A practical way to measure intonation quality of woodwind instruments using standard equipment without custom made adapters

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Woodwinds are not much different from brass instruments in how intonation is determined by air column resonances. Nevertheless, it is easier to measure input impedance of brasses because the input cross-section at the mouthpiece rim is circular, plane and big enough to be easily coupled to standard measuring heads. In reed instruments the input cross-section is neither flat nor circular nor well defined. Flute instruments not even have any definable input cross-section as this is controlled by the player's lower lip. On top of that, flutes are played at an open end where some coupled impedance considerably influenced by the nearby environment like lips, mouth and face of the player has to be taken into account. Existing approaches to measure input impedance of woodwind instruments usually require custom made adaptors optimized to yield nearly accurate intonation results for a specific instrument and playing range only. The proposed new approach is to separate instrument head or mouthpiece from the body and measure both parts from their cylindrical ends. During the measurement a natural playing condition can be simulated at the now available end. Both measurements can be assembled computationally yielding useful intonation results as will be demonstrated for flutes and saxophones.

1 Introduction

Acoustical input impedance measurements have become quite common for the analysis of brass wind instruments and it is agreed that such results do have considerable significance for main quality aspects of such instruments, like intonation and response. It is not a big technical challenge to couple a wide-band sound source with known source impedance to the circular cross-section of the mouthpiece and to measure the sound pressure close to that plane.

Rugged commercial input impedance measurement systems for production tests in professional instrument manufacturing lines as well as for quality analysis of prototypes or for other diagnostic purposes in the workshops of traditional instrument makers exist for several years now [1][2]. Similar systems for woodwind instruments would be just as important but are still lacking. The main reason is, that there is no easy way to couple an impedance measurement head to the mouthpiece of any single or double reed instrument nor to the embouchure hole of a flute.

Attempts have been made to replace the mouthpiece of e.g. a clarinet by a reed-less surrogate part with circular coupling cross-section which has been customized and may be even optimized in order to resemble the main acoustic properties of the original mouthpiece as perfectly as possible. This approach was working but unpractical. It turned out, that custom coupling parts had to be manufactured not only for instrument groups but rather for specific instruments.

For flutes this approach is even less viable although it has been done experimentally [3]. First, the flute is played at an open end where acoustical characteristics of the near environment including the player's lips, nose and face cannot be neglected. Second, the player's embouchure varies significantly between playing registers and especially the area of the embouchure hole which is covered by the lips has to be taken into account.

Therefore it was investigated whether woodwind instruments can be measured in parts using the natural separation plane between flute head and flute body (or between two saxophone or clarinet parts) as the reference plane (as shown in Figure 1). It will be shown that it is indeed feasible to mathematically derive the acoustical impedance at the reference plane starting from input impedance measurements of the separated instrument parts. The head part measurements can even be made while the player is pretending to play a certain note thus taking real embouchure parameters into account (see Figure 2). This is especially important for flutes in order to get realistic intonation results. Figure 3 shows flute body impedances measured with different fingerings.

(a) Head   *(b) Body*

Figure 1: BIAS Head with flute parts.
The player can simulate the embouchure during the measurement of the head.

2 Deriving acoustical properties of whole wind instruments by measuring their parts

All resonances of a flute originate from standing waves inside the instrument. Pressure wavelets are propagated in the tube being partially reflected at all discontinuities
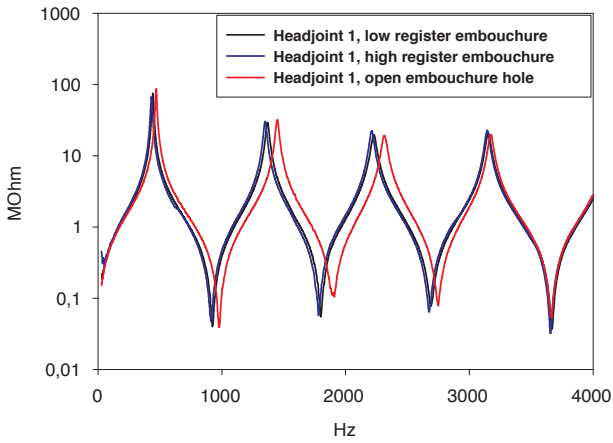
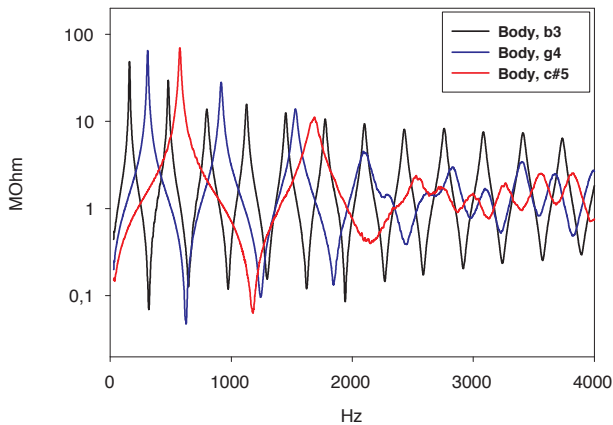Figure 2: Flute head impedances (different embouchure)

