How do clarinet players adjust the resonances of their vocal tracts for different playing effects?

Claudia Fritz * and Joe Wolfe

UNSW, School of Physics, NSW 2052 Sydney, Australia

Abstract

In a simple model, the reed of the clarinet is mechanically loaded by the series combination of the acoustical impedances of the instrument itself and of the player's airway. Here we measure the complex impedance spectrum of players' airways using an impedance head adapted to fit inside a clarinet mouthpiece. A direct current shunt with high acoustical resistance allows players to blow normally, so the players can simulate the tract condition under playing conditions. The reproducibility of the results suggest that the players' "muscle memory" is reliable for this task. Most players use a single, highly stable vocal tract configuration over most of the playing range, except for the altissimo register. However, this "normal" configuration varies substantially among musicians. All musicians change the configuration, often drastically for "special effects" such as glissandi and slurs: the tongue is lowered and the impedance magnitude reduced when the player intends to lower the pitch or to slur downwards, and vice versa.

PACS:43.75.Pq, 43.75.Yy, 43.75.St, 43.58.Bh

1 INTRODUCTION

Acousticians (Backus [1], Benade [2], Hoekje [3], Johnson et al.[4], Wilson [5]) are divided over the extent of the influence of the respiratory tract in playing reed instruments, of which the clarinet is the most studied example. The reed and the airflow past it interact with acoustical waves in the bore of the instrument and with waves in the player's tract. A simple argument shows that the acoustical impedances of these are approximately in series[2]. The cross section of the clarinet bore is rather smaller than that of the tract, so its characteristic impedance is higher. Further, the resonances in the instrument have a high value of quality factor, so the peaks in

---

*Current address: LIMSI-CNRS, BP 133, 91403 Orsay, France; Electronic mail: claudia.fritz@ens-lyon.org

impedance have high value and, to first order, usually determine the playing regime of the bore-reed-tract system [6]. Nevertheless, the effects of the impedance spectrum of the vocal tract, even if smaller than those of the clarinet, may be important, because musicians are often interested in subtle effects. For instance, a 1% change in frequency could be a large mistuning for a musician, and subtle changes in the spectral envelope may be important in controlling timbre and musical expression. Most researchers agree that the effect is small but important - even if they do not necessarily agree about how the vocal tract affects the sound production - except for Backus who considers that the player's tract has a negligible influence on the instrument tone.

Strictly speaking, it is the impedance of the entire airway of the player, from mouth to lungs, that loads the reed or lips and that drives the air flow past them. However, Mukai [7] reported that experienced players of wind instruments keep the glottis (the aperture between the vocal folds) almost closed when playing. This is very important to the possible influence of the tract: with an open glottis, the airway has relatively weak resonances, because it is terminated with the high losses in the lungs and lower airways. In contrast, an almost closed glottis provides a high coefficient of reflection for acoustic waves at all but the lowest frequencies, and so would be expected to give strong resonances, similar to those that give rise to formants in speech. For that reason, we shall refer hereafter to the player's vocal tract as the resonator that is controlled by the player.

Impedance measurements have been made previously (Benade [2], Backus [1], Hoekje [3] and Wilson [5]) but are not fully exploitable or applicable due to the fact that they either were performed under conditions that do not closely resemble those used to play an instrument, or that they lacked phase information, or contained high levels of background noise. Moreover, they were made in most cases on only one subject. The measurement conditions should reproduce, as much as possible, the playing condition, so that the player can automatically adopt the tract configurations used in playing under particular conditions. For example, Benade [2] measured the impedance of a clarinettist's tract by inserting into the player's mouth a pipe containing the acoustical source and the microphone. The pipe inner diameter was 20 mm, which forces the player to open the mouth considerably more than he would when playing a clarinet. This problem was solved by Hoekje [3], who used a similar arrangement, with the exception that he reduced the size of the part which goes into the musician's mouth. Overall, Hoekje measured somewhat low values of the impedance (maxima about 8 MPa.s.m^{-3}), therefore much smaller than the maxima measured for the clarinet using most fingerings (Wolfe *et al.* [8], Backus [9]). This may be explained by the fact the player could not breathe into the apparatus, nor was the glottis aperture monitored. It is likely, therefore, that the subject may have relaxed the glottis, and thus reduced the magnitude of the airway resonances, as discussed above. This is the case too with Backus [1]'s measurements which only give a maximum magnitude of 5 MPa.s.m^{-3}. That would explain as well why he reported that the values he obtained could not be consistently reproduced, as a musician cannot be consistent with his glottis if he cannot blow. Moreover, all these studies only give the amplitude of the impedance but not the phase. Wilson [5] measured the complex impedance in a situation in which a clarinettist could mime playing while exhaling, in order, to her opinion, to keep the glottis open (so in contradiction with Mukai's cliches). These measurements were made with a chirp of one third of a second duration, and so have a relatively high noise component. The performers were three professional clarinettists and two advanced amateurs. She was also able to obtain values for the impedance during playing at the frequencies of the harmonics of the note played. These are interesting values but, because they are widely spaced in frequency, the give little information about the tract configuration and few data for numerical simulations. There may have been problems in consistency, because the two methods did not always give similar results.

It has not yet proved possible to make accurate impedance measurements in the vocal tract during playing because of the very high sound levels produced by the reed. (The acoustic current produced in the tract by the reed is comparable with that produced in the clarinet, so peak pressure levels are high.) Consequently, it is still necessary to measure clarinettists miming playing. In our measurements reported here, a direct current shunt was placed in parallel with the impedance head, to allow the players to blow normally, and so to adopt a tract configuration approaching that used for playing.

Our measurements were done on professional clarinettists and advanced students. They were asked to play notes on their own clarinet, set up for normal playing, and then to mime playing on the instrument containing the impedance head. Notes over the range of the instrument were chosen, and players were asked to play and to mime a range of conditions requiring different embouchures to adjust the intonation or register, or to produce other effects.

2 MATERIALS AND METHODS

2.1 The impedance spectrometer

The setup is based on the impedance spectrometer developed previously [10], which uses a source of acoustic current produced from an output with high acoustic impedance (see FIG. 1) and which is calibrated using an acoustically infinite waveguide as the reference impedance. This reference is a straight, cylindrical stainless steel pipe, 7.8 mm in diameter and 42 m long, so that echos, in the frequency range of interest, return attenuated by about 80 dB or more. Several compromises were made to incorporate an impedance head of this type into the clarinet mouthpiece so that it can measure the impedance that loads the clarinet reed without disturbing the player.

