Proceedings of the International Symposium on Music Acoustics
(Associated Meeting of the International Congress on Acoustics)
25-31 August 2010, Sydney and Katoomba, Australia

Clarinet parameter cartography: automatic mapping of the sound produced as a function of blowing pressure and reed force

André Almeida (1), Julie Lemare (1,2), Mark Sheahan (3), John Judge (4), Roman Auvray (2), Kim Son Dang (5), Sebastian John (2), Jean Geoffroy (2), Jay Katupitiya (5), Paul Santus (2), Andrei Skougarevsky (2), John Smith (2) and Joe Wolfe (2)

(1) Laboratoire d'Acoustique de l'Université du Maine, France
(2) School of Physics, The University of New South Wales, Sydney, Australia
(3) School of Computer Science and Engineering, The University of New South Wales, Sydney, Australia
(4) NICTA, Sydney, Australia
(5) School of Mechanical and Manufacturing Engineering, The University of New South Wales, Sydney, Australia

PACS: 43.75.EF

ABSTRACT

In simple models of a single-reed instrument mouthpiece, important control parameters include the air pressure in the mouth, the force applied by the lip on the reed, the position at which it is applied and the damping of the reed. In these simple models, position and damping are usually considered constant while pressure and force are regarded as the key control parameters. Pressure in the mouth is easy to measure during human performance. The lip force is harder to relate to the gesture of the musician because the range of forces applied by a player depends on several factors including the reed stiffness and profile, and the distribution of force on the reed. When the instrument is played by a mechanical device, greater independence and control of these parameters is possible. This study uses an automated clarinet playing system developed during a series of student projects involving NICTA and UNSW (hence the long author list). The mouth pressure is controlled, and two further parameters control the lip force and its position of application. The precision and short-term stability of this control allow a systematic study of the pitch and volume of the clarinet for a wide range of these three parameters and, in principle, up to 2^{15} fingerings. This allows the mapping, in fingering, pressure and lip parameter space, of the regions that produce the intended note, poorly tuned notes, notes in another register, slowly starting notes, squeaks or no sound at all. Maps measured with different protocols are here compared with the predictions of theoretical models.

INTRODUCTION

Control variables to music variables

Performance on a wind instrument requires the player to provide physical gestures that comprise variation in a number of physical variables, which we regard here as inputs to the instrument. These gestures produce musical sounds: the output of the instrument. The mapping from gestures to music is a fascinating topic: On one hand, a complete knowledge of the mapping would be an important physical characterisation of the operational properties of the musical instrument. On the other, an implicit knowledge of aspects of this mapping is an important part of the technical side of being a performing musician.

Some researchers measure the gestures of expert musicians and the sound produced (e.g. [1,2,3,4]). Although such studies are of great intrinsic interest, they are scientifically complicated because, in such performances, several variables are varied simultaneously. Further, large regions of parameter space are not investigated – perhaps including regions well traveled by beginners.

For wind instruments, these complications and limitations may be avoided by using artificial mouths (e.g. [8]). These and more elaborate playing machines can, in principle, hold some variables constant for extended periods of time while others are varied. In principle, this allows detailed, regularly sampled mapping of a large region of the space defined by the input variables.

The mechanical clarinettist

The mechanical clarinet player here was only partly inspired by this aim: its primary motivation came from staff of an information technologiy research centre (NICTA) who wished to enter a competition for automated instrument players and who consulted the music acoustics laboratory for that reason [7]. The player was designed and constructed rapidly by staff and students from several disciplines from both NICTA and UNSW, whence the lengthy author list.