Figure 3: Flute body impedances (different fingerings)

of the bore. The biggest discontinuity of the flute body is, of course, the first open tone hole or the open end of the instrument, if all holes are closed. The main reflection of the flute head when measured from the separation plane will be the open embouchure hole with its specific radiation impedance defined by its open, uncovered area and the acoustic properties of the near proximity given by the player's lips, nose, face and - to an again smaller extent - the room.

A Dirac-impulse generated by a non-reflecting (perfectly impedance-matched) sound pressure source would reveal the complete acoustical characteristics of an instrument part, provided that the pulse response is recorded using a microphone at the separation plane until all higher order reflections have decayed to a negligible level.

The Fourier-transform of such a pressure-to-pressure reflection function is here named input impulse response (IIR) function of flute head resp. flute body, and must not be mistaken with the corresponding input impedance functions. The input impedance function (Z_{in}) is the frequency domain spectrum of a pressure response to a sound flow stimulation and is usually measured at a more or less perfectly reflecting source end.

Comparing the input impulse response IIR and the

input impedance Z_{in} in the time domain applying the inverse Fourier transform to both spectra, it will immediately become obvious that the latter exhibits strong periodicity with little decay caused by two strong reflections at the begin and at the end of the tube, while the former decays quickly as it does not have any reflection at the stimulated end absorbing perfectly all the waves traveling back into the source. The former could be thought of as an open-loop pressure transmission function while in the latter case the loop is closed by the characteristic impedance of the input cross-section.

Fortunately there is a mathematical way to transform the input impedance Z_{in} into the input impulse response IIR. It is the transform

$$IIR(e^{j\Theta}) = \frac{1 - \frac{Z_0}{Z_{in}e^{j\Theta}}}{1 + \frac{Z_0}{Z_{in}e^{j\Theta}}} \qquad (1)$$

with Θ being the discretized frequency [4, p.41].

With the complex input impedance vector defined by $Z_{in} = Z_{mag}e^{jZ_{arg}}$, IIR becomes

$$IIR = \frac{Z_{mag}\,(\cos(Z_{arg}) + i\,\sin(Z_{arg})) - Z_0}{Z_{mag}\,(\cos(Z_{arg}) + i\,\sin(Z_{arg})) + Z_0} \qquad (2)$$

The characteristic impedance Z_0 of the open cross sectional area with the radius r (area S, air density ρ, speed of sound c) at the entry of the part is mainly a function of temperature $temp$ in $[°C]$ and can be approximated by

$$Z_0 = \frac{\rho c}{S} \approx \frac{428\,(1 - 0.0017\,temp)}{r^2\,\pi} \qquad (3)$$

The open-loop input impulse responses IIR_{head} and IIR_{body} of both parts can be multiplied in the frequency domain to obtain the open-loop input impulse response function IIR_{tot} of the whole instrument.

$$IIR_{tot}(e^{j\Theta}) = IIR_{head}(e^{j\Theta})\,IIR_{body}(e^{j\Theta}) \qquad (4)$$

IIR_{tot} can be interpreted as the primary pressure response spectrum of the complete instrument in the separation plane when it has been stimulated by a δ-pulse at that same position. Secondary reflections could therefore be calculated according to IIR_{tot}^2, tertiary reflections by IIR_{tot}^3, and so on. The total response would consist of the stimulus and an infinite number of reflections. This transmission function $H_{ClosedLoop}$ (Eq (6)) will exhibit all resonances of the assembled instrument which do not accidentally have pressure nodes in the separation plane (see Figure 4).

$$H_{ClosedLoop} = 1 + IIR_{tot} + IIR_{tot}^2 + IIR_{tot}^3 + \dots \quad (5)$$

$$H_{ClosedLoop} = 1 + \sum_{n=1}^{\infty} IIR_{tot}^n = \frac{1}{1 - IIR_{tot}} \qquad (6)$$