A range of impedance heads and (cylindrical) reference waveguides are available. For this experiment, we chose to use one with diameter 7.8 mm, because it yields a cross sectional area comparable with that of the effective surface area of the reed protruding past the lower lip inside the mouth. Such an impedance head was mounted inside a modified clarinet mouthpiece as is shown in FIG 2. The angle is chosen so that the head passes through the upper surface of the mouthpiece just beyond the point where the player's teeth rest and meets the lower surface at the position of the reed tip. The end of the attenuator (the current source) and a small microphone

(Countryman CAI-B6 miniature B6, diameter 2 mm) positioned $l = 9$ mm from the end of the head, and the impedance at the end is calculated using the transfer matrix for a cylindrical waveguide.

This angle produces an elliptical area at the end of the measurement head. For calibration, this was simply sealed on the circular area of the reference waveguide, with the centers aligned. Several other geometries were also tried: one used a bent waveguide between the measurement plane and the reference plane. Another used straight tubes as here, but the extra volume at the ends of the ellipse were filled with modelling compound. To estimate the effect of the discontinuities thus produced, the impedance was measured for a range of waveguides with simple, known geometries (cylindrical pipes of different diameters and lengths), for which the impedance is known from other measurements to agree well with theory. The most successful fits were obtained from the geometry shown: the simple straight impedance head with the open elliptical end. For pipes of same diameter as the head, the comparison between the measurement gives an error of 1% in frequency and up to 20% in amplitude at high frequency.

The mouthpiece was sealed with epoxy so that the measurement head is connected only to the player's tract and not to the clarinet. In any case, the position of the head, which should measure the impedance in the plane of the reed near its tip, prohibits the installation of a reed. Preliminary experiments showed however that musicians could reproduce embouchures that had very similar acoustic impedance spectra. This suggested that they have a high developed sensory or muscle memory and can mime easily a configuration that they use regularly. This is not surprising: it is presumably what they must do normally before playing in order to have the desired pitch and timbre from the beginning of their first note. However, players are not usually aware of the position of the vocal folds and the glottis and so, if they are not blowing air, they may close them or relax them. For that reason, a shunt with a DC impedance, judged by a clarinettist to be comparable with that of a clarinet under normal playing conditions, was introduced to allow subjects to blow normally. A small pipe (40 mm long and 3 mm diameter) was positioned to provide a shunt or leak from the mouth to the outside air. Its short length ensured that resonances and antiresonances fell beyond the frequency range of interest and measurement, its diameter ensures that its characteristic impedance is between 10 and 100 times larger than the maxima in the vocal tract impedance with which it is in parallel, and it was filled with acoustic wool which makes the impedance largely resistive, reduces the turbulent noise due to flow and provides a DC resistance comparable to that of a real clarinet.

To prevent water condensation in the measurement apparatus, a low voltage electrical circuit was used to raise the temperature of the impedance head to 40°C.

2.2 Procedure

Seventeen players took part in the experiment and their musical level varied between advanced student and professional. They first answered a survey about their musical backgrounds and their opinions about the influence of the vocal tract when playing. Throughout all measurement sessions, a digital audio tape recorder was used to record players comments and played sounds. The microphone was positioned 10 cm from the bell.

For measurements, each player was asked first to play a note *mezzo forte* on his/her own clarinet, and then to mime playing the same note on the modified clarinet. The notes, selected after discussion with clarinettists, were (written) G3, G4, G5 and G6. G3 is close to the lower end of the instrument range and uses almost the full length of the nearly cylindrical part of the bore. It is a good example of a note in the chalumeau register. G4 use the fundamental mode of a relatively short section of the bore: it is an example of a note in the throat register. G5 uses the speaker or primary register key and the second resonance of a medium length tube: it is an example of the clarion register. G6 uses two open register holes and is an example of a note in the altissimo register.

The subjects then played and mimed some unusual embouchures: some peculiar configurations such as pitch bending (lowering the pitch without changing the fingering), slurring a register change and embouchures of their own suggestion used for different playing conditions. They were also asked to mime embouchures described in terms of vowels (in particular "ee" and "aw"), a description used by some clarinettists. For the slurred register change, the musicians were asked to mime over 5 seconds what they usually do less than a second, during the transient between two notes.

The measurements were made over the range 0.1-3 kHz, which includes the playing range of the instrument. In this range, there are usually three vocal tract resonances, at typically 0.3, 1.3 and 2.3 kHz, although the frequency varies among different players and playing conditions. The sampling in the frequency domain was chosen as a compromise between a high signal to noise ratio and precision in frequency. The frequency resolution was set at 5.4 Hz. The measurement time was set at 10 seconds (except for some unusual embouchures) as it is tiring and hard for a musician to hold a constant embouchure longer.

3 RESULTS

3.1 The survey

Except from one amateur player, all the participating musicians consider that their vocal tract has a very important influence on the timbre. Regarding the pitch, four of them think that the vocal tract is important whereas the thirteen others regard it as very important.

For more specific details, we shall only quote here the musicians who were the most able to describe their own utilisation of the vocal tract. We shall retain their own vocabulary, which often corresponds to mental and musical images. Some of the subjects, with busy schedules as performing musicians, had done no teaching for many years and were therefore not in the habit of describing what they do with the mouth.

Player B, a very experienced music teacher, reported having reflected at depth on what she does in order to explain it to her pupils. She changes the vocal tract shape for:

- note bending (i.e. adjusting the pitch using the mouth, rather than keys on the instrument);
- changing tonal colours to give character to interpretations. For that effect, she especially uses two configurations. In one, which she names for the vowel in "hee", she reports that she has the back and middle tongue in a high position, increased lip tension, the soft palate is lowered and the throat somewhat closed. This embouchure she uses and recommends for for brightening the sound. In another named for the vowel in "haw", she reports a high soft palate, the back of the tongue lowered and the throat more open. This she recommends and uses for darkening the timbre;
- for changing articulation : the tongue has to be as close as possible to the tip of the reed to have a light articulation. So the "hee" configuration is usually more appropriate than the "haw" one.

Her tongue touches the lower lip but not usually the lower teeth. The tongue can actually touch the lip/teeth in low or clarion register but not in altissimo register. It is in general between 1 and 2 mm away from the teeth.

Player D, another experienced player and teacher reported lifting the soft palate in order to obtain more resonance and projection which, she said, induces a richer sound. She reports that her tongue touches neither the lower teeth nor the lower lip, and is in different positions according to the register:

- for the low register, the tongue is low and arched, 1 cm away from the lip
- for the high register: the tongue is higher in the mouth, moves a little forward (about 8 mm away from the lip), becomes wider and flattens.

One advanced student, player H, prefers having the tongue high in the mouth so the sound is more "focused". He uses changes in the vocal tract for register change, large intervals, pitch bend and multiphonics.

Player C, a very experienced professional player, reported that he enriches the sound in high harmonics by opening the oral cavity. Further, he "opens the throat", but not necessarily the glottis, when he descends a register. Above all, however, he reports using his facial muscles in order to modify the embouchure.