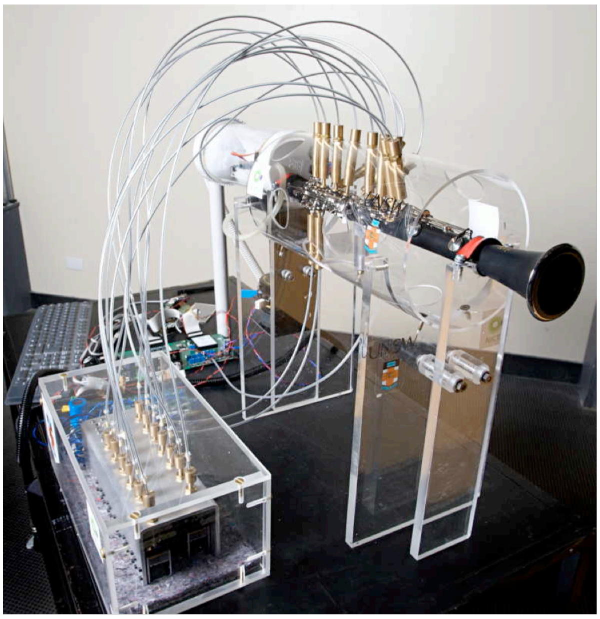

Figure 1. The automated clarinettist

In this study of the clarinet, the output variables that we report are the frequency, sound level and spectrum, all of which vary in time. For a given clarinet, these outputs are expected to depend on the following inputs:

- the fingering (i.e. which keys are closed or open),
- the average pressure P in the mouth (hereafter mouth pressure),
- the reed stiffness and geometry,
- the magnitude F and the distribution in space of the force applied by the lip on the reed,
- the damping provided by the lip on the reed,
- transient application of the tongue to the reed,
- the impedance spectrum of the vocal tract,
- aero-acoustic effects in the mouth and
- the temperature and humidity of the air in the instrument.

Of these inputs, we control fingering, mouth pressure and the force distribution on the reed. The keys and tone holes are controlled by pistons pushed by springs and withdrawn by latching solenoids. The pressure is controlled on the time scale of seconds by controlling the speed of a pump that supplies air to the 'mouth' and, on short time scales, by a variable shunt from the mouth to the atmosphere. The short-time variations are controlled automatically by a PID loop which compares the requested pressure to a measurement in the mouth. This allows the pressure to be held constant even when the flow changes due to variations in the short term average flow through the mouthpiece.

