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Measurements of exhaled air effects in the pitch of wind instruments*

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Abstract
The present paper deals with measurements of the sounding frequency of wind instruments as a function of the ever-changing gas contents of the player’s respiratory system. During the playing process with a wind instrument, the carbon dioxide level continuously increases, while the oxygen percentage decreases. These two variables are taken into account for the calculation of the expected pitch variation. An experiment is run to measure the effective variations occurring with the recorded sounds, under constant blowing pressure and with the use of a device that replaces the natural embouchure. The results show a systematic fall in the fundamental frequency that amounts to almost 20 cents for long tones in the oboe and the bassoon.

Introduction
In a previous article (Fuks, 1996), variations in carbon dioxide (CO₂) in expiratory air were measured and recorded during real performance of long notes in the clarinet and a solo piece for oboe. The results showed that the referred gas entering the instrument varied between 0%, on the beginning of a phrase, up to 8.5%, after approximately fifty seconds of continuous playing without air renewal in the player’s lungs. A calculation of the sound speed for such gas was performed, in which the oxygen (O₂) was supposed to decrease linearly with the CO₂ variation, from 21%, at the starting point, to 15% when the CO₂ achieved its maximum value of 8.5%. The predicted variation in sound speed, equivalent to the shift in the sounding frequency, would achieve 30 cents (100 cents = 1 semitone) for the whole range of gas variation if the model was close to reality.

For a full appreciation of the total gas change effect it is also required an accurate measurement of the oxygen curve. In this paper, simultaneous measurements of CO₂ and O₂ are performed during long notes with an oboe and a bassoon, enabling a better basis for the prediction of the playing frequency shift. As a way of corroborating the predicted effect, an experiment is run in which a device is used to replace the natural embouchure while the instrument is blown by a player, the mouth pressure being kept constant; the blowing pressure and the audio signal of the “fixed tones” were recorded for further frequency analysis. The reason for keeping the blowing pressure constant is due to the fact that the sounding frequency is also a function of the input pressure (Bak & Doemler, 1987), having a positive relation: the higher the mouth pressure, the higher the resulting frequency.

Measurements of CO₂ and O₂ levels during playing

Materials and methods
The experimental protocol consisted of two different procedures:
1) Measurement of the percentage of CO₂ and O₂ in exhaled air during the playing of long notes, at constant dynamic level and blowing pressure, in the oboe (note E₅, 60 cm H₂O of pressure, sounding mezzoforte) and bassoon (note B♭₃, 30 cm H₂O of pressure, mezzoforte). The instruments were regularly played by a musician, starting immediately after a deep breath. The air inside the instrument bore was continuously sampled by an air pump unit (Ametek R-1 Flow Control Device), at a rate of 180 ml/min. The sampled gas flowed through a 1 meter long, 2.5 mm Ø plastic hose inserted into the instrument, with the open extreme located at the medium distance of the air column. The aspirated gas flowed first through a Capnograph (Ametek P-61B Sensor Unit and CD-3A Carbon Dioxide Analyser) and then through the oxygen meter (Ametek N-22 Oxygen Sensor and S-3A/I Analyser). The readings from the devices, and the audio signal were recorded by a multichannel...

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Figure 1. Mouthpiece device which enables the reed to vibrate without contact with the player’s lips. The player blows directly through the air inlet. The adjustable clamp, not shown in detail, incorporates a piece of rubber to press against the reed, thus simulating the effect of the lips. For the bassoon experiment, a similar device was used.

TEAC (RD-200T) PCM DATA recorder, for eventual transfer into a personal computer.

2) A musical subject blowing through a special mouthpiece device (Fig. 1), which enables the reed to vibrate at a fixed degree of tension, without contact with the player lips, while the exhaled air is kept at fixed pressure. The task consisted of playing a long note after a deep breath, then breathing again and producing long notes (two times in sequence), then taking a 5 seconds break and attacking again (with the same breath), taking a new breath and attacking again and finally doing a circular breathing manoeuvre (see description at discussion section) before a final long note. Blowing pressure was sensed by a calibrated transducer (Gaeltec S7b) placed in the mouthpiece device chamber and recorded in the PCM DATA recorder, together with the signals of the gas sensors referred above. A microphone (Sony ECM-959DT) picked up the audio signal, also recorded into a 20 kHz channel.

Experiments were run in a well ventilated room, for which the pre-calibrated analyser showed a reading of 0.03% ambient CO2. A professional musician (the author) was the sole subject. During the experiment, all output signals, excepted by the blowing pressure readings, were out of the subject’s sight. The visual feedback for the blowing pressure values was necessary as a means of ensuring the subject a fine control for a fixed input pressure.

