# THE PLAYER–WIND INSTRUMENT INTERACTION

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## ABSTRACT

Players control a range of parameters in the player-instrument system. First we show how loudness and pitch vary over the plane of mouth pressure and force on the reed of a clarinet, and thus how these parameters can be used in compensation to produce trajectories in this plane that have varying loudness and timbre but constant pitch. Next we present impedance spectra for several different types of musical instruments and for the vocal tract, to allow general observations. We report different ways in which the acoustic properties of the player's tract interact with those of the instrument bore to control the frequency of reed vibration in some wind instruments. We also show how vocal tract resonances can influence timbre.

## 1. INTRODUCTION

The player often is more interesting than the instrument: in general, a good musician on a poor instrument sounds better than a poor musician on a good instrument. Some of what makes a musician good lies outside the realm of science, let alone acoustics, but acousticians can contribute to understanding good performance by researching the player-instrument interaction, aiming to understand how good players achieve their musical goals. Beyond its intrinsic interest, this has possible applications: an improved and explicit understanding of how good players play could help guide students and teachers.

Some of the player-instrument interaction consists in the former doing something to the latter: pushing the right keys in the right sequence, applying certain values of force with the lips, certain pressures from the lungs, etc. These are of continuing interest in our lab, and we begin by presenting one such set of parameters.

Another part of the player-instrument interaction for wind instruments is directly acoustic in that it involves the acoustics of the player's vocal tract.

### 1.1 The elements

Performance involves the interaction of the principal acoustical elements of the wind instrument–player system: (i) a source of air at positive pressure, (ii) a vibrating element, usually an air jet, a reed or the player's lips, (iii) the downstream duct, *i.e.* the bore of the instrument and (iv) the upstream duct, comprising the player's airway.

Players control all of these: (i) The air pressure and flow are controlled by muscles of the torso and also, in some cases, by the glottis. On the very short time-scale, flow is also controlled in an almost binary fashion by the tongue, which can cease the flow by contact with the roof of the mouth (in gestures like *ta*, *la*, *da*, *ka* etc) or by contact with the reed. (ii) The valves are diverse: Flutists control lip aperture size and geometry. Brass players vary the geometry and mechanical properties of the lips. Reed players choose or make their reeds and vary their mechanical properties with their lips. (iii) The geometry of the downstream duct is varied with valves and slides in brass instruments and by opening or closing covering tone holes in woodwind. (iv) In many cases, players vary the shape and position of the tongue, palate and the opening of the glottis, to control the acoustic properties of the upstream tract.

Two teams discussed the acoustics of the upstream duct at the last SMAC [1,2] and a friendly rivalry began. Scavone [1] presented circuit models of an upstream resonator and a downstream waveguide. We reported results using physical models of the vocal tract and either a cantilever valve or water filled latex 'lips' to represent player's lips [2]. We next used a broad-band signal and the capillary technique to measure the acoustic impedance in the mouth of a player while he played the didjeridu [3]. Later, we applied the technique to saxophone, clarinet and trumpet [4-6]. Meanwhile, Scavone developed a different technique to study the tract involvement: microphones inside bore and mouth give the ratio of the two impedances for harmonics of the note [7]. The two techniques are somewhat complementary and the teams progressed in parallel: Scavone's technique uses the vibrating reed as the (large) signal, which gives large signal:noise ratio and so allows rapid measurements and the ability to track rapid changes in time. However, because it only samples the frequency domain at multiples of the playing frequency, involvement of the vocal tract support must be inferred from a sparse representation (it does not directly measure tract resonances). Our technique gives the impedance spectrum in the mouth but, because our probe signal's energy is spread over hundreds of frequencies, we need windows of tens of ms up to seconds.

In this paper, we review aspects of the musician's control in all four areas and present new work. The review disproportionally cites our own work, in part because the player-instrument interaction has been one of the main lines of research in our lab since the last SMAC.

# 2. COMPENSATING CONTROL PARAMETERS

In many instruments, increasing pressure in the mouth, with all other parameters held constant, changes the pitch. On a recorder, the only parameter that the player can use to control the jet is the mouth pressure. Consequently, it is difficult to play a *decrescendo* on a sustained note without a fall in pitch. Some accomplished players compensate for these pitch changes using the downstream duct by partially opening and closing tone holes.

In other instruments, the effect of changing pressure may be compensated with other parameters to keep the pitch constant. In reed instruments, for a given configuration of the bore, the pitch is also dependent on the forces applied to the reed and to the configuration of the upstream duct. Consequently, a player can play a *decrescendo* at constant pitch by following an iso-frequency contour through the space of control parameters.

The clarinet is the 'lab rat' of wind instruments: many scientific studies and models exist [*e.g.* 8-10]. One way to study control parameters is to measure some of them in the player as in [11] or in a blowing machine, as in [12]. Here we use a systematic study of on how pitch, loudness and spectrum depend on mouth pressure, lip force and reed parameters. To control these parameters and to maintain a constant configuration of the upstream duct, we use an automated clarinet playing system.