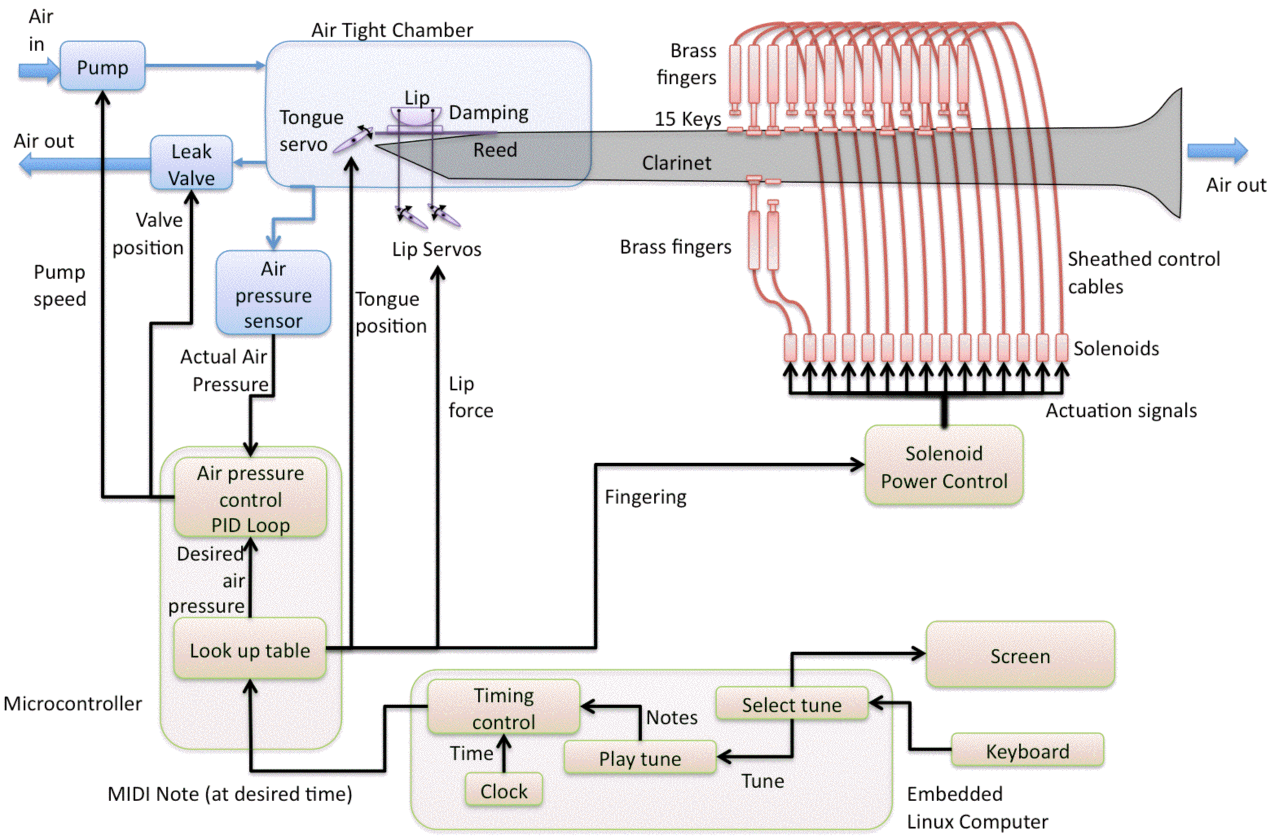

Figure 2. A schematic of the clarinettist showing the mechanisms and controllers. Not to scale.

The 'lip' is a layer of flexible plastic pushed against the reed by a rigid, curved plate (the 'teeth', see Figure 2). Two servo motors provide the force at either end of this plate via two loops of thread: the sum F of these forces can be varied, and varying the proportions of F provided by the two motors effectively applies the force at different positions (see Figure 3). The 'tongue' is connected to a third servo motor but has only binary control: a soft pad either touches or not the tip of the reed, allowing the production of an initial transient, which is sometimes important in achieving the desired steady state. This control is not used in the present work.

Reed stiffness, reed geometry and lip damping are not deliberately varied and are assumed to remain constant as long as the mouthpiece is kept in place, and the temperature and humidity of air in instrument are effectively constant. The 'mouth' was designed to have no strong variation in aero-acoustic effects and no strong 'vocal tract' resonances.

Both the mouth and fingers are controlled by a microcontroller that is, in turn, connected to an embedded linux computer. Programs running on the embedded computer control the clarinet by requesting actuation of the various components via a serial line connection with the microcontroller. The microcontroller also runs the PID loop to maintain the requested air pressure in the mouthpiece. Measurements that require several hours can be performed, in a controlled way, with no human intervention after the initial setting-up.

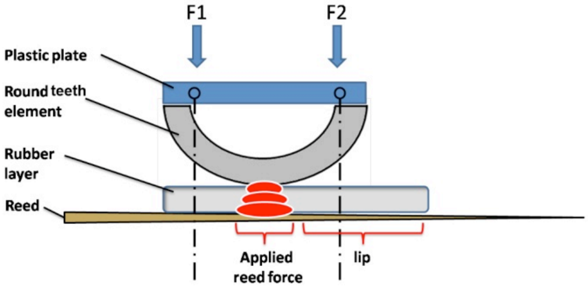

Figure 3. Forces $F1$ and $F2$ are applied to the elements that take the roles of teeth and lips to press against the reed.

Setting aside for the moment the sound spectra, this control allows us to map sound level L and frequency f as functions of fingering, P and F. Here we restrict fingering to one 'standard' fingering for each note over the standard range of the instrument. This is a simplified subset of the controls available to human musicians. Measurements of vocal tract impedance have shown that, even in normal playing, experts adjust resonances of the vocal tract [3]. However, in normal playing, the acoustic impedance in the mouth has a magnitude rather smaller than that in the bore of the instrument and so such resonances are expected to have only a small acoustic effect.