Another very experienced professional player, player A, imagines, when playing, "focussing the sound through the nose". She has the impression that the more her soft palate is arched the more the sound is "focussed". (It should be remarked that the velum must be closed or very nearly closed during clarinet playing, to avoid a DC shunt through the nose that would prohibit playing. However, the muscular tension in the velum could in principle affect the impedance spectrum.)

In at least one case, disagreements among the opinions of the musicians were reported. Player D reported that large mouth cavity was useful for a "rich, focussed" sound, while others reported that they achieved such a sound by lifting the tongue close to the soft palate. One possible explanation is that the musicians in question have different meanings for "rich" and especially for "focussed" in this circumstance.

3.2 Reproducibility of the impedance measurements

Reproducibility was tested on each musician by making about five measurements of the embouchure for the same note (written G3) over the course of a session (typically 40 minutes). Players were able to repeat their embouchures rather reproducibly: in the typical result shown in FIG. 3, the second resonance is obtained at 1250 Hz with a standard deviation of 3 % in frequency and 15 % in amplitude.

3.3 General comments

Most of the subjects in our study reported that, for normal playing, they use an embouchure that varies little over most of the range, except for the highest register. This was confirmed by the measurements: for all players, the form of the impedance spectra is quite stable over the whole register, except sometimes from the altissimo register.

The geometric average amplitude of the impedance is similar for all musicians. The first peak, whose frequency is between 200 and 300 Hz, has an amplitude between 1.8 and 5.6 $\mathrm{MPa.s.m^{-3}}$. The next resonances are on the other hand different for both amplitude and frequency. For some player embouchure combinations, the amplitudes are in the range 30 to 100 $\mathrm{MPa.s.m^{-3}}$ which is of the same order as that of the impedance of the clarinet at its resonances [8].

The difference between the impedance spectra recorded for the "normal" playing configuration and that measured for the tract configuration used for "special effects" is not very large for any of the student players measured. For some of the professional players, however, the effect was very large. However, the spectra measured for the different special effects also varied substantially among these players, just as it did for normal playing.

For several players, the "ee" configuration produced a strong peak between 560 and 1000 Hz, a peak that is associated with the constriction between tongue and palate (see FIG. 7). For many players, however, the configuration they produced when asked to mime the "ee" embouchure, had no such peak and indeed resembled somewhat the impedance measured when they were asked to mime the "aw" embouchure. However, the average level of impedance, even for these players, was in general higher for "ee" than for "aw". Not all players use the "ee" and "aw" terminology for the embouchure and it is possible that the instruction was in this case confusing. It is important to remark that this terminology in terms of vowels refers more to the position of the tongue in the mouth than to the real configuration of the vocal tract in speech as the mouth of the player is of course closed around the mouthpiece.

3.4 Differences among players for "normal" playing mode

We study here the configurations that musicians use in "normal" playing, which means the configuration they adopt usually, when they have no special musical intentions, in the *mezzo forte* nuance. For comparisons, we choose the note G4 which is representative of the low and medium register and the note G6 for the high register. In FIG. 4, the same two musicians mime playing each of the notes.

The configuration for the note G4 is qualitatively similar for both musicians. A few exceptions apart, it is a configuration used by many players in the normal playing mode for almost the whole range of the clarinet, as shown in the figures available in [11]. However, the configuration adopted for the very high register can differ quite considerably among players: some musicians adopt a configuration that enhances the second peak and moves it into the frequency range of the note played whereas some others tend to adopt a configuration that reduces the amplitude of this peak.

3.5 Variations used by players

Players agree that they use different embouchures for different effects. The embouchure includes the lip and jaw position, and hence the force, the damping and the position on the reed may vary. The aspect being studied here is the way in which the mouth or vocal tract geometry changes can affect the impedance spectrum. The substantial changes shown in FIG. 5 suggest that this latter effect may not be negligible. even if the configuration in normal playing is quite stable over the whole register.

It is interesting to note the remarkable similarity in the impedances for "special effects" between two professional players who played together for several years in a major national orchestra, whereas they do not adopt the same configuration for normal playing (FIG. 6).

One of the professional players expressed her control of pitch and timbre thus: she uses a "ee" for the high register or for brightening the sound and in contrarily she adopts a "aw" configuration for darkening the timbre and lowering the pitch. The differences between these two configurations are represented in FIG. 7.

3.6 Subtlety

In most cases, different tract configurations that were reported to be used to produce different effects on the sound were found to have different impedance spectra. However, for some of the players, the impedances measured when they were miming "good" and "bad" embouchures differed by amounts comparable with the measured reproducibility of a single embouchure. For example, FIG. 8 shows a large similarity between the impedances for embouchures described by a very experienced soloist as those corresponding to a "nice" and a "bad" sound. We presume that in this case the differences had more to do with aspects of the embouchure such as lip tension and position, and less to do with the tract configuration.

3.7 Summary of the measurements

The players are classified into groups for which the impedances look similar for notes G3 to G5. The results of one player contained unexpected and unexplained high levels of noise, and are omitted. Results are summarised in TABLE 1.

Table 1: Summary of the features of impedance spectra measured on 16 players for the vocal tract configurations they used for the different cases listed.

players	normal playing		special effects
	G3, G4, G5	G6	pitch bend
A, B, C, E and one other	2 resonances: 1000-1400 Hz ($3.2\ 10^6$-10^7 Pa.s.m^{-3}) and 2100-2400 Hz.	The second resonance disappears for players A, C and D. For player F, the second resonance is lowered by 500 Hz.	Only one resonance: 600 Hz ($1.3\ 10^7$ Pa.s.m^{-3}) for player D, 1400 Hz ($4\ 10^7$ Pa.s.m^{-3}) for F, 2500 Hz for A and 2700 Hz (in the last two cases, it is actually the first resonance which disappears).
Player D	One resonance: 700 Hz, $5.6\ 10^6$ Pa.s.m^{-3}.	This resonance is shifted to 1400 Hz.	Strong resonance ($1.8\ 10^7$ Pa.s.m^{-3}) at 700 Hz which suggests that she uses a “ee” configuration.
Player H, F and 4 other players	The impedance grows continuously with the frequency, with a slope of 30 dB for 2500 Hz. 2 small resonances at 1200 Hz and 2000-2300 Hz.	The second resonance is slightly enhanced.	For half of the players, the resonances disappear; for the others (like player E), the first resonance is strongly enhanced.
Player G	G3-G4: 2 acute resonances at 1200 and 2100 Hz. G5: one strong resonance at 1400 Hz.	As for G5.	As for G3 and G4.
2 players	Same configuration for all playing modes. 1 strong resonance at 2200 or 2500 Hz, between $3.2\ 10^7$ and 10^8 Pa.s.m^{-3}.		