Analysis and results from gas measurements

The recorded signals were transferred from the TEAC recorder into computer files, using the Swell™ DSP software package installed in a PC computer with an Ariel DSP-16 board. The results were obtained after a simple procedure of calibration, implying that the zero and range of the computer files were adjusted so as to match the corresponding original readings from the CO2 and O2 analysers.

Both gases varied continuously during all measurements, and as expected, the CO2 percentages increased simultaneously to the decrease of O2. The variations for CO2 percentages ranged between 0% and 8.5%, as previously observed by Fuks (1996). The O2 contents at the end of long phrases decreased to values of less than 12%, and in some extreme cases reached approximately 11%. These values substantially extend the range as presented by Schmidt & Thews (1983), where a minimum of 14% is referred. A typical curve for both gases variations is presented in the upper part of the graph in Figure 2. In that particular case, the subject played the tone E5 in the oboe, using a blowing pressure of 50 cm H2O. The curves obtained for different tones and blowing pressures all present the same general aspect, with minor differences as a function of playing time and airflow through the reed.

Calculations of expected pitch variations

Once the realistic values for the CO2 and O2 percentages were obtained during the former measurements, we proceeded with the computation of the expected pitch variations. A spreadsheet program was used for implementing expressions (1.1) and (1.2), according to Nederveen (1969), and plotting the results, shown in the lower part of Figure 2. A temperature of 25.5°C was assumed as the equilibrium value for a warmed up instrument, in good agreement with previous measurements in the oboe as 25.6°C (Meyer, 1961) and in the flute, 26.8°C (Coltman, 1966). At that temperature, the
specific humidity of saturated air is approximately 2.07%.

\[
\frac{c}{c_0} = 1 + \frac{T}{546} + \sum \frac{1}{2} r_v \left[ 1 - \frac{\rho_v}{\rho} - \frac{2(h_v - h_0)}{h_v(2+h_v)} \right] \tag{1.1}
\]

\[
\frac{\rho}{\rho_0} = 1 - \frac{T}{273} + \sum r_v \left( \frac{\rho_v}{\rho_0} - 1 \right) \tag{1.2}
\]

c = velocity of sound in the gas mixture
c_0 = velocity of sound in typical dry air, at 0°C
\( \rho, \rho_0, \rho_v \) = densities of the mixture, the typical air and the additional gas, respectively
\( r_v \) = fractional pressure of additional gas

\( T \) = temperature of the mixture, in Centigrade.
\( h_0, h_v \) = number of degrees of freedom of standard air and each additional gas, respectively, whereby

\[
h = \text{Int} \left( \frac{2}{\gamma - 1} \right) \tag{1.3}
\]

Int \([ \ ]\) being the closest integer value of \([ \ ]\)

As can be seen in Figure 2, the expected pitch variations are more pronounced in the early period of blowing after a deep breath. During an initial time interval of approximately 5 seconds, a relevant dip of 15 to 20 cents (approximately one fifth of a semitone) was calculated.

**Measurements of variations from performance**

Procedure (2) was performed in the oboe and bassoon. The sound files, at a sampling rate of 20kHz, had their fundamental frequency extracted by a signal processing program (FoX-Nyvalla). A typical example of such data is shown in figure 3, the bassoon producing the note B3 with a blowing pressure of 30 cm H2O, sounding as a mezzoforte tone.

The curve in figure 3 is shown in its raw appearance, without any filtering or smoothing. This aspect is due to the program’s algorithm for pitch extraction. A quite similar pattern as shown in figure 3 was observed in all recordings done with the oboe and bassoon. The pitch invariably decreases from the attack and reaches an almost plateau line. Immediately after a new breath, there is a sudden increase in pitch and a similar pattern is repeated. After a break in the sound, followed by a new attack and without the player re-breathing, the tone re-starts at the same pitch level and keeps decreasing (Fig. 3).

When a circular breathing is performed, the air content of the lungs is renewed without the interruption of the sound, and a sudden increase occurs, as in the previous events.

*Figure 2. Measured CO2 and O2 contents (upper part of graph) and computed expected pitch shift (lower part). The zero cent reference corresponds to ambient air. The temperature was assumed as 25.5°C and the air is saturated with specific humidity of 2.07%.*
Discussion

The results from the preceding section show that the sounding frequency considerably fall in the order of 10 to 17 cents between the onset just after a new inspiration and a time interval of approximately 15 seconds, when the pitch tends to stabilise. However, the pitch variations observed never reached the predicted 23 cents, shown in the lower part of figure 2. This error may have different factors, probably one of them related to variations in the humidity of the gas blown into the instrument, which was not controlled or measured in this experiment.