## 2.1 The automated clarinet player

The clarinet player was built partly for this purpose [13] and partly for a competition (Artemis International) for such automata. A film clip of the player in concert is at www.phys.unsw.edu.au/jw/clarinetrobot.html. A pump provides air whose pressure is regulated in the long term by controlling the pump and on short time scales via a controlled leak. In this experiment, the reed force was applied by the weight of suitable masses through a soft sorbothane pad, which provided losses somewhat like those from a human lower lip. The reeds are synthetic (Légère, Barrie, Ontario) with 'hardness' ratings 2 and 3.5, the clarinet a Yamaha YCL250 with a Yamaha CL-4C mouthpiece.

## 2.2 Pitch and loudness control

Figure 1 plots the frequency *f* and sound level *L* as functions of the gauge pressure *P* in the 'mouth' and the force *F* applied by the 'lip'. The force is applied at 10 mm from the reed tip. The shaded region represents the parameter combinations that produce notes, except that the upper pressure limit near 7 kPa is imposed by the pump used. The reed has a manufacturer's 'hardness' rating of 2, the note played is F4 (written G4) and the frequencies are a little low because the instrument is playing at 19±1 °C. This note is in the clarinet's 'throat register': it is an octave and a minor third above the lowest note, it is still in the first mode of vibration, and 12 tone holes are open.

Above the shaded region, no sound is produced because the combination of lip force and pressure push the reed closed against the mouthpiece. This extinction line has a negative slope with a magnitude of a few $cm^2$. Left of the edge of the playing region, with a rather steeper slope, either no sound or squeaks are produced. At very low *F*, the damping is insufficient to prevent squeaks: *i.e.* sounds with frequencies close to the resonance of the reed, rather than the resonance of the bore.

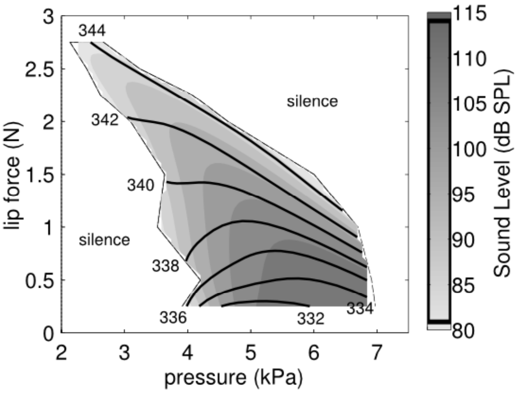

**Figure 1** In the space of pressure in the artificial mouth and force exerted on the reed, we plot frequency in Hz (black lines) and sound pressure level (shading) measured at 50 mm from the bell on the axis of the clarinet.

*f* is higher at higher *F* and also, over most of the playing regime, at higher *P*. The iso-*f* lines have negative slopes of a few $cm^2$ over most of the playing regime. This is qualitatively explained by a simple effect: Both *F* and *P* tend to close the reed against the mouthpiece, which reduces the compliance of the air in the mouthpiece and also the effective compliance of the reed. This raises the frequency of the peaks in the parallel impedance of reed and bore.

Figure 1 shows that, over part of the range, a player could vary sound level and constant frequency by blowing harder and making a compensating reduction in lip force, and adjusting no other parameters. At high *P* and *F*, however, the iso-*f* lines and the iso-*L* contours are nearly parallel. So, if no other control parameters were used, the player would need to fall to a lower pitch (by relaxing the jaw (lower *F*)) to play more loudly. Going flat when playing loudly is a fault often identified by clarinet teachers.

In most instruments, vibrations of increased amplitude produce greater nonlinearities in the valve, with the consequence that the amplitudes of higher harmonics increase more rapidly than those of the fundamental. A simple quantification of this is the spectral centroid, the frequency weighted average of the amplitude of all spectral components. The spectral centroid is strongly correlated with the perceived brightness of timbre. Contours of the spectral centroid on the *P*,*F* plane have shapes similar to those of sound level (data not shown).

F4, the note shown in Figure 1 is one of the easiest to sound on the clarinet. For notes one octave below and one octave above, the playing regime is rather smaller. Lip force application at 10 mm from the reed tip facilitates sound production: in experiments with the lip force applied 5 mm either side of this position, the playing regimes are smaller. Finally, in similar experiments using a stiffer reed, the results are qualitatively similar, but notes are only produced in the higher range of *F*, above about