4 Theoretical model

4.1 Model for the vocal tract

This model draws on work in speech science, where scientists are more interested in what happens at the glottis and usually calculate either the transfer function or the impedance at the glottis. However, numerical simulations which were done in speech synthesis to calculate the impedance at the glottis can be used in our study by inverting the calculation and using the appropriate impedance at the glottis. The model used is the one developed by Sondhi [12, 13] with yielding walls. The vocal tract is represented by concatenated cylinders and the relation between the variables at the input of cylinder $k+1$ and cylinder k (k=0 at the glottis) is the following:

$$\begin{pmatrix} p_{k+1} \\ u_{k+1} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} p_k \\ u_k \end{pmatrix}$$

with

$$\begin{aligned} A &= D = \cosh(\frac{\sigma l}{c}) \\ B &= \frac{\rho c}{S}\gamma \sinh(\frac{\sigma l}{c}) \quad C = \frac{S}{\rho c}\gamma \sinh(\frac{\sigma l}{c}) \end{aligned} \tag{1}$$

with

$$\gamma = \sqrt{\frac{r + j\omega}{\beta + j\omega}} \tag{2}$$

$$\sigma = \gamma(\beta + j\omega) \tag{3}$$

$$\beta = \frac{j\omega\omega_t^2}{(j\omega + r)j\omega + \omega_w^2} + \alpha \tag{4}$$

$$\alpha = \sqrt{j\omega q} \tag{5}$$

where r and ω_w are related to the yielding properties of the vocal tract and represent respectively the ratio of wall resistance to mass and the mechanical resonance frequency of the wall. Their values are set to $r = 408\text{rad.s}^{-1}$ and $\omega_w/2\pi = 15\text{Hz}$. ω_t is the frequency of a resonance of the tract when sealed at both the glottis and the lips, and which is associated with the finite mechanical compliance of the walls (like the "breathing mode" in a string instrument): $\omega_t/2\pi = 200\text{Hz}$. The parameter q is a correction for thermal conductivity and viscosity, which is set to $q = 4\text{rad.s}^{-1}$.

The calculation was done was done using a program written by Story [14], except that it was inverted in order to calculate the impedance at the mouth (and not at the glottis). To complete the calculation we need the glottis geometry (tube 0) as, in contrast with speech, the vocal folds are not entirely closed. We also need the boundary condition at the glottis: $p_0 = Z_{sg}u_0$, where Z_{sg} is the input impedance of the subglottal tract.

4.2 The glottis

According to the laryngoscopic study by Mukai [7], the glottis of professional wind musicians is usually a narrow slit, to which our first order approximation is a rectangle of length $a = 10$ mm, width $b = 1.5$ mm and thickness $e = 3$ mm.

However, the discontinuity between the cross section of this slit and that of the trachea requires an acoustic end correction. Here the glottis is treated as a tube baffled at both ends, having an effective length of $e_{eff} = e + 0.85 r_g$ where r_g is the equivalent radius [1] of the glottis ($r_g = \sqrt{ab/\pi} = 2.2$ mm).

Consequently, cylinder 0, which represents the glottis and thus connects the vocal tract to the subglottal tract in the model, has a length $e_{eff} = 4.7$ mm and area ab.

4.3 The subglottal tract

For all but very low frequencies, the results depend only very weakly on the subglottal tract, so we use a very simple model. (FIG. 9)

The lungs are very lossy at the frequencies of interest, and so reflections are minimal. For that reason, they are modelled here as a purely resistive load with the same characteristic impedance (i.e. an infinitely long pipe whose radius equals that of the trachea, r_t =9 mm)

$$Z_{sg} = \frac{\rho c}{\pi r_t 2} \tag{6}$$

4.4 Correction at the input of the mouth

In comparison with the cross sectional area of the mouth, the area of the reed inside the mouth is small, as is that of the impedance head. It resembles thus a small piston vibrating in a baffle that seals a larger waveguide, or a discontinuity in waveguides, which is often modelled by adding an end correction to the smaller element. Physically, the volume of air in the end correction has an inertance comparable to the that of air in the strongly diverging part of the radiation field in the larger guide. The end correction for a baffled pipe is used at this end of the vocal tract, too: an element with radius r =3.9 mm and length $l = 0.85r$ [16].

As we used mainly the MRI data from Story and Titze [17], we divided the vocal tract, of length 170.4 mm, in finite elements of length 4 mm, giving 44 elements, plus the zeroth element representing the glottis (this one is actually divided in two elements: the first has the same length as the others whereas the second is used to adjust the effective length of the glottis). A complication is due to the insertion of the mouthpiece about 10 mm in the mouth, which puts the first two tract elements effectively in parallel with the rest. The iterative calculation of section 4.1 is conducted on 33 tract elements, beginning at the glottis, which is loaded with the subglottal resistance. This gives the impedance Z_1. The two elements closest to the mouth and sealed at the mouth end give an impedance Z_2. The total uncorrected impedance is therefore

---

[1] In principle, the end correction for a slit is greater than that for a circular aperture of the same area [15]. However, this approximation is appropriate, given the experimental uncertainties.

$$Z_{nc} = \frac{Z_1 Z_2}{Z_1 + Z_2} \qquad (7)$$

which, when the end correction mentioned above is added, gives:

$$Z_{CV} = Z_{nc} + jZ_0 \frac{\omega}{c} l \qquad (8)$$

with $Z_0 = \rho c/(\pi r2)$.

The result of end effects and the parallel elements at the mouth are noticeable primarily at high frequency ($>$ 3000 Hz). However, at such frequencies the unidimensional model fails anyway because of its neglect of transverse modes. For example, El-Masri *et al.* [18] showed how the plane wave approximation gave poor predictions for the behaviour of the tract at frequencies above 4500 Hz. Further refinement is therefore inappropriate in this simple model. What is of practical importance in these corrections is their substantial reduction of the amplitude of the resonances at high frequency, which avoids artifacts in simulations that have strong high frequency resonances that do not correspond to those of the tract made of flesh. Further, the cutoff frequency of an array of open tone holes in the clarinet is typically around 2000 Hz, so our interest need not exceed the range 0-3000 Hz.

4.5 Results for two vowels. Adjustment.

The aim of this simulation is to 'invert' the model, i.e. to obtain the area function from the impedance spectrum. Solutions to inversion are not unique, but other constraints on vocal tract shape eliminate many. An inversion was obtained with assistance from Brad Story, which mapped the calculated impedance of the complete model, including corrections to the area function. The program begins with the first three resonance frequencies and the mapping was generated using area functions such as given by [17] (using 4 mm elements). In general it was found that the impedance spectra calculated from the mapped area functions differed noticeably from the original impedance measurements. A further program was therefore written to allow iteration by local adjustment of the area function to improve the fit. By such iterations, anatomically possible area functions giving the experimental impedance spectra were obtained.

Two important results are shown. Clarinettists often refer to two tract configurations as “ee” and “aw”, being those for the vowel sounds (those of “heed” and “hoard”) sensibly resembled by the playing position. The resemblance is only approximate, of course: for the vowels, the mouth is open to different extents, whereas in the playing configuration the mouth is sealed by the mouthpiece of nearly constant area.