Transient response of the control parameters

During performance, rapid but small variations in pressure are achieved by controlling a leak valve. To raise the pressure from zero using the pump, however, takes about 200 ms (the maximum flow rate from the pump divided by the air volume in the mouth and in the airway tubes leading to it).

Fortunately, this slow response is not important for musical contexts: music performance does not call very often for notes to be initiated by fast increases of the mouth pressure: rather, they are either initiated by tonguing or, when tied to a preceding note, by a change in fingering. The mechanical tongue (5 in figure 2) acts like a human player's tongue: it seals the reed to the mouthpiece while the desired initial pressure is achieved. Then it opens suddenly, providing both a reed displacement transient and a pressure transient to initiate reed vibration. Once the mouth pressure transient is past, its value is stable, with variations of less than 5%. However, unlike an expert human player, the automaton does not make any prediction on how much the air supply has to be adjusted when the flow through the clarinet changes, so the pressure response to the changed conditions when two notes are slurred together is determined by the PID controller.

The time required to change the lip force depends on the amplitude of the change. However, a full range change (from 0 to about 3 N), takes less than to 100 ms to accomplish.

Musical paths on the map

For any given fingering and reed arrangement, a small part of the (P,F) plane represents the region over which a steady note is possible. From the physical point of view, the boundaries of this region are theoretically interesting. From the musical point of view, a line in the $f(P,F)$ surface represents good intonation. Along that line, varying P and F allows one to vary sound level independently of frequency: a much desired control for expressive playing. For these reasons, we concentrate here on the maps $f(P,F)$ and $L(P,F)$, to investigate how L may be varied at constant f by suitable coordinated adjustment of P and F.

Calibration and control parameters

The device can be programmed to run by itself or under remote control either to perform tunes or to perform experiments. A prerequisite is what we call a recalibration of the control parameters for a particular set-up being used.

As human clarinettists are aware, even small changes in the properties of a reed or in its position on the mouthpiece require different regimes of the control parameters to produce the desired outputs. Having set up a new (or newly modified) reed on the mouthpiece, the human clarinettist typically plays a selection of notes across the range and, by a subtle process that we cannot emulate, 'calibrates' the range of control variables that will be required. The musician also relies on a real-time adjustment based on his perception.

Our calibration is a simplistic reproduction of this. The clarinet system is very sensitive to small changes in the force distribution over the reed and, at the moment, this variable is only controlled by varying $F1$ and $F2$ and thus rolling the teeth element. Consequently, for the device to play music, any material modification (reed or mouthpiece change, lip position adjustment) demands a new calibration of the device. For each desired note (and thus fingering) the range of values of P and of $F1$ and $F2$ that produce a stable and homogeneous tone has to be determined across the playing range of the instrument. One of the incidental outcomes of the current study will be, we expect, an automated procedure for determining these values.

For the simple cartography experiment, however, we are interested in all regions of control parameter space, even those that produce no sound or a squeak.

A computer equipped with a sound card is used to adjust the mouth parameters systematically within a specified range and at regular intervals. Once the parameters are stable, a 500 ms sample of sound is recorded and analysed for its spectral content.

RESULTS AND DISCUSSION

Mapping of sound characteristics throughout parameter space

The aim of this experiment was, for each standard fingering of a B^b clarinet, to sample accessible regions of the parameter space and to analyse the sound produced for each set of parameters. To reduce the number of dimensions of this space, only the front servo ($F2$) and the pressure (P) were varied.

The procedure was as follows:

- Set the fingering for a note,
- Set the pressure and reed position to a low value (corresponding to an open reed),

- For each value of reed position run through increasing then decreasing pressures (maximum and minimum pressures are chosen)
- For each value of pressure record 0.5 seconds of sound and analyse it
- Set a new value of reed position.