3 N. Space precludes including these data here: they have been submitted for publication elsewhere [14].

# 3. THE UPSTREAM AND DOWNSTREAM DUCTS

In some cases, there is a limited symmetry between the two ducts [15]. Call the total and acoustic pressures immediately upstream from the reed, inside the player's vocal tract, $P_{\mathrm{mouth}}$ and $p_{\mathrm{mouth}}$ and use the subscript bore for those immediately downstream, in the duct provided by the instrument. A clarinet reed tends to bend inwards towards the mouthpiece, thus tending to close the flow pathway, when the pressure difference $P_{\mathrm{mouth}} - P_{\mathrm{bore}}$ is positive. Under some playing conditions, $P_{\mathrm{mouth}} - P_{\mathrm{bore}}$ acts to bend a brass player's lips outwards into the instrument, opening the flow pathway [16,17]. Defining the acoustic impedances $Z_{\mathrm{mouth}}$ and $Z_{\mathrm{bore}}$ as $p/U$, where $U$ the acoustic volume flow into the duct then, if the flows out of the mouth ($-U_{\mathrm{mouth}}$) and into the instrument ($U_{\mathrm{bore}}$) are equal, say $U$, then $p_{\mathrm{mouth}} - p_{\mathrm{bore}} = -UZ_{\mathrm{mouth}} - UZ_{\mathrm{bore}} = -U(Z_{\mathrm{mouth}} + Z_{\mathrm{bore}})$. In words, $Z_{\mathrm{mouth}}$ and $Z_{\mathrm{bore}}$ are in series with regard to the mechanisms described. It is therefore worth comparing and contrasting the impedance spectra of some of the ducts involved, which we do in the next section.

It can also be shown that the passive impedance of a reed or lip is in parallel with the series combination mentioned above. Further, the pressure difference $P_{\mathrm{mouth}} - P_{\mathrm{bore}}$ across the valve is not the only source of force acting to open or close it: for instance, the dynamic or 'Bernoulli' pressure $\frac{1}{2}\rho v^2$ can also play a role, so the two ducts are not necessarily in series with respect to all possible regeneration mechanisms in the valve.

## 3.1 Impedance measurements

With one exception, the impedance spectra shown in Figure 2 are made using the three-microphone technique calibrated with three non-resonant loads, one of which is an acoustically infinite duct [18]. The smallest microphone spacing in this impedance head is 40 mm, which limits the frequency response to about 4 kHz. The lower limit is about 10 Hz, giving a range of 9 octaves. The use of non-resonant calibration loads and the iterative optimisation of the measurement signal together allow a dynamic range of more than 90 dB. The frequency resolution depends on the period of the measurement signal.

## 3.2 Ducts, resonances and antiresonances

Figures 2, 3 and 4 show the impedance spectra $Z$ of some simple ducts, several instruments and a vocal tract, to allow some general discussion. Figure 2 shows the measured impedance spectra of a number of ducts. (a) shows the impedance of an open cylinder with an internal diameter of 15 mm. (b) shows an open cone with a half angle of 1.74° (equal to that of a soprano saxophone) [19]. The cone is truncated at the small (input) end to allow flow into the cone via the impedance head used to measure it, and the truncation replaced with a cylinder of equal volume. Their effective lengths are 325 mm, chosen so that the first maximum in $Z$ of the cylinder occurs at C4 and the first minimum at C5.

## 3.3 The downstream duct: woodwinds

The player's control of the downstream duct often involves complicated co-ordinations, such as manipulating different keys in the same transition. Departures from simultaneity are sometimes systematic [20], which raises interesting acoustic and pedagogical questions, which we shall not pursue further here, but instead concentrate on quiescent states.

Below the cylinder in Figure 2 we show $Z$ for a flute [21] and clarinet [22], whose bores include cylindrical sections. (To save space, phase is not shown for these curves.)

The array of open tone holes creates a cut-off frequency, which is about 1.5 kHz for the clarinet. Below this frequency, sound waves are reflected at a point near the first of the open holes. Well above this, they travel down the whole length of the bore, which explains why the spacing of the peaks in $Z$ decreases above that frequency. That cut-off for the flute is around 2 kHz but the more closely spaced peaks are less evident, because at several kHz the bore is short circuited by a shunt provided by the Helmholtz resonator in the head joint [21].

The observation that there is only a little similarity between $Z$ for these instruments and that for a cylinder explains why highly simplified models fail: for example, the statement that clarinets have weak even harmonics is not usually true.

Below the cone are shown $Z$ for soprano and tenor saxophones [19]. The soprano sax, the clarinet, the flute and the two simple geometries all have the same effective length, so all play C5 in this configuration (dashed circles) except the clarinet, which plays C4.

The tenor saxophone is shown on an expanded scale to show that it is roughly a 1:2 scale model, playing an octave below, although the cone half-angles are different: 1.74° and 1.52° respectively.

For the saxophones and clarinet, the dotted line shows the bore impedance in parallel with the compliance of a typical reed. This is important in intonation: a soft reed (as much as twice the compliance used here) lowers the peak of the parallel impedance and the instrument would play flat unless the tuning slide were shortened.

Note that the saxophones have only two large peaks in $Z$. The clarinet has three and, above the cut-off frequency, further sharp peaks, whose narrower frequency spacing indicates that they are standing waves over the whole length of the bore. The conical bores of saxophones give little reflection for high frequencies, and so only weak standing waves. As we'll see later, this makes the vocal tract especially important for the high range of the saxophone.

## 3.4 The downstream duct: lip valves

The $Z$ for four lip valve instruments are shown in Figure 3. (To conserve space, phase is not displayed.)