For “ee”, FIG. 10 shows the plausibility of the area function, which is rather similar to that of the vowels /i/ (“heed”)and /ɪ/ (“hid”). This configuration has a cross section at the palatal constriction lying between the values reported for the two vowels, which in English differ little except in their duration. At the mouth end, the area function is set equal to the cross section of the clarinet mouthpiece, 15 mm from the end.

It proved impossible, however, to fit the first peak, for which the inversion gave frequencies that were systematically too high (e.g. between 230 and 250 Hz instead of 200 Hz for "aw" and between 250 and 280 Hz instead of 230 Hz for "ee").

A resistance of 1.5 MPa.s.m-3 was added at the glottis. Although this was an empirical adjustment to fit the measured height of the peak values of impedance, it might be justified by considering that energy would be lost from propagating waves due to turbulence produced by flow through this narrow slit.

For the case of "aw" (FIG. 11) the area function found by inversion closely resembles that of the corresponding vowel. However, the magnitude of the first peak is too great, even allowing for the fact that the peak for this musician is systematically lower than that of other musicians. Thus for the same vowel, the first peak of player G has an amplitude between 5 and 7 MPa.s.m^{-3}, and is thus better predicted by the numerical simulation.

Overall, the inversion results have only moderate agreement, and the area functions must be adjusted "by hand" in order to give impedance spectra close to those measured. Further, some effects have been neglected, such as the fact that some players place the tip of the tongue just behind the lower lip, which might plausibly add a parallel compliance associated with the air volume under the tongue. Nevertheless, this does not prevent the obtaining of approximate area functions and allows in particular the determination of a palatal constriction.

4.6 Influence of the glottis opening

FIG. 12 shows the impedance for an "ee" configuration (as described in FIG. 10) calculated in three cases:

- the glottis is an expert's glottis, almost closed, i.e. a slit of area 15 mm^2;
- the glottis is an amateur's glottis, partially closed, of section 90 mm^2;
- the glottis is the same as the previous case and the section of the last two cylinders of the vocal tract (just above the glottis) was increased for more realism: it is indeed very likely that the amateur not only open wider the glottis but as well the upper part of the vocal tract.

This figure shows that the opening of the glottis can have a large effect (a factor of 2 or 6 dB) on the amplitude of the peaks. Some important levels in the impedance data allow us thus to assume that in many cases, the glottis is almost closed.

5 CONCLUSION

The newly configured spectrometer permitted the measurement of the impedance spectra of the vocal tracts of experienced clarinet players in a situation that allowed them to mime the conditions of playing. In contrast with most previous measurements, the players could blow into the mouthpiece and, probably as a consequence of this, the impedance spectra showed the strong resonances that are characteristic of a nearly closed glottis, which is the case both for speech and for the playing of experience wind instrument players [7]. As the glottal opening could not be monitored, this deduction is only made on both the good reproducibility which ensures us that the glottis is well controlled by the musician during the measurement and the high level of the impedance in comparison to previous measurements.

The peak values of impedance measured were in some cases comparable with the peak values of that of the clarinet (Wolfe *et al.* [8], Backus [9]). Moreover, the vocal tract impedance is much larger than the clarinet impedance around the even harmonics. The phase of these harmonics, when we consider the whole impedance (i.e. the sum of the clarinet impedance and the vocal tract one) is thus shifted, which may affect the playing frequency. This suggests that the acoustic effects of the vocal tract should not be neglected and that they may have a musically significant influence on the sound produced.

The combination of these measurement with a survey about the utilisation by clarinet players of their vocal tract allow us to relate observed acoustical responses to the reported embouchures of the players. All players agreed that the vocal tract had a large influence on the sound, but their opinions regarding the best configuration to adopt differ considerably. This is a potentially important conclusion for musicians: many highly respected professional clarinettists achieve fine sound quality using rather different tract configurations. Nevertheless, two general trends can be observed. The players try to keep their configuration stable for most part of the register, which is in contrast to Johnson's suggestion [4] that players may tune one of the vocal tract resonances to the note played. On the other hand, the configuration can be changed substantially for special effects such as difficult slurs across registers or pitch bend: players lower the tongue and the overall magnitude of the impedance when they aim to bend the pitch down, or to slur downwards over registers, and vice versa. To examine this phenomenon in more detail, we hope that, in the future, it may be possible to make such measurements in real time in order to determine how the musician changes his configuration during a transition.

ACKNOWLEDGMENTS

We are grateful to John Smith and David Bowman for ACUZ program and to the Australian Research Council for funding. We would like to thank also Brad Story for his help with the numerical model.

References

[1] J. Backus, "The effect of the player's vocal tract on woodwind instrument tone," J. Acoust. Soc. Am. **78**(1), (1985).

[2] A. Benade, "Air column, reed and player's windway interaction in musical instruments," in *Vocal Fold Physiology*, edited by I. Titze and R. Scherer (The Denver Center for the Performing Arts, Denver Colorado, 1983).

[3] P. Hoekje, "Intercomponent energy exchange and upstream/downstream symmetry in nonlinear self-sustained oscillations of reed instruments," Ph.D. thesis, CaseWestern Reserve University, Cleveland, Ohio, 1986.

[4] R. Johnston, P. Clinch, and G. Troup, "The role of the vocal tract resonance in clarinet playing," Acoustics Australia **14**(3), (1986).

[5] T. Wilson, "The measured upstream impedance for clarinet performance and its role in sound production," Ph.D. thesis, University of Washington, 1996.

[6] J. Backus, "Vibration of the reed and the air column in the clarinet," J. Acoust. Soc. Am. **33**(6), (1961).

[7] M. S. Mukai, "Laryngeal movement while playing wind instruments," in *Proc. of the International Symposium on Musical Acoustics* (Tokyo, Japan, 1992), pp. 239–242.

[8] J. Wolfe, Clarinet Acoustics, `http://www.phys.unsw.edu.au/music/clarinet`.

[9] J. Backus, "Input impedance curves for the reed woodwind instruments," J. Acoust. Soc. Am. **56**(4), 1266–1279, (1974).

[10] J. Smith, C. Fritz, and J. Wolfe, "A new technique for the rapid measurement of the acoustic impedance of wind instruments," in *Proc. of the Seventh International Congress on Sound and Vibration*, edited by G. Guidati, H. Hunt, H. Heller, and A. Heiss (Garmisch-Partenkirchen, Germany, 4-7 July 2000), Vol. III, pp. 1833 – 1840.

[11] C. Fritz and J. Wolfe, Impedance measurements of clarinet player's airway, `http://www.phys.unsw.edu.au/~jw/AirwayImp.html`.

[12] M. Sondhi, "Model for wave propagation in a lossy vocal tract," J. Acoust. Soc. Am. **51**(6), 1070–1075 (1974).