As an example, Figure 4 shows the results produced using the procedure described above for a particular fingering corresponding to (written) A#3, a note in the middle of the chalumeau or first register. Frequency is represented as a gray scale and intensity as bar height. Frequencies that differ more than half an octave relative to A#3 are plotted as thinner bars. They usually correspond to high pitch tones known as squeaks.

The two graphs distinguish increasing (top) and decreasing (bottom) pressures. The differences between them show hysteresis: the pressure limits within which a note is produced are not the same for the two graphs, nor are the intensities and frequencies of the corresponding notes. A consequence is that it is not sufficient to aim for a particular pressure and mouth configuration to produce a desired sound, but it is also important to take into account the evolution of these parameters before arriving to the target values.

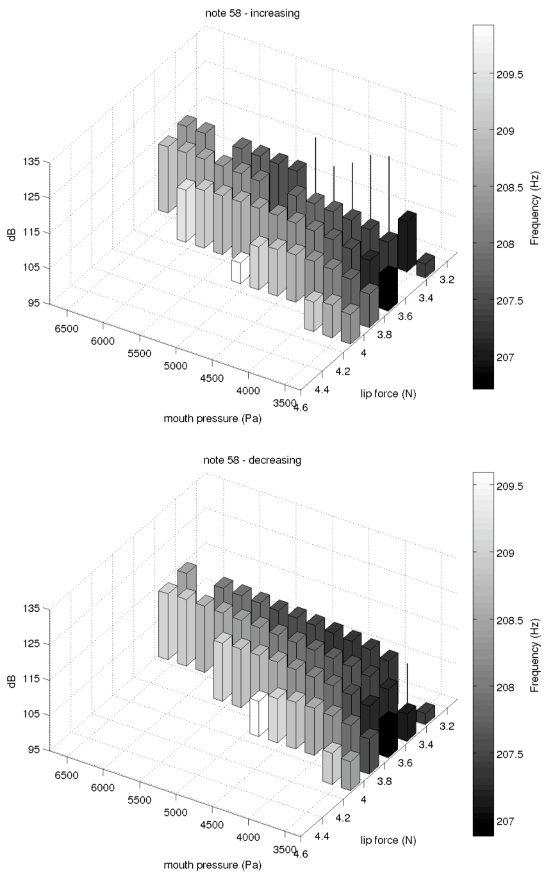

Figure 4: Plots of playing frequency as a function of air pressure and lip force $f(P,F)$ for the note (written A#3). In this run, F was held constant while P was increased (top) or decreased (bottom). Narrow columns are 'wrong' notes produced with this fingering, usually squeaks.

A similar experiment is done sequentially varying reed forces. The aim is to check whether the sound characteristics vary on the parameter path used to reach a particular state. The limits of the playing range do not seem to vary greatly with the direction of lip force variation. The oscillation threshold is slightly extended relative to the measurements made with sequential pressure increases.