The first is a didjeridu. The first several extrema are qualitatively consistent with a slightly flared duct, as the

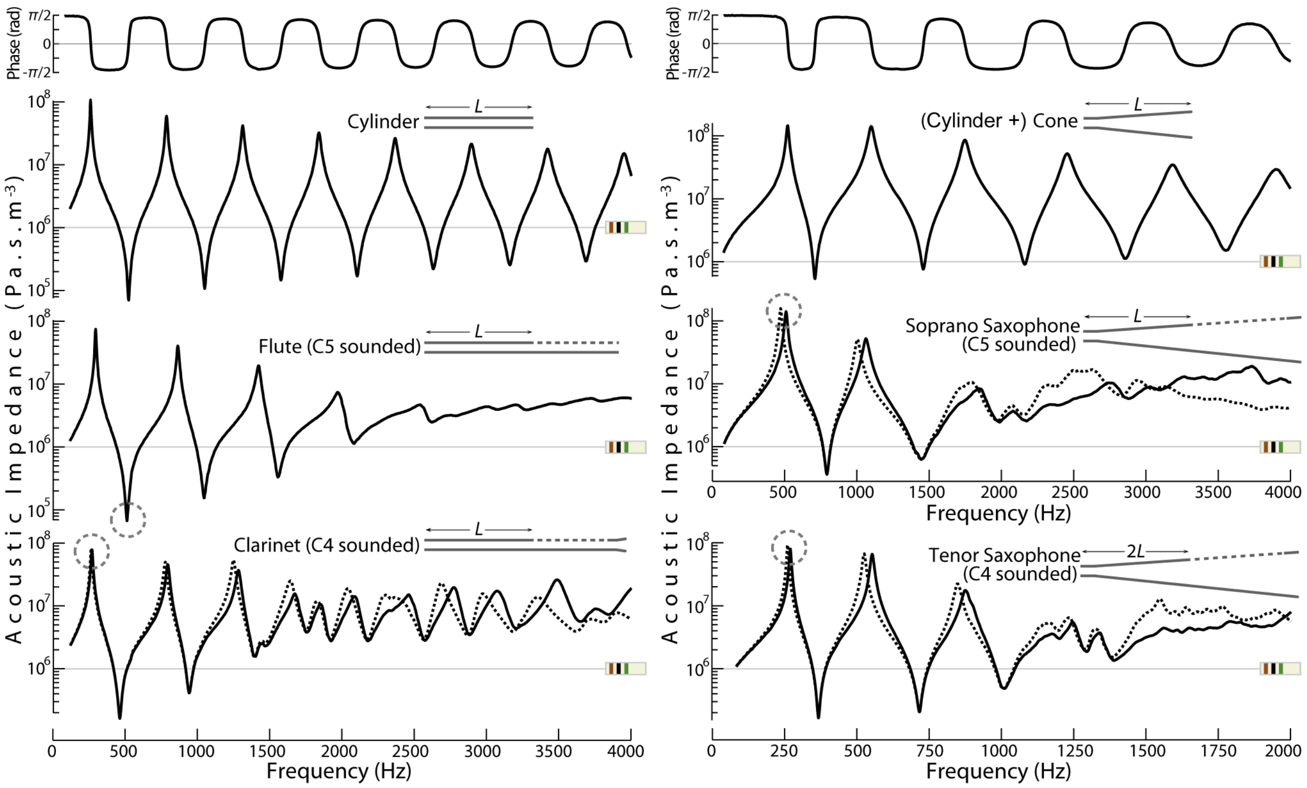

**Figure 2**. Impedance spectra. At top, a cylinder (left) and a truncated cone (right). These have the same effective length as the flute and soprano saxophone (fingering for C5) and the clarinet (C4). The tenor saxophone has the same fingering as the soprano but is plotted on an expanded frequency axis to show that it is roughly a 1:2 scale model. (Some phase plots are omitted to save space.)