The impedance Z_{cut} at the separation plane could be calculated according to

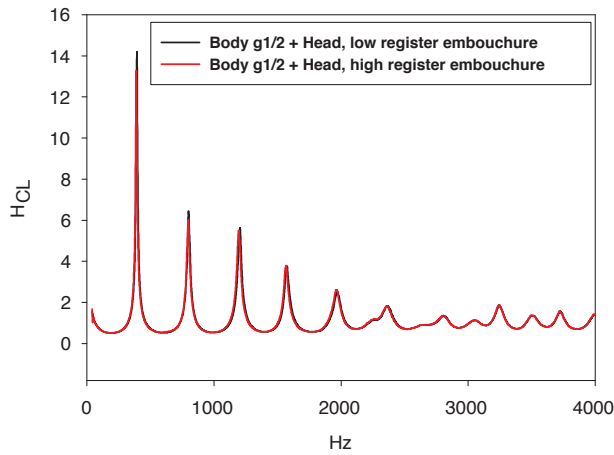$$\frac{Z_{cut}}{Z_{0,cut}} = \frac{1 + IIR_{tot}}{1 - IIR_{tot}} \qquad (7)$$

Figure 4: Closed loop transmission function of flute

3 Length Correction

A certain complication is caused by the fact that the acoustically effective length of the whole instrument is not simply the sum of the acoustical lengths of its parts. Usually some centimeters of the length of either part is lost when the parts are joined together. This difficulty can be overcome mathematically as the measured input impedance is given by the required unknown impedance at the effective coupling cross section multiplied by the well-known transmission matrix of a nearly cylindrical wave guide. If this matrix is inverted, the unknown termination impedance required to assemble the flute can be calculated.

Useful models for such wave guides are not reviewed here. A fairly general lossy transmission line model has been published by Mapes-Riordan in [5] based on the work of Keefe, Caussé, Benade et al. [6, 7, 8, 9, 10]. It has been reviewed by the author in [11] in a way ready to implement it in a computer program.

The matrix

$$\underline{A} = \left(\begin{array}{cc} a_{11}(j\Theta) & a_{12}(j\Theta) \\ a_{21}(j\Theta) & a_{22}(j\Theta) \end{array} \right) \qquad (8)$$

describing the usually cylindrical part of the duct which will become ineffective after composition has to be inverted in order to calculate the desired unknown termination impedance $Z_{out} = \frac{p_{out}}{u_{out}}$. The input impedance $Z_{in} = \frac{p_{in}}{u_{in}}$ can be measured directly.

$$\left(\begin{array}{c} p_{in}(j\Theta) \\ u_{in}(j\Theta) \end{array} \right) = \underline{A}(j\Theta) \left(\begin{array}{c} p_{out}(j\Theta) \\ u_{out}(j\Theta) \end{array} \right) \qquad (9)$$

It should be noted that it is not at all required for the eliminated part of the duct to be cylindrical. Any arbitrary bore shape can be eliminated by composing it from simple conical or cylindrical elements, multiplying their transmission matrices $\underline{A}_i$ before solving for Z_{out}:

$$Z_{out} = \frac{a_{22}Z_{in} - a_{12}}{a_{11} - a_{21}Z_{in}} \qquad (10)$$

4 Flute Intonation

Two different flutes have been studied in greater detail to evaluate the proposed method of determining their intonation. The head-joints have been measured without player and with a player simulating an embouchure required to play the lower register and one required to overblow the notes. The body part was measured with all fingerings required to play a complete chromatic scale from B4 to D7.

All measurements have been made with the BIAS measurement system. A two-second long chirp signal was used as a stimulus signal and it took a few seconds only to obtain calibrated impedance curves for each fingering, ready to be saved in the user's database. In automatic mode the player is prompted for all selected fingerings while all the other steps are repeated automatically for all notes.

The BIAS software has also been used to do the length corrections of all body measurements and to combine all body measurements with all available head-joint measurements. This way one or more complete sets of flute transmission functions for all playable notes can be generated by a single command. The resulting intonation chart shows the intonation in Cent of all available notes in one diagram (see Figure 6).

A comparison between the intonation of one of the instruments when played by an expert player and when composed from part impedances is shown in Figure 5. The head joint has been measured with the embouchure required to play the lowest resonance of the separated head joint with a closed end (a sharp A4) and with an embouchure to overblow this note into the twelfth (about an E6). From these plots it can be seen how important the coverage of the embouchure is to control the intonation and that it should be taken into account when the head-joint impedances are measured.

Especially in the low register there is an almost perfect match between played and measured intonation values. In the higher register players have to adjust their embouchure quite significantly in order to correct the natural intonation offered by the instrument. This is mainly done by covering a bigger part of the embouchure hole with the lips thus reducing the effective cross-sectional area making the pitch more flat.

