedance of the vocal tract of a professional saxophonist playing notes in the standard and altissimo register. In the former, there is no relation between the tract resonance at about 550 Hz and the note played, whose harmonics are visible as (useful) artefacts superposed on the Z measurements. In the latter, the strong resonance in the vocal tract lies close to the fundamental frequency of the note played, which in turn is very close to the (relatively weak peak) of the operating resonance of the instrument.

Figure 15 shows the frequency of peaks in the vocal tract impedance plotted against the sounding pitch over both ranges. On this plot, the magnitudes of Z are indicated by the size of the circles used to plot them, and empty and filled circles distinguish professional and (less experienced) amateur players. This figure shows that, over the lower part of the standard range, neither amateurs nor professionals tune the tract near a note played. Over the altissimo range however, and also over the upper part of the standard range, the professional players tune the tract impedance peak near to or slightly above the frequency of the note played.

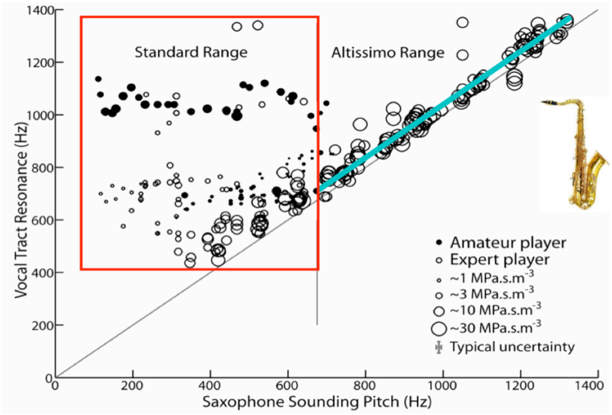


Figure 15. Frequency and magnitude of peaks in the vocal tract impedance, measured during playing the tenor saxophone. The red rectangle encloses the region of normal playing, and the green line summarises playing in the altissimo region.

Figure 16 shows measurements made in the mouths of clarinettists, also made using an impedance head in the mouthpiece, while they played the second and higher registers (clarino and altissimo ranges). On the clarinet, because it is not conical and because it doesn't have a Helmholtz short circuit like the flute, the impedance peaks remain relatively large, even at high frequency. Thus the altissimo range can be played without the extensive practice needed to tune vocal tract resonances. (Sound files and examples are at www.phys.unsw.edu.au/music/clarinet/)

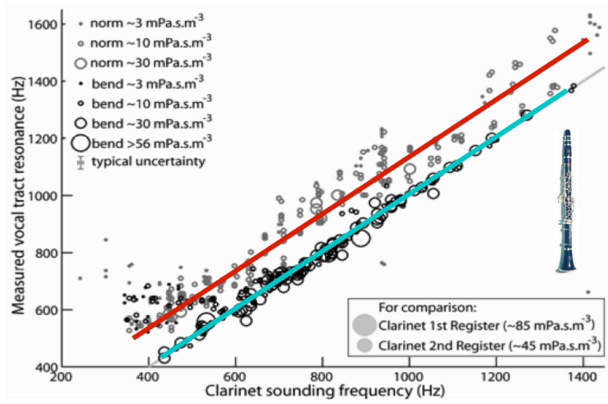


Figure 16. Frequency and magnitude of peaks in the vocal tract impedance, measured during playing the clarinet. The red line summarises typical playing in the clarion register while the green line summarises pitch bending in the same range.

For the vocal tract of a clarinettist to influence or to determine the pitch, the tract resonances must have rather large magnitudes. This is used by advanced players when 'bending' the pitch over large intervals, or in producing the glissandi that are used in klezmer playing and also in the well-known solo that begins Gershwin's *Rhapsody in Blue*.

The clarinet results include both normal playing (grey circles), and pitch bending (black circles) where again the size of the circle indicates the magnitude of the peak in Z. For the pitch bending, the tract resonances have large magnitudes and the playing frequency is close to that of the peak in Z. For normal playing in the clarino register, as expected, the magnitudes are not so large. What is perhaps surprising is that they are tuned to frequencies about 100 to 200 Hz above that of the note played.