[13] M. Sondhi and J. Schroeter, "A hybrid time-frequency domain articulatory speech synthesizer," IEEE Trans. Acoust., Speech, Signal Processing **35**, 955–967 (1987).

[14] B. Story, A. Laukkanen, and I. Titze, "Acoustic impedance of an artificially lengthened and constricted vocal tract," J. Voice **14**(4), 455–469 (2000).

[15] P. Morse and K. Ingard, *Theoretical acoustics* (Princeton University Press, ADDRESS, 2000).

[16] N. Fletcher and T. Rossing, *The Physics of Musical Instruments* (Springer-Verlag, New York, 1995).

[17] B. Story, I. Titze, and E. Hoffman, "Vocal tract area functions from magnetic resonance imaging," J. Acoust. Soc. Am. **100**(1), (1996).

[18] S. El-Masri, X. Pelorson, P. Saguet, and P. Badin, "Development of the transmission line matrix method in acoustics applications to higher modes in the vocal tract and other complex ducts," Int. J. Numer. model **11**, 133–151 (1998).

List of Tables

List of Figures

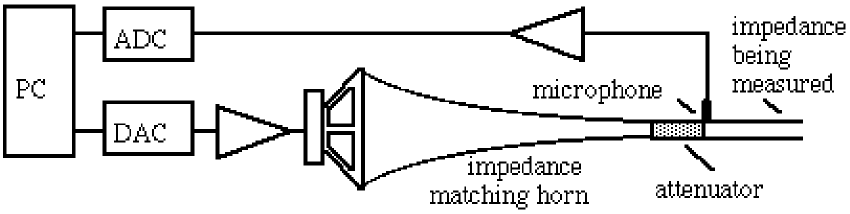

Figure 1: A schematic of the impedance spectrometer using the capillary method.

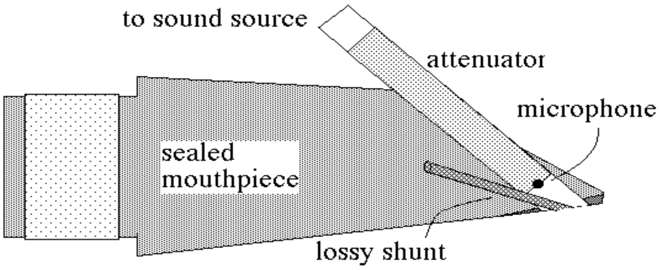

Figure 2: Cross section of the clarinet mouthpiece containing the impedance head and a lossy shunt.

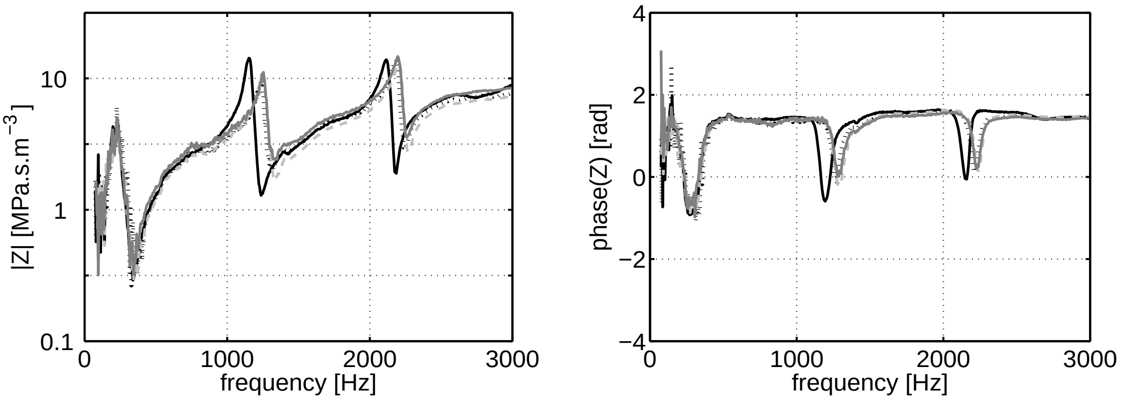

Figure 3: Typical results of measures testing the reproducibility of the player's tract configuration: the impedance spectra of the vocal tract of the same player (player G) miming playing the note G3 on three occasions over an interval of 40 minutes.

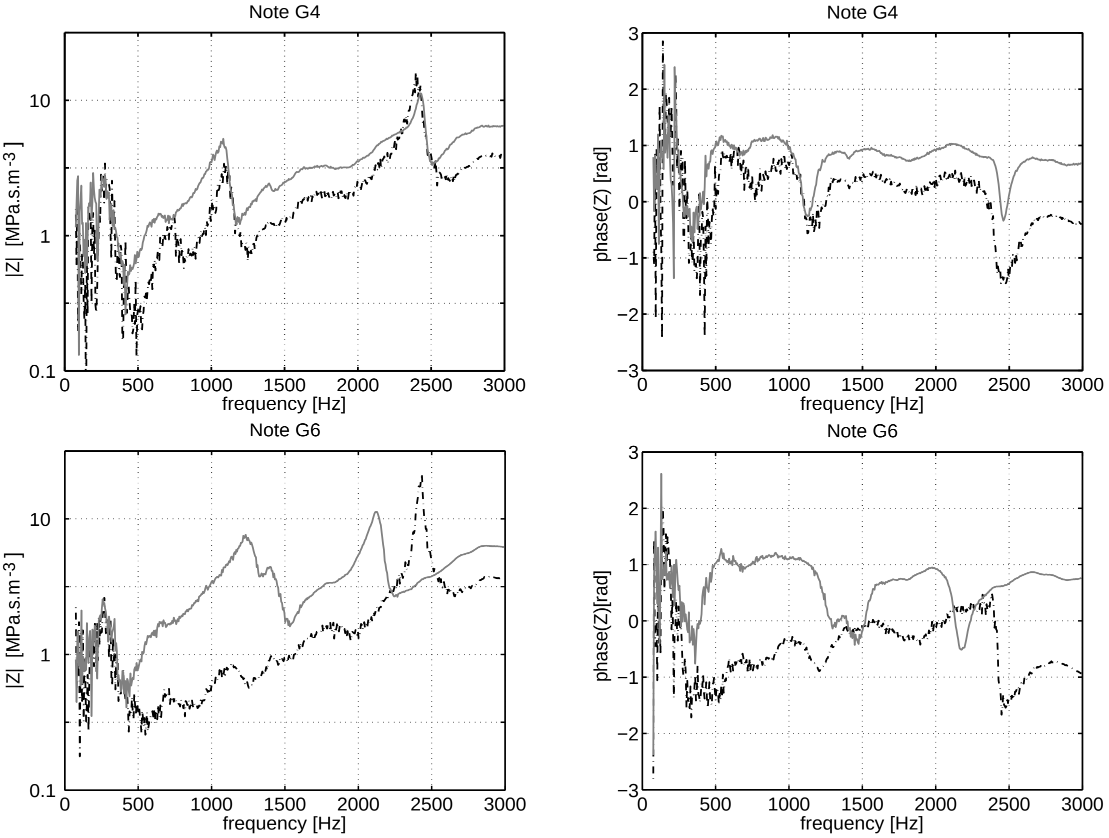

Figure 4: The impedance spectra of the respiratory airway of two experienced professional musicians (player B in black and player E in grey), for notes G4 (top) and G6 (bottom).