Temperature is generally regarded as a factor of major relevance to the tuning of feedback wind instruments. Thus, warming the instrument, e.g. by playing or by blowing expired air through the bore, is a routine among wind instrumentalists. As explained in a preceding section, a warming from room temperature of 20°C to 25°C corresponds to a sharpening of the pitch by about +17 cents. It is interesting that the rarely discussed variations of exhaled air content during playing are comparable to the commonly recognised effects of temperature. However, the variations in pitch due to gas composition are necessarily cyclic, while the temperature effect tends to stabilise with continuous playing.

The formulae used for the air speed calculation (expressions 1.1 and 1.2) apply to small changes in the gas percentages. It is beyond the scope of this article to investigate the error in velocity prediction for the percentages used, which is being planned for future work.

The mouthpiece device used for the experiment has an internal volume of ca. 40 cm³. This fact produces an increase in the anatomical dead space. Probably, it works as a buffer that attenuates at some extent the quick fall in pitch predicted by our calculations.

Presumably, the pitch effects induced by the gas variations are compensated for by the player by means of varying embouchure, blowing pressure and other playing characteristics. The ambient CO₂ and O₂ contents depend on many factors, e.g., the number of people in a room and the air quality. However, if the player is in a room with acceptable levels of ventilation, there is no reason to consider that the effect will reflect in very different results.

In addition to the gas-changes effect, one could also argue that on the beginning of a note, if the player has comparatively higher levels of lung volumes, it is much easier to produce higher blowing pressures. Also, blowing pressure affects the sounding pitch in a positive way (Bak & Doemler, 1987). We could suggest that the

Figure 3. Pitch variations observed during a B3 played in a bassoon (mezzoforte), blowing pressure of 30 cm H₂O. The player used the device depicted in Figure 1, following the procedure described above. The zero reference is defined by the initial pitch at the first attack.
combination of both effects give rise to a strong trend of playing at higher pitch on the beginning of a phrase and a progressive decrease with time (lung capacity), mainly for instruments and tones that require higher pressures. It is a well known fact in human speech production that there is a general trend for the average voice pitch to fall, as the lung volume is reduce and also the subglottal pressure. It would be interesting to investigate if the same phenomenon ($F_0$ fall) takes place in solo wind playing.

We could propose that the same pitch variation effect will take place in other winds, including brass instruments and the flute. However, due to large differences in the airflow used in each case, there is a need of further experiments for a realistic account of the phenomenon.

Some anecdotal evidence and technical recommendations among professional musicians seems to support the assumption that the predicted gas effect on pitch in wind instruments is realistic. Oboe, clarinet and bassoon players tend to agree that there is a general trend for the pitch of the instrument to drop during long phrases. Particularly for the notes in the lower range of the instruments; it may be very difficult to keep the pitch in tune, even with the use of all possible compensatory efforts. It is generally assumed that this is due to a fatiguing of the muscles involved in playing. While this seems a reasonable assumption, there are also reasons to believe that the gas variations are also important. For example, the use of a quick inhalation or of the so-called circular breathing technique is said to help restoring the desired pitch. Circular breathing is a technique in which the player keeps blowing into the instrument while air exchanges take place through the nose. To accomplish it, an amount of air is saved in the mouth cavity, isolated from the remaining airways by pressing the soft palate against the back of the tongue. Also, many professional players recommend exhalation of a small volume of air just after the inhalation and before starting a tone (e.g. Robinson, 1996). This procedure is usually claimed to improve production of soft attacks, facilitate intonation control and create a more relaxed respiratory feeling.

Conclusions

During playing wind instruments such as the oboe and the clarinet, the content of CO$_2$ in the expired air varies between the ambient level and up to 8.5% in extremely long phrases, while for the O$_2$ it may vary from the ambient 21% down to 12%, or even less. The increase in CO$_2$ tends to decrease the pitch and the fall in O$_2$ tends to increase pitch. Even then, due to differences in gas properties and the rate with which the gases vary, the total effect is that of pitch decrease. This effect may account for a fall in fundamental frequency of the tones by almost 20 cents. Although we could presume that the pitch effects induced by gas variation are compensated for by the player by means of varying embouchure, blowing pressure and other playing characteristics, this effect still seems a relevant factor in wind instrument playing.

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