So far, we have not mentioned the phase of the impedances in equation (1). Let's return to the Benade model mentioned above, where the impedance loading the reed generator is ($Z_{mouth} + Z_{bore}$) || Z_{reed}. The reed is largely compliant, with its compliance being larger if the reed is soft. Consider what happens when this is added in parallel to the series combination of mouth and bore.

Figure 17 shows the magnitude and phase for all of these terms in an example where the player was pitch bending on the clarinet. In normal playing of this fingering (with no strong peak in Z_{mouth}), the note produced has a frequency almost exactly at that of the peak in Z_{bore} || Z_{reed}, which is not far below that of the peak in Z_{bore}. In this example, however, the note produced fell close to the peak in ($Z_{mouth} + Z_{bore}$) || Z_{reed}, which lay nearly 20% or a minor third lower.

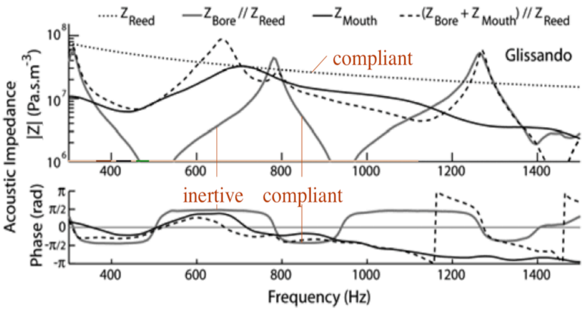


Figure 17. Measurements of the magnitude and phase of ($Z_{mouth} + Z_{bore}$) || Z_{reed} and its components. A clarinettist was pitch bending on the clarinet (Chen *et al*., 2009).

Near one of the resonances in the bore, the impedance is largely inertive (pressure leads flow) at frequencies below the peak, and compliant at frequencies above. The same is true for the peaks in Z_{mouth}. Adding the reed compliance in parallel lowers the frequency and raises the magnitude of the resultant peak. Because the peak in Z_{mouth} is broader than that in Z_{bore}, the effect of the reed compliance on the frequency of the peak is greater when the series spectrum is dominated by Z_{mouth}. This has the consequence that a peak in Z_{mouth} located below a peak in Z_{bore} with comparable magnitude can have a bigger effect on the playing frequency than can a peak in Z_{mouth} located above that in Z_{bore}. This explains why it is easier to bend notes down using the vocal tract than up. More details on the single reed research are given by Chen *et al.* (2010) in the proceedings of ISMA, a satellite meeting of ICA, and published in the same collection.

Provided that the peaks in Z_{mouth} are of small magnitude, it is possible to play the clarinet in tune without tuning the tract resonances, however. Figure 18 shows a clarinet playing machine built in our lab in collaboration with the ICT research organisation NICTA. It was built to contest a competition for automated 'musicians' (Artemis, 2008). The original version was designed to have no strong impedance peaks in its 'mouth', so that only the resonances of the bore determine the playing frequency. (Sound recordings, including a duet with a live player, are available at www.phys.unsw.edu.au/music/clarinet/). This version plays fairly well in tune – in summer. Although originally built for the competition, it now provides us with an alternative experimental tool for studying the effects, not only of vocal tract geometries, but also some of the other control parameters used in performance, including the air pressure, the force and damping on the reed and the coordination of finger motions. This research is also presented in the ISMA proceedings (Almeida *et al*., 2010).

By comparing and contrasting measurements on human players of woodwind and brass instruments with those on the artificial systems, we expect to learn more about the subtleties of control used by expert players. We shall also learn more about the acoustics of wind instruments – and of the musicians who play them.