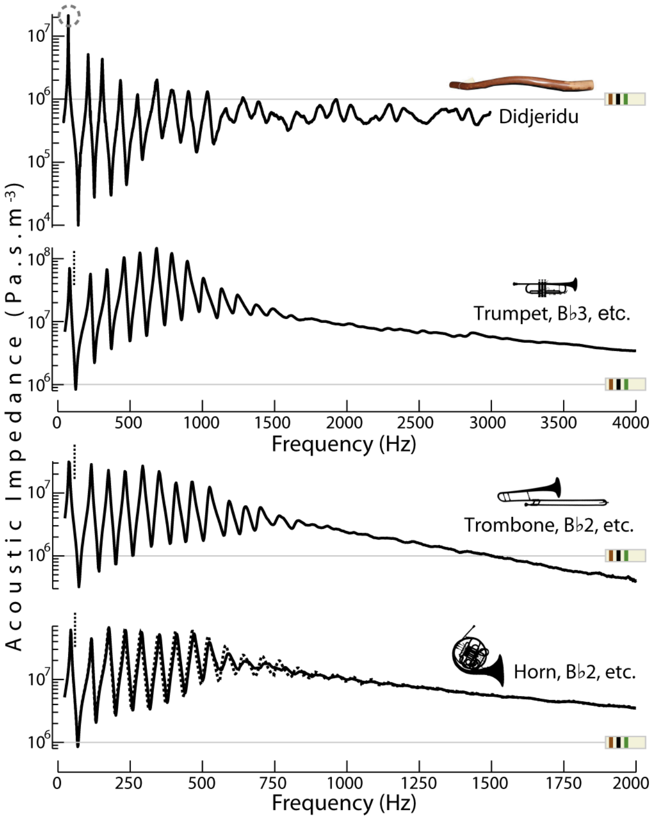

**Figure 3**. Impedance spectra of lip-valve instruments: a didjeridu, trumpet, trombone and horn: the last two on expanded scales as they are approximately 2:1 scale models of the trumpet. On Figures 2, 3 and 4, the 1 MΩ line is marked.

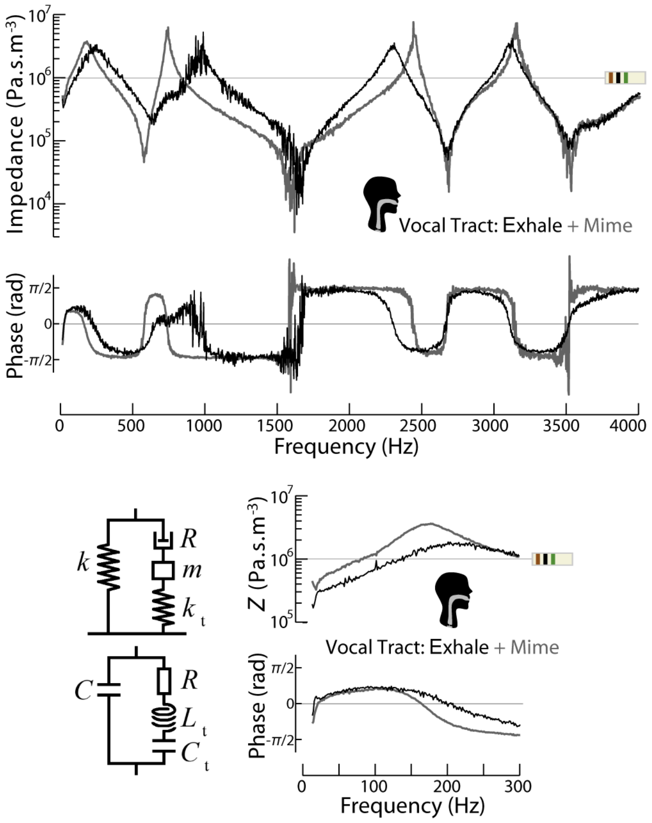

**Figure 4**. Impedance spectra of a vocal tract measured at the lips over 370 ms: glottis closed (pale) and exhaling (black). The compact-object equivalent circuit is shown next to the plots of low frequency behaviour on an expanded axis.

outer shape suggests. The impedance peak at which it plays is indicated (dashed circle). The irregular features in *Z* and the absence of strong resonances at high frequencies are due to the irregular interior, which is made by termites in a branch or trunk of a eucalypt tree.

The *Z* for trombone (slide in) and horn (B♭ side, no valves depressed) are shown on an expanded scale to show that they are, very approximately, scale models of the trumpet (no valves depressed). In all three cases, the cut-off frequency is provided by radiation from the bell, which becomes important when the wavelength is comparable with the radius of curvature of the bell. For the horn, the hand in the bell (dotted line) reduces the efficiency of radiation and so raises the cut-off frequency and the height of the higher frequency peaks.

The three brass instruments each have about 10 or 12 impedance peaks. Starting from the second, these are approximately equally spaced. In this configuration, notes near all of those peaks are played. They correspond to a harmonic series whose fundamental is half the frequency of the second peak. A note with that pitch can be played as a pedal note (dashed vertical line). (The first peak, well below the pedal pitch, is not played.)

Comparing these plots, we might expect that considerably more control over the valve is required of a brass player, whose impedance peaks are more closely spaced. In contrast, when the saxophonist and clarinetist wish to use the second (or third), weaker peak, they can simply use register key(s) to weaken and to detune the lower peak(s).

### 3.5 The upstream duct: the vocal tract

Figure 4 shows *Z* for a vocal tract. The impedance head has a diameter of 26 mm and the lips are sealed around that, as described in [23]. The tongue is in the position to pronounce /əː/ as in 'heard'. For the grey curve, the glottis is closed, so there is no DC flow. For the black curve, the subject is exhaling into the impedance head, which has a downstream vent for this purpose.

Nine octaves covers the first five resonances. Because of the long period of the first resonance, the measurements were made over a single window of 370 ms (= $2^{14}$/44.1 kHz). For the exhalation case, this shows a measurement limitation: noise due to the turbulent air flow is superposed over the broad-band measured signal. Integration over longer time-scales can improve this, but the subject must sustain the gesture for longer.