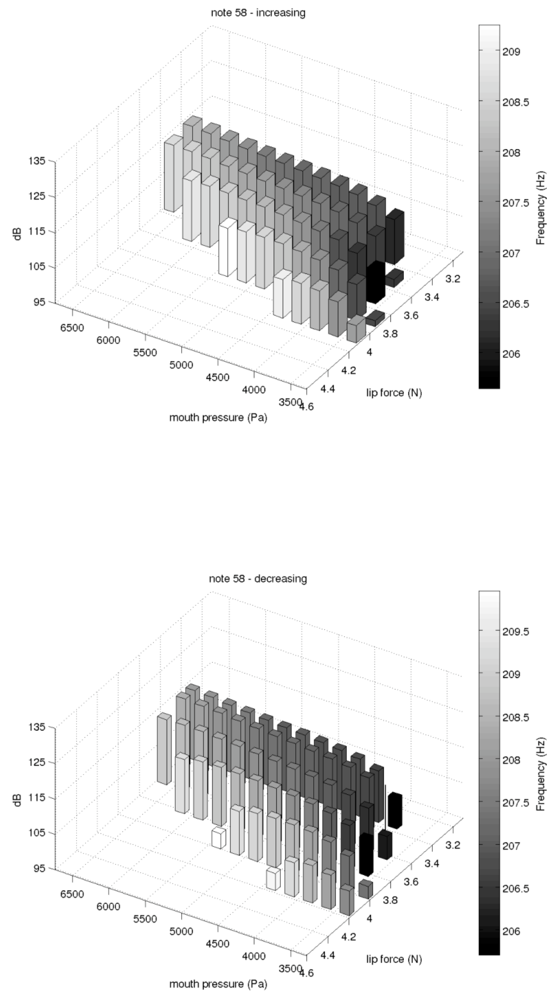

Figure 5: $f(P,F)$ for the same note (written A#3). In this run, P was held constant while F was increased (top) or decreased (bottom).

In the following discussion, we compare our results to analyses found in the literature. We make the simplistic assumption that a decrease on the reed force is proportional to a more open reed rest position.

Role of the back force

By comparing the maps with different back forces $F1$ (data not shown), we conclude that the force added to the back part of the reed has a negligible influence both in frequency and intensity of the played note. A change in the timbre of the note can be perceived, and for wide open reeds a softer back force (i.e. having the teeth closer to the tip) produces more stable notes and prevents the appearance of squeaks. All of the results presented in this article are performed with the same relatively low back force.

Extinction and reverse oscillation threshold

A comparison of the maps for increasing and decreasing pressures shows that the oscillation starts and stops at slightly different values of pressure.

As the reed opening is increased, a higher pressure is necessary to stop the oscillations, as seen by Dalmont and Frappé [6]. In their work, the difference in high-end pressures is typically about 30%. In our experiments the difference is not as high. An explanation to this fact could be found in Raman's model [5], which predicts that the two limit pressures become closer to each other as the acoustic losses increase in the resonator.

Raman's model does not predict a difference between the ‘oscillation’ threshold and the ‘reverse-extinction’ threshold at the low pressure ends, which is nevertheless observed in our results. This may be related to an observation with (human) clarinettists: a typical time-variation curve of the pressure in the mouth of a musician usually has a short overshoot: a higher pressure at the attack than in the sustained part. This is probably related to the fact that, at threshold, the growing time of the oscillation tends to infinity. A sharper attack can be obtained by first increasing the pressure and in a second stage reducing it to the desired value at sustain. In the mechanical clarinettist, this overshoot is not easy to perform with the current pressure control. However a limited time (less than 1 second) is allowed for the oscillation to grow which can be shorter than the time needed for a significant oscillation near threshold.

Dalmont and Frappé [6] observed an oscillation threshold that did not change as the force on the reed increased, in agreement with model predictions. Our data show a slightly increasing oscillation threshold as the force on the reed decreases.

Characteristics of the sound in the playing range

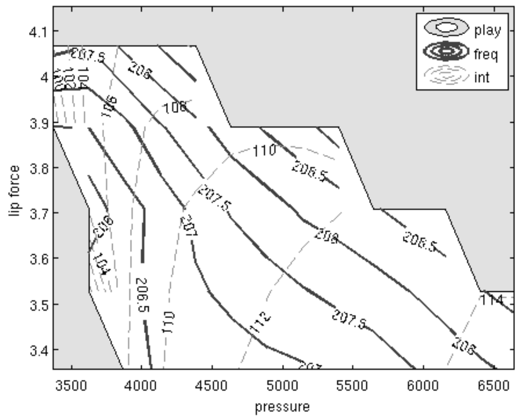

Figure 6: $f(P,F)$ for an experiment with varying F for the note written A#3.

A simple interpolation technique allows tracing of regions of the parameter space corresponding to constant frequencies or constant intensities of the note played by the instrument. As shown in Figure 6, constant-frequency lines are roughly parallel to the extinction threshold.