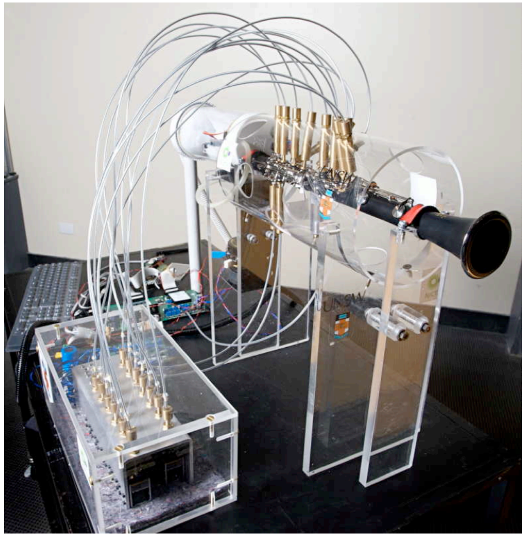


Figure 18. The NICTA-UNSW artificial clarinet player (see Almeida *et al.*, 2010).

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REFERENCES

A. Almeida, J. LeMare, M. Sheahan, J. Judge, R. Auvray, K.S. Dang, S. John, J. Geoffroy, J. Katupitiya, P. Santus, A. Skougarevsky, J. Smith and J. Wolfe, "Clarinet parameter cartography: automatic mapping of the sound produced as a function of blowing pressure and reed force" *Proc. Int. Symp. Music Acoustics*, Sydney (2010)

Artemis Orchestra competition: https://www.artemisia-association.org/photo_gallery_2007-2008

J. Backus, "The effect of the player's vocal tract on woodwind instrument tone" *J. Acoust. Soc. Am.* **78**, 17-20 (1985)

J. Backus "Input impedance curves for the brass instruments", *J. Acoust. Soc. Am.*, **60**, 470-480 (1976).

A.H. Benade, "Chapter 35: Air column, reed, and player's windway interaction in musical instruments" in *Vocal Fold Physiology, Biomechanics, Acoustics, and Phonatory Control*, edited by I. R. Titze and R.C. Scherer, (Denver Center for the Performing Arts, Denver, CO, 1985) pp. 425-452

A.H. Benade, "On the mathematical theory of woodwind finger holes", *J. Acoust. Soc. Am*., **32**, 1591–1608 (1960)

L. Berio, "Sequenza V; Solo Trombone" (Universal, NY, 1966)

J.M. Chen, *Vocal tract interactions in woodwind performance*, Ph.D. thesis, the University of New South Wales, Australia (2009)

J.M. Chen, J. Smith and J. Wolfe, "Vocal tract interactions in saxophone performance" *Proc. Int. Symp. Music Acoustics*, Barcelona, Agulló, J. and Barjau, A., eds. (2007)

J.M. Chen, J. Smith and J. Wolfe, "Experienced saxophonists learn to tune their vocal tracts" *Science* **319**, 726 (2008a)

J.M. Chen, J. Smith and J. Wolfe, "Saxophone acoustics: introducing a compendium of impedance and sound spectra", *Acoustics Australia* **37**, 18-23 (2009a)

J.M. Chen, J. Smith and J. Wolfe, "Pitch bending and *glissandi* on the clarinet: roles of the vocal tract and partial tone hole closure" *J. Acoust. Soc. Am.* **126**(3), 1511-1520 (2009b)

J.M. Chen, J. Smith and J. Wolfe, "How players use their vocal tracts in advanced clarinet and saxophone performance" *Proc. Int. Symp. Music Acoustics*, Sydney and Katoomba, Australia (2010)

P. Clinch, G.J. Troup and L. Harris, "The importance of vocal tract resonance in clarinet and saxophone performance" *Acustica* **50**, 280-284 (1982)

J.P. Dalmont and C. Frappé, "Oscillation and extinction thresholds of the clarinet: comparison of analytical results and experiments" *J. Acoust. Soc. Am.* **122**, 1173-39 (2007)

P. Dickens, R. France, J. Smith and J. Wolfe, "Clarinet acoustics: introducing a compendium of impedance and sound spectra" *Acoustics Australia*, **35**, 17-24(2007a)

P. Dickens, J. Smith and J. Wolfe, "Improved precision measurements of acoustic impedance spectra using resonance-free calibration loads and controlled error distribution *J. Acoust. Soc. Am.* **121**, 1471-1481 (2007b)