Opening the glottis (going from a closed to a somewhat open pipe), one expects extrema in impedance to rise slightly in frequency. For example, whisper uses a larger glottal opening than normal speech, and measurements of the tract resonances from normal phonation to whisper in the same gesture show an increase in frequency [24]. The measurements in Figure 4 were not measured in the same gesture, so other geometrical changes may also contribute, particularly at high frequencies. It is believed that players use a slightly open glottis [25], so a playing configuration could be between these two conditions.

If the vocal tract were a rigid cylinder, 170 mm long and closed at the glottis, we should expect minima at 0.5, 1.5, 2.5 and 3.5 kHz, and maxima at about 1, 2 and 3 kHz, which is roughly what we observe.

In a closed, rigid cylinder, *Z* would be very large at very low frequencies. Human tissues are not infinitely rigid, of course, and this gives rise to the zeroth minimum and maximum, shown in the inset in Figure 4. The maximum at about 200 Hz is due to the mass of the tissue surrounding the tract and the 'spring' of the air inside it, which is approximately a compact object at this wavelength (2 m).

The minimum at about 20 Hz is due to the mass of the tissue and the 'spring' of its own elasticity. Because the two resonances are three octaves or more apart, impedance maxima and minima occur at $\omega \sim 1/(LC)^{1/2}$ and $1/(LC_t)^{1/2}$ respectively, where $L$ is the inertance of the tissue, $C_t$ the compliance due to the supporting tissues, and $C$ the compliance of the air in the upper tract. Taking a volume of 100 ml for the air in the tract and a surface area of the surrounding tissues of $10^{-4}$ m$^2$, $L$ gives a tissue thickness of ~1 cm and $C_t$ a spring constant of ~1/N.cm$^{-1}$.

### 3.6 Varying the resonances of the upstream duct

How much can the upstream resonances be adjusted by articulation? Opening and closing the glottis makes little difference at high frequency, because the inertance of air in the glottis effectively seals it. Of course, other geometrical changes associated with this variation also may make a difference. In speech, the first resonance is varied primarily by varying the opening at the lips, which connects the tract to the very low impedance of the radiation field. This option is not available to reed and brass players, whose mouths make an airtight seal to the instrument. So the first resonance cannot be varied much and, in our measurements on a range of instruments, we usually see an acoustic maximum between about 200 and 400 Hz, and a minimum a few hundred Hz above that.

The shape of the vocal tract can be used to adjust the resonant frequencies. This is most effective once the half wavelength becomes comparable with the length of the upper vocal tract – when the frequency approaches 1 kHz, but even the first maximum can be varied. As a general rule: a constriction near a pressure node lowers the frequency while one near a pressure antinode raises it.

Let's compare the magnitudes of impedance peaks in figures 3, 4 and 5: those in the vocal tract, with jaw low and tongue neutral, are several MΩ. This already approaches the values of the instrument impedance at high frequency. Further, players can raise this value by raising the tongue near the instrument, which makes the front of the mouth act like an impedance matching cone and produces rather higher impedances, as we shall see. It is easier for an impedance peak in the tract to compete with one in the bore at high frequencies, where the bore resonances are weaker.

## 4. VOCAL TRACT EFFECTS

### 4.1 Tract-bore series combination can control pitch

A reed and the air that flows past it are driven by the pressure difference between mouth and bore, which means that, as described above, the tract and bore act in series.

For the saxophone, this solves a problem: Figure 2 shows that, because of effective radiation and weaker reflection from the large end of the cone, the instrument's *Z* has only two strong impedance peaks. Although the first register is extended downwards in pitch with the use of extra keys, and the second similarly upwards, the range of the instrument using these first two peaks is just 2 octaves and a musical fifth.

Figure 5 contrasts the situation for a note, G4, in the second register of a tenor saxophone and A#5, in the *altissimo* range. Even beginners can play the first note, with relatively little attention to control parameters. The *altissimo* notes require expertise, because they are only possible when a large amplitude peak in $Z_{\mathrm{mouth}}$ is produced and tuned to select one of the instrument's weaker high resonances [4].

Advanced saxophonists can also use large magnitude peaks in $Z_{\mathrm{mouth}}$ to select and to adjust the amplitude of notes in mulitphonics (chords) and also to 'bend' the pitch of notes [26].

Because its bore is partly cylindrical, the higher resonances in the clarinet produce stronger peaks in $Z_{\mathrm{bore}}$ (Figure 2), so less assistance from the upstream duct is required for altissimo playing. However, like saxophonists, clarinetists use peaks in $Z_{\mathrm{mouth}}$ in multiphonics and in pitch bending, including the famous *glissando* in *Rhapsody in Blue* [5].