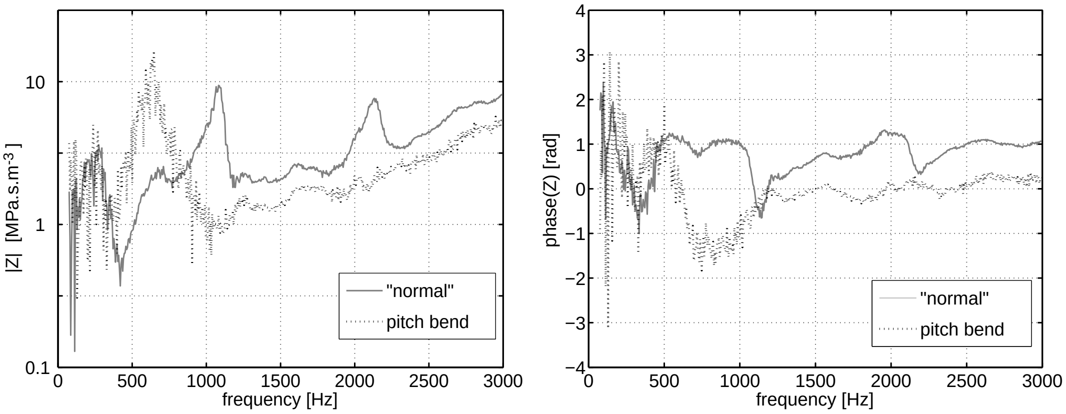

Figure 5: A comparison of the impedance spectra measured on player C for the configurations for normal playing and for performing a pitch bend.

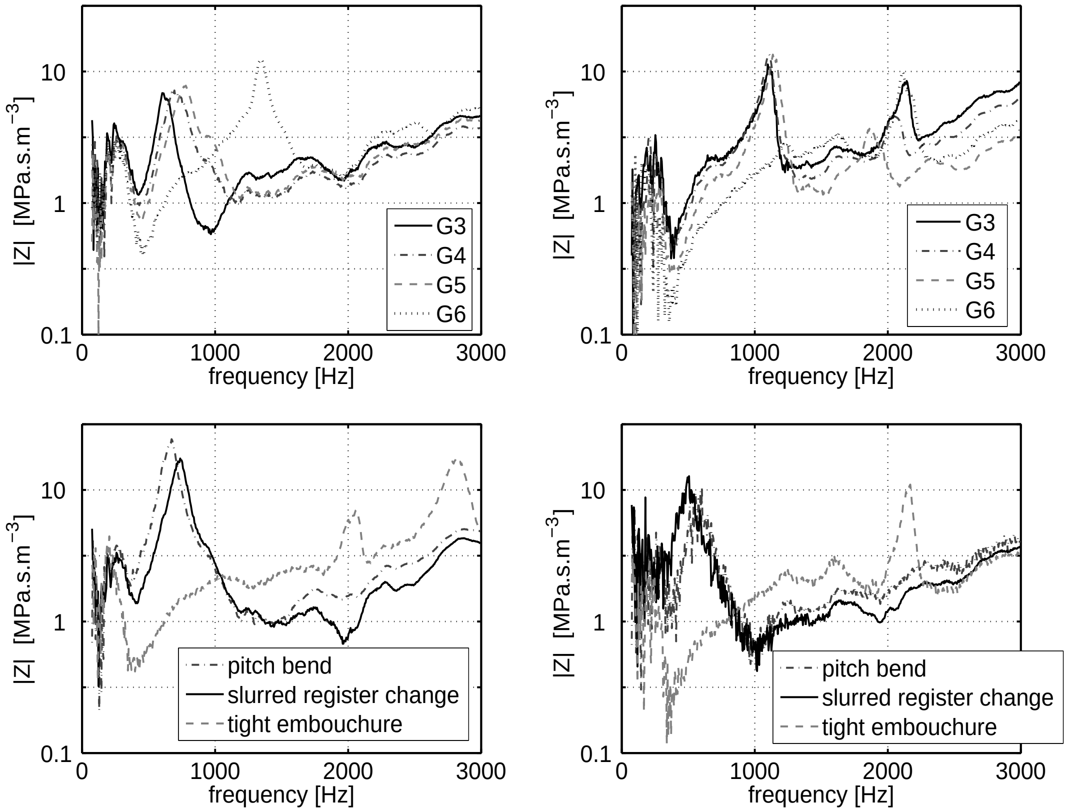

Figure 6: A comparison between two professional players (player D at left and C at right) for their normal playing configurations (top) and for those used for some less usual effects (bottom).

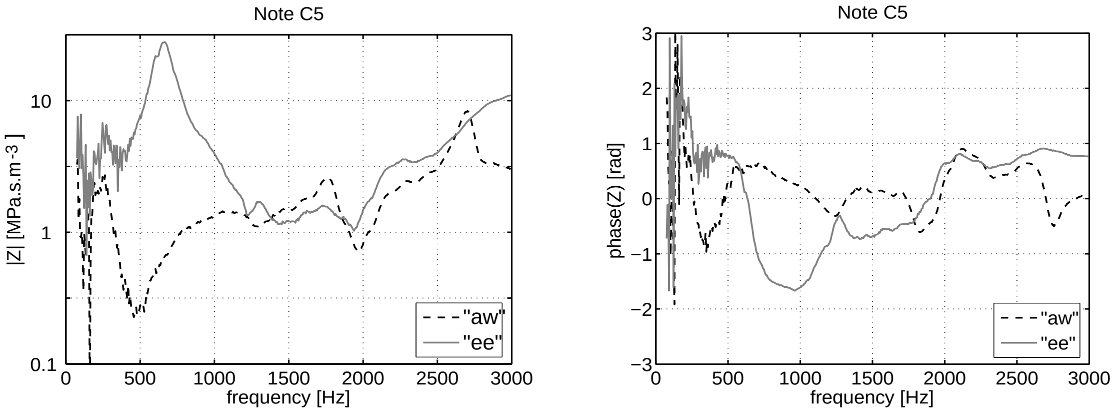

Figure 7: The impedance spectra of player D's airway for two configurations described as "ee" and "aw", for the note C5.