This result is of interest in music performance: to produce a crescendo at constant pitch, as mouth pressure is increases, F must be decreased. One of the reasons for this is that both lip and air pressure tend to increase the contact between the reed and the lay, and thus change the mechanical properties and thus the resonant frequency of the reed. The reader is reminded, however, that changing F in this case simultaneously changes the position at which it is applied.

The shape of constant intensity lines is slightly more complex, and is more dependent on the note played and the reed properties. Globally, however, higher intensities are usually produced in the central region of the playing range. The pressure amplitude in the bore is expected to follow roughly the mouth pressure until a saturation limit is reached when the reed starts beating against the lay. Beyond this point, the reed stays closed for an increasing fraction of the oscillation until it finally closes completely and stops oscillating.

Squeaks and timbre

Squeaks tend to occur near the limits of the playing range. Boundaries between squeaking regimes and normal tones are less repeatable than the limits of the playing range. They are also harder to explain with a static model such as Raman’s, as their appearance can depend on the time evolution of the parameters. As described above, the current mechanical clarinettist does not allow a fine control of this evolution.

Although timbre is out of the scope of this article, it was clear by listening to the produced sounds that the timbre of the note becomes brighter close to the high-pressure edge of the playing range, where squeaks often occur.

CONCLUSION

The mechanical clarinettist developed by NICTA and UNSW has shown in the past its capacity for music performances [7] and in a competition for automated musicians [9]. The scientific interest in the device is as a tool for exploring the behaviour of the clarinet in controlled playing conditions. This example of its use is the determination of parameter maps showing the characteristics of the sound for a wide range of parameters applied to the clarinet. Much of the behaviour predicted by simple models is found in the maps, of which examples are shown here. The results show a dependence on the history of the system in reaching a particular point in the parameter space, even if the evolution cannot be precisely controlled.

Further improvements, such as the stabilisation of the reed position can be expected to improve the results obtained in these maps. The results from these maps, and an automatisation of the algorithm will allow an automatic adjustment of the parameters to changes in the interface between the reed and the lip. The ability, not discussed here, to control the opening and closing of the lateral holes in the resonator will be used in future to study transients in note transitions.

ACKNOWLEDGMENTS

NICTA is funded by the Australian Government as represented by the Department of Broadband, Communications and the Digital Economy and the Australian Research Council through the ICT Centre of Excellence program. We thank Légère for providing synthetic reeds.

REFERENCES

1 I. Cossette, P. Monaco, A. Aliverti and P.T. Macklem “Chest wall dynamics and muscle recruitment during professional flute playing” *Respir Physiol Neurobiol.* **160**, 187-95 (2008)

2 A. Almeida, R. Chow, J. Smith and J. Wolfe, "The kinetics and acoustics of fingering and note transitions on the flute” *J. Acoust. Soc. Am.* **126**, 1521-1529 (2009)

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

4 C. Palmer, E.,Koopmans, J.D. Loehr, and C. Carter, “Movement-related feedback and temporal accuracy in clarinet performance” *Music Perception,* **26,** 439-449 (2009)

5 J.P. Dalmont, J. Gilbert, J. Kergomard, J. and S. Ollivier, “An analytical prediction of the oscillation and extinction thresholds of a clarinet”. *J. Acoust. Soc. Am*, **118**, 3294-3305 (2005)
6 Dalmont, J.-P. and Frappé, C. “Oscillation and extinction thresholds of the clarinet : Comparison of analytical results and experiments” *J. Acoust. Soc. Am.* vol. **122**, 1173-1179 (2007)
7 Music Acoustics UNSW “Robot clarinet” www.phys.unsw.edu.au/jw/clarinetrobot.html
8 A. Almeida, CA. Vergez, and R. Caussé, “Quasistatic nonlinear characteristics of double-reed instruments”. *J. Acoust. Soc. Am*, **121**(1), 536 (2007).
9 Artemis Orchestra competition: https://www.artemisia-association.org/photo_gallery_2007-2008