It should be noted that there are additional parameters which do have influence on intonation when flutes are actually played. These parameters, like temperature distribution and chemical composition of air (CO_2 content, humidity) in the flute have been investigated by Coltman [12, 13] quite early.

Even the jet itself seems to have considerable influence on air column resonance frequencies. It is being studied currently by means of Lattice-Boltzman simulations [14] and PIV (particle image velocimetry) experiments [15].

5 Saxophone Intonation

It has also been investigated whether the method can be adapted for saxophones. Especially alto and tenor saxophones seem to be well suited as they can be separated between neck and body. Preliminary results from
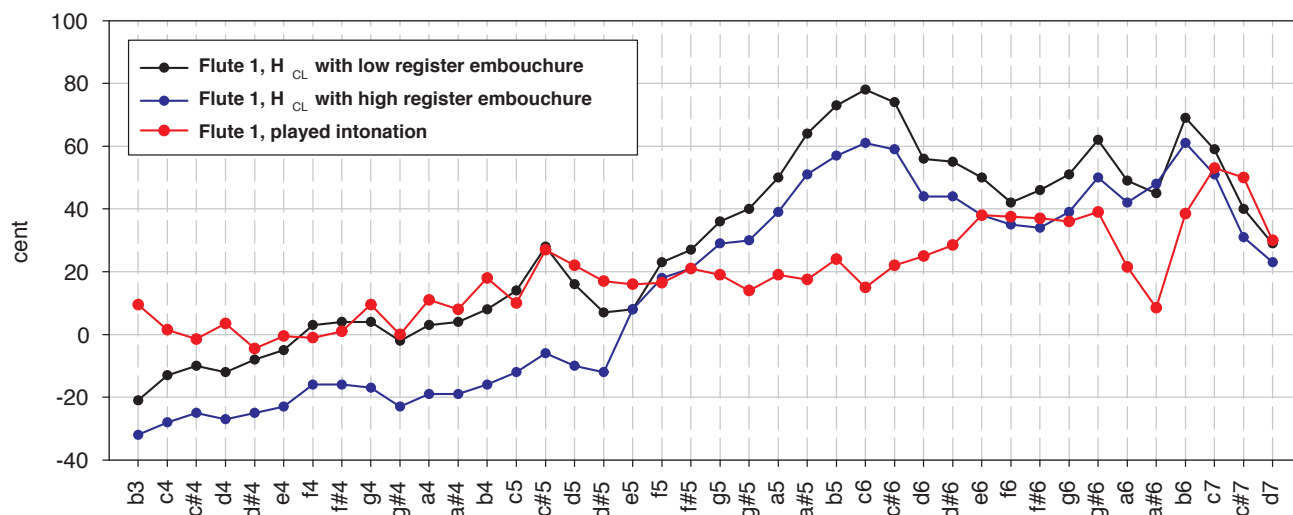
Figure 5: Intonation overview: Flute 1, A4 = 440Hz
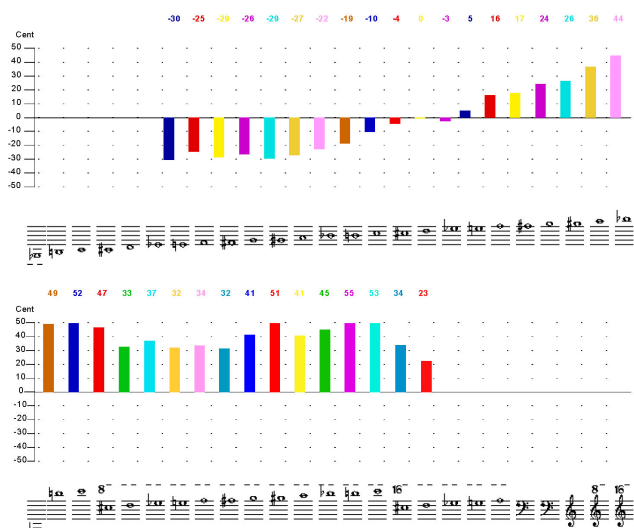