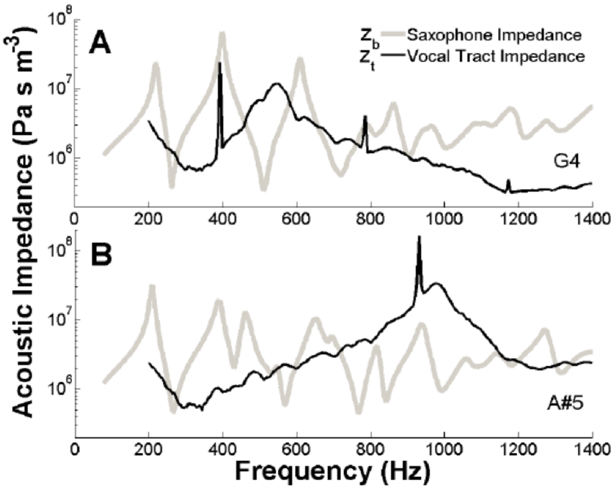

**Figure 5**. The bore (grey) and vocal tract impedance (black) for two notes played on a tenor saxophone. The narrow peaks are harmonics of the notes played. G4 is in the instrument's second register. A#5 is in the *altissimo*, and is accessible only by tuning a peak in $Z_{\mathrm{mouth}}$ to select one of the weak, higher resonances. Reproduced from [4].

Figure 6 shows the vocal tract resonances of saxophonists, clarinetists and trumpeters. In the normal range of the saxophone, neither advanced nor less advanced players show tuning of peaks in $Z_{\mathrm{mouth}}$ to the played note. In the *altissimo* range, however, peaks are tuned either to or slightly above the note to be played and those unable to do this cannot play in this register.

For clarinetists, peaks in $Z_{\mathrm{mouth}}$ are tuned to the note to be played during pitch bending. In normal playing, however, peaks in $Z_{\mathrm{mouth}}$ are tuned a couple of hundred Hz above the note to be played, which means that the upstream impedance is inertive [5].

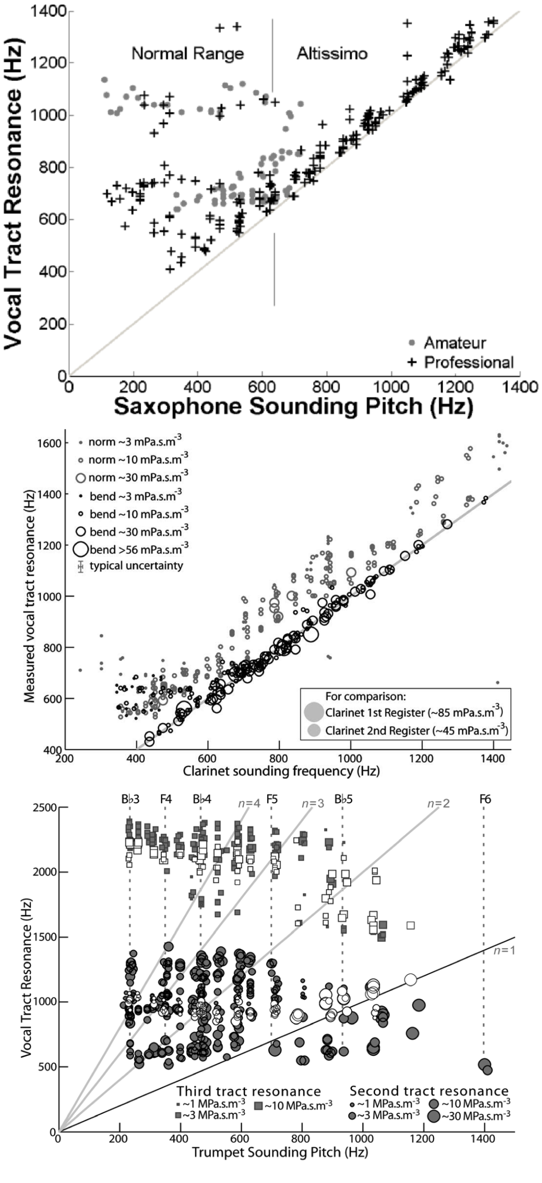

**Figure 6**. Vocal tract resonance frequency against pitch frequency. Top: tenor saxophone in normal (left) and altisimo ranges, showing resonance tuning in the latter. Middle: clarinet pitch bending (black) and normal playing (gray): resonance tuning for pitch bending, and the resonance held somewhat above the pitch in normal playing. Bottom: the seven trumpet players in this study show no consistent resonance tuning. Reproduced from [4,5,6].

What about trumpet players? Some players can play in the upper part of the third octave, where the peaks in peaks in $Z_{\mathrm{bore}}$ are weak. Do they tune a peak in peaks in $Z_{\mathrm{mouth}}$ to assist playing in this *altissimo* range? When we started this study [6], we expected to find vocal tract tuning like that of saxophonists. But the answer, in general, is no. Figure 6 shows no consistent tuning by the seven players in our study.

So, what are the effects of $Z_{\text{mouth}}$ in players of brass and other lip-valve instruments? At the previous SMAC, we presented Figure 7, the results of a trombone-playing system using, as the 'lip-valve', an outward swinging cantilever spring with a mass added to give a suitable natural frequency. Upstream, we used different shaped simple cavities as models of the mouth with tongue low in the mouth and high in the mouth. The trombone slide was then moved into its standard positions for notes on the chromatic scale. While the valve operated on the same peak in $Z_{\text{bore}}$ (i.e. played in the same register), the pitch decreased by approximately a semitone for each step increase in the slide position, as expected. Depending on the natural frequency of the valve, the system would jump from one register to the next at a particular position.