P. Dickens, J. Smith & J. Wolfe, "Improved method of measuring reflection or impedance spectra using adapted signal spectra and resonance-free calibrations" *Proc. 20th Intl. Cong. Acoust.*, M.Burgess, ed.,Sydney (2010)

N. Dell, R. James, J. Davidson & J. Wolfe, 'The effect of mouthpiece, hand, and mute on the impedance spectra of the horn' *Proc. Int. Symp. Music Acoustics*, Sydney, (2010)

R. Erickson, "General speech: for trombone solo (with theatrical effects)" (Smith publications, Baltimore 1969)

N.H. Fletcher, "Autonomous vibration of simple pressure-controlled valves in gas flows" *J. Acoust. Soc. Am*. 93: 2172-2180 (1993)

N.H. Fletcher, "The didjeridu didgeridoo" Acoust. Aust. **24**, 11–15 (1996)

N.H. Fletcher and T.D. Rossing, *The Physics of Musical Instruments* (Springer-Verlag, New York, 1998) pp. 470-480

C. Fritz, and J. Wolfe, "How do clarinet players adjust the resonances of their vocal tracts for different playing effects?" *J. Acoust. Soc. Am.* **118**, 3306-3315 (2005)

M.S. Mukai, "Laryngeal movements while playing wind instrument" *Proceedings of the International Symposium on Musical Acoustics*, Tokyo, Japan, 239-242 (1992)

Music Acoustics "Didgeridoo acoustics" www.phys.unsw.edu.au/jw/didjeridu.html (2004)

Music Acoustics "Clarinet acoustics" www.phys.unsw.edu.au/music/clarinet/ (2006)

Music Acoustics "Saxophone acoustics" www.phys.unsw.edu.au/music/saxophone/ (2008)

G.P. Scavone, A. Lefebre and A.R. Da Silva, "Measurement of vocal-tract influence during saxophone performance" *J. Acoust. Soc. Am.* **123**, 2391-2400 (2008)

J.R. Smith, N. Henrich and J. Wolfe, "The acoustic impedance of the Boehm flute: standard and some non-standard fingerings" *Proc. Inst. Acoustics* **19**, 315-330 (1997)

J. Smith, G. Rey, P. Dickens, N. Fletcher, L. Hollenberg and J. Wolfe, "Vocal tract resonances and the sound of the Australian didjeridu (yidaki): III. Determinants to playing quality", *J. Acoust. Soc. Am.*, **121**, 547-558 (2007)

A. Tarnopolsky, N. Fletcher, L. Hollenberg, B. Lange, J. Smith and J. Wolfe, J. "The vocal tract and the sound of a didgeridoo". *Nature*, **436**, 39 (2005)

A. Tarnopolsky, N. Fletcher, L. Hollenberg, B. Lange, J. Smith and J. Wolfe, J. "Vocal tract resonances and the sound of the Australian didjeridu (yidaki) I: Experiment", *J. Acoust. Soc. Am.*, **119**, 1194-1204 (2006)

S. Tusch, *A system for measuring impedance spectra in the mouths of brass players*, Practicum project report, The University of New South Wales, Sydney (2010)

T.D. Wilson, *The measured upstream impedance for clarinet performance and its role in sound production*, Ph.D. dissertation, University of Washington, Seattle, WA (1996)

J. Wolfe and J. Smith, "Cut off frequencies and cross fingering in baroque, classical and modern flutes" *J. Acoust. Soc. America*, **114**, 2263-2272 (2003)

J. Wolfe, A.Z. Tarnopolsky, N.H. Fletcher, L.C.L. Hollenberg, and J. Smith, "Some effects of the player's vocal tract and tongue on wind instrument sound". *Proc. Stockholm Music Acoustics Conference (SMAC 03)*, (R. Bresin, ed) Stockholm, Sweden. 307-310 (2003)

J. Wolfe, "Introduction to brass acoustics" www.phys.unsw.edu.au/jw/brassacoustics.html (2005)

J. Wolfe and J. Smith, "Acoustical coupling between lip valves and vocal folds", *Acoustics Australia*, **36**, 23-27 (2008)