Figure 6: Flute 2, A4 = 442Hz,
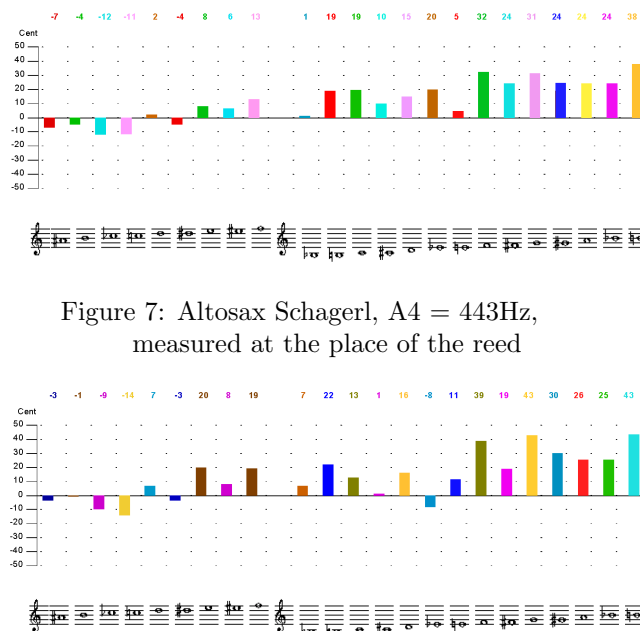embouchure for high register

Figure 7: Altosax Schagerl, A4 = 443Hz,
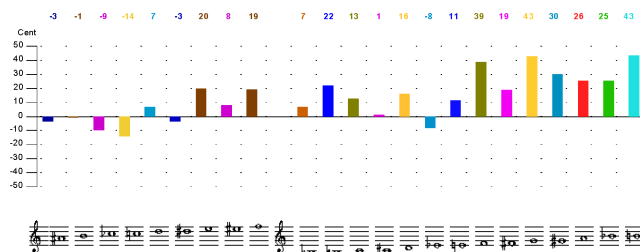measured at the place of the reed

Figure 8: Altosax Schagerl, A4 = 443Hz,
measured in separate parts

measurements done on two different alto saxophones indicate that application of the composition method does yield useful results for this type of wind instruments.

The instruments have been measured using the BIAS system in two different ways. First, it was tried to determine their resonance frequencies in their assembled state by using a soft rubber pad to couple the mouthpiece without the reed tightly to the measurement head. Second, measurements have been made in the disassembled state where the reed was pressed to the mouthpiece using tape in a way to ensure air tight closure of the mouthpiece when measuring the neck part.

The intonation charts for both instruments measured in the two different ways can be compared in the Figures 7..10. The results are quite consistent for both methods and expert players state that the measured values do agree with their subjective experiences. Especially when played with heavy reeds results seem to be realistic and useful. Anyhow, more thorough evaluations have still to be made.

6 Conclusion

It can be concluded that the proposed method of measuring the resonance frequencies of wood wind instruments by determining the input impedances of their parts and composing their acoustics numerically is feasible and practical. Results obtained this way are accurate and consistent with results obtained by other methods and they are in acceptable agreement with intonation figures obtained from actually playing these instruments.

No customized adaptor parts are required to obtain useful intonation charts which makes this method suitable for quality control of wood wind instruments in a production environment.

The matching between measured intonation values and intonation values obtained by human players de-
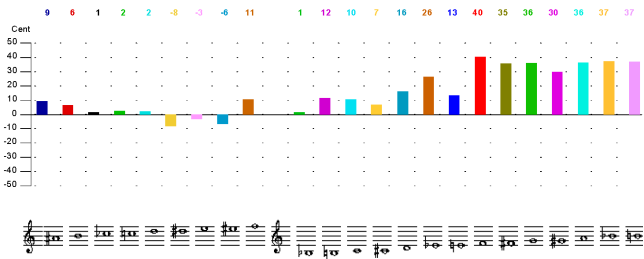
Figure 9: Altosax Selmer III, A4 = 443Hz, measured at the place of the reed

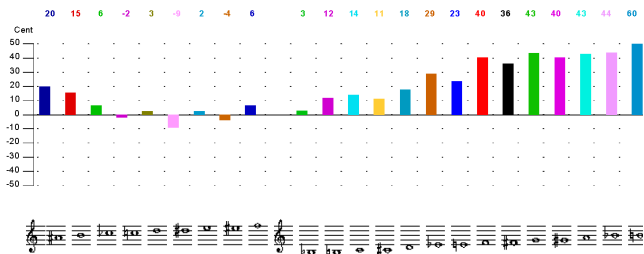Figure 10: Altosax Selmer III, A4 = 443Hz, measured in separate parts

pends on the type of instrument, the type of reeds used for playing them and, of course, the skill and experience of the players themselves. Some of these influences can be taken into account during the measurements because the player has a chance to simulate "her or his embouchure" while performing the head or neck measurement. Special fingerings (e.g. partly closed tone holes or loosely pressed keys) can also be simulated while measuring the body part.

Acknowledgments

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