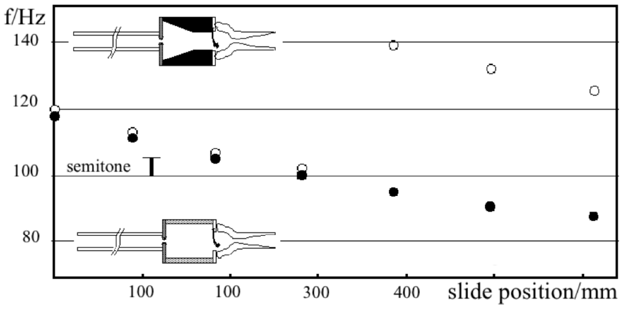

**Figure 7**. A trombone is 'played' with different slide positions by an artificial valve with two upstream cavities with different shapes.

Without the constriction in place ('low tongue'), the system played the same register flatter than with the constriction in place ('high tongue'). Further, the jump between registers occurred at lower pitches without the constriction. This is consistent with players' observations that lowering the tongue either lowers the pitch slightly or else causes the instrument to jump to a lower register. More recent measurements of the player-trombone interaction are given in another paper in this volume [27].

### 4.2 Vocal tract interactions with higher harmonics

In the saxophone and clarinet, impedance peaks in $Z_{\text{mouth}}$ can contribute to reed vibration, either on their own or in collaboration with peaks in $Z_{\text{bore}}$. Peaks in $Z_{\text{mouth}}$ can also, of course, inhibit acoustic flow. Which of these applies?

Players of various wind instruments report that they use different configurations of the vocal tract to control timbre. This is most spectacularly evident on the didjeridu, an indigenous Australian instrument, which is played almost entirely at its lowest resonance. Its musical interest comes from rhythmic variations in timbre produced, *inter alia*, by varying vocal tract shapes, including those used for the cyclic breathing that allows the didjeridu to be played continuously without pauses for breath.

At the last SMAC, we also presented this sound file www.phys.unsw.edu.au/jw/sounds/dij_trombone.wav. It was produced by a pair of artificial lips (water-filled latex cylinders) with a cylindrical pipe downstream modelling the didjeridu. Upstream was a model vocal tract with continuously variable resonances.

Figure 8 shows the spectrum of sound radiated from a cylindrical pipe being played as a didjeridu by a human player. While the subject played, a small impedance head placed between the lips measured $Z_{\text{mouth}}$ using the capillary method. On the same figure, vertical tics indicate the harmonics of the note played and the resonances of the pipe. Unlike a typical clarinet note, the first eleven odd harmonics in this note really are all weaker than their even neighbours, though of course this is not the case with a real didjeridu. The spectral envelope shows minima around 1.5 and 2 kHz. The lower part of the figure shows that $Z_{\text{mouth}}$ has maxima at these frequencies: at these frequencies, very little current can pass between the lips, so there is little power input to the instrument, and so little power in the radiated sound.

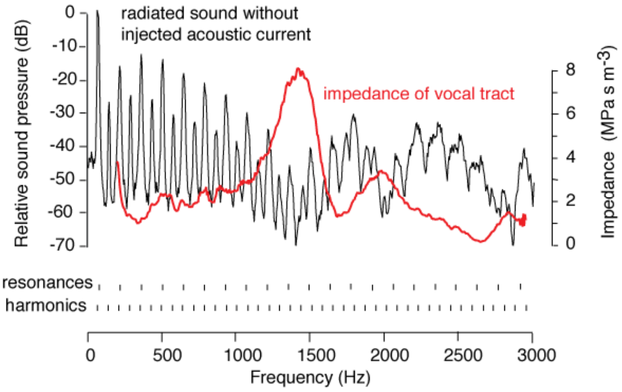

**Figure 8**. A cylindrical pipe played like a didjeridu. The spectrum of the radiated sound, the frequencies of the pipe resonances and the harmonics and the impedance spectrum of the vocal tract.

The didjeridu has no constriction comparable to that in the mouthpiece of a typical brass instrument and the magnitude of its $Z_{\text{bore}}$ is, overall, rather less than those of typical woodwind or brass instruments (see Figures 2-4). Are similar effects observed on other wind instruments? In other papers in this volume, we report $Z_{\text{mouth}}$ measurements for the saxophone and the trombone [27,28].

## 5. CONCLUSIONS

Players must simultaneously control several parameters simultaneously in order to produce desired contours of pitch, loudness and timbre. Features of the acoustic impedance of the vocal tract contribute to pitch, especially when an impedance peak lies near the playing frequency, and to timbre, when peaks fall close to higher harmonics.

### Acknowledgments

We thank the Australian Research Council for support, Yamaha for instruments and our volunteer subjects.

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