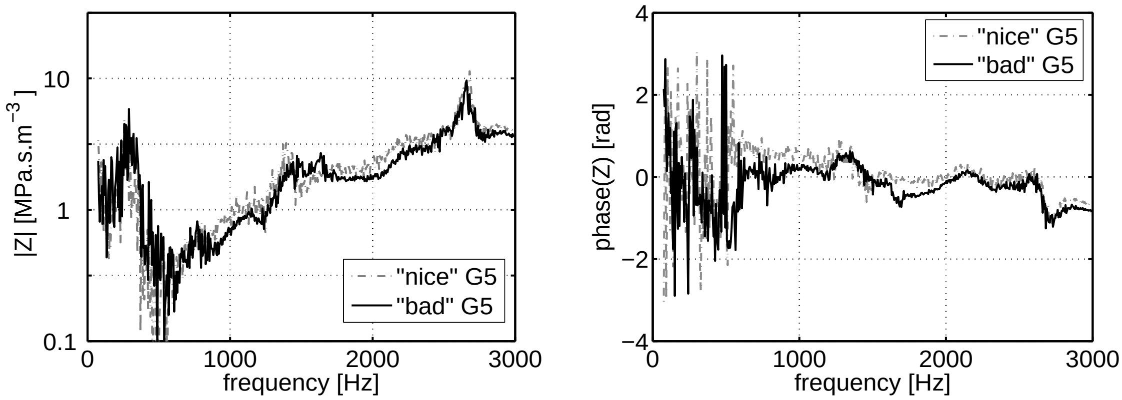

Figure 8: The impedance spectra of the vocal tract of player A for two configurations associated with a “nice” sound or with a “bad” one, i.e. one which is to be avoided (note G5).

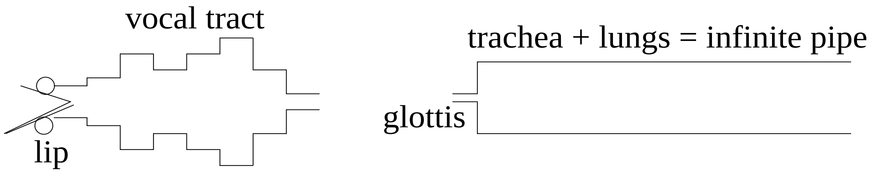

Figure 9: A schematic of the waveguide used to model the respiratory airway. It is not to scale, and the number of elements has been reduced for clarity. The clarinet mouthpiece is inserted between the lips at left.

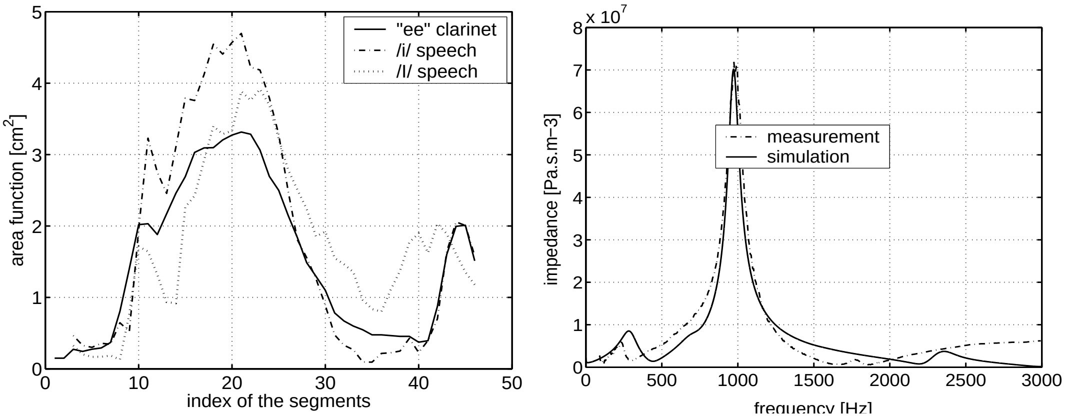

Figure 10: At left: area function for the vowels /i/ and /ɪ/ (data from Story and Titze with glottis added). Also shown are the calculated tract configuration named “ee” by clarinettists, as determined from inversion. The abscissa is the element number: the first two are the glottis (see 4.4), the next 44, of length 4 mm comprise a tract 174 mm long. At right: the impedance spectrum for the “ee” tract configuration measured on one of the authors (player G) an amateur clarinettist.

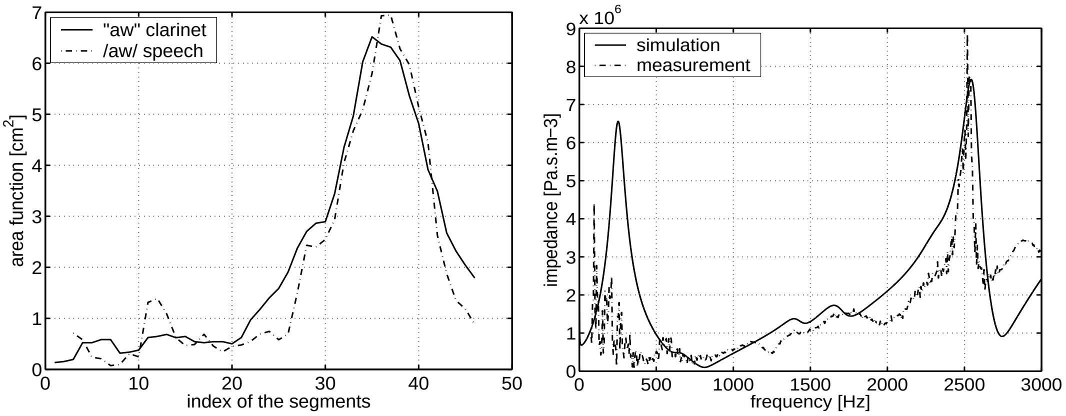

Figure 11: At left: area function for the vowel /ɔ/ (data from Story and Titze with glottis added). Also shown are the calculated tract configuration named "aw" by clarinettists, as determined from inversion. The abscissa is the element number: the first two are the glottis (see 4.4), the next 44, of length 4 mm comprise a tract 174 mm long. At right: the impedance spectrum for the "aw" tract configuration measured on player B.

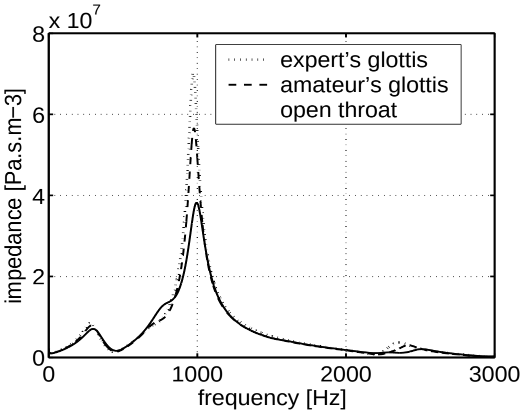

Figure 12: Calculated impedance spectra for a tract in the configuration "ee" with three different values of the glottal opening. Two are taken from the data of Mukai for an expert and an amateur player, the third is for an open glottis.