Acquisition and study of blowing pressure profiles in recorder playing

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ABSTRACT

This paper presents a study of blowing pressure profiles acquired from recorder playing. Blowing pressure signals are captured from real performance by means of a a low-intrusiveness acquisition system constructed around commercial pressure sensors based on piezoelectric transducers. An alto recorder was mechanically modified by a luthier to allow the measurement and connection of sensors while respecting playability and intrusiveness. A multi-modal database including aligned blowing pressure and sound signals is constructed from real practice, covering the performance space by considering different fundamental frequencies, dynamics, articulations and note durations. Once signals were pre-processed and segmented, a set of temporal envelope features were defined as a basis for studying and constructing a simplified model of blowing pressure profiles in different performance contexts.

Keywords

Instrumental gesture, recorder, wind instrument, blowing pressure, multi-modal data.

1. INTRODUCTION

The process of music performance offers great opportunities for pursuing research on instrumental gestures when investigated from a computational approach based on data observation and analysis. Within the process, the musical message is represented as a written score containing an ordered sequence of note events and annotations of discrete nature. Such message implicitly conveys a significant amount of instrumental gesture-related information that is relevant to the musician. The performer interprets the score and transforms it into a set of physical actions of continuous nature intended to serve as controls for the musical instrument. Those are called instrumental gestures [8]. The acquisition and study of instrumental gestures is a very important task in music performance modeling because they provide relevant information about the internal process that develops the trained musician during the interpretation of a score. Furthermore, in the case of excitation-continuous musical instruments (e.g., bowed strings or wind instruments) the complexity of interaction makes the problem becoming much more interesting [8, 11, 10]. In general, modeling and studying instrumental gestures represents a challenging research pursuit from which many applications could benefit: music performance analysis and modeling, score-fed automatic sound synthesis, computer-aided musical pedagogy, etc.

In recorder playing, the blowing pressure is often seen as the most important instrumental gesture parameter modulated during performance. The recorder could be considered among the simplest excitation-continuous musical instruments, but the study of instrumental gesture parameters from real performance have been strongly limited by the intrusiveness resulting from a range of measurement techniques, all based on the introduction of plastic tubes (or *catheters*) in the mouth of a performer while playing. Moreover, the direct measurement of blowing pressure signals in flute-like instruments have been limited to the transverse flute, with many different studies carried out in the recent history. Fletcher [6] pursued a study of the relationship between blowing pressure and fingering, among other parameters. For that purpose, he used a $1mm$ catheter tube inserted into one corner of the performer lip opening. The tube was then connected to a sensitive aneroid pressure gauge which had been calibrated by comparison with a water column. As already pointed out, other researchers also dealing with transverse flute approached the acquisition of blowing pressure (or *breath* pressure) by inserting plastic tubes in the mouth of the musician: in the extraction of respiratory parameters during performance [3], in the study of performance techniques [10, 4], or in the analysis of frequency content of the breath pressure [12]. The main drawback of these approaches is the intrusiveness of the measurement: the performer is forced to modify her natural performance in order to adapt to the modified instrument. In fact, one does not find studies dealing with deep instrument modifications resulting in a reduced intrusiveness or enhanced measurement accuracy, mainly because strongly altering the instrument structure could easily lead to an alteration of the timbre of the produced sound [1]. This fact motivates the design of an acquisition system that enables the musician to play naturally (reduced intrusiveness) and provides accurate measurements of blowing pressure in order to observe and analyze different performance techniques.

In this paper, we present the use of a low-intrusiveness technique for the acquisition of blowing pressure in recorder playing, and the study of acquired pressure profiles. The technique is based on altering the mouth piece of a recorder by adding an additional air conduct, separated from the windway, to which a linearized pressure measurement device is attached. The system, while enforcing low intrusiveness and natural playing, provides an accurate measure of

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blowing pressure. A multi-modal database including aligned blowing pressure and sound signals is constructed from real practice, covering the performance space by considering different fundamental frequencies, dynamics, articulations and note durations. The temporal profiles of segmented blowing pressure signals is then analyzed on the basis of a number of envelope features defined from observations, and a series of numerical relationships is computed by matching pressure profile features and performance contexts.

The remainder of the paper is organized as follows. Section 2 provides an overview of the basic pressure-driven sound production mechanisms of the recorder, and previous related work. In Section 3, we introduce the acquisition device and setup, the construction of a database, and data pre-processing. Section 4 presents the definition of the envelope features being considered after observations, and a series of analyses regarding the relation of blowing pressure profile features and performance contexts. Finally, Section 5 concludes by summarizing important results and shedding some light on the imminent future work.

2. BLOWING PRESSURE IN RECORDER PLAYING

The recorder belongs to the family of the aerophones, which produce sound primarily by causing a body of air to vibrate without the use of membranes nor strings [15]. Normally, recorders are made up of three separable sections: the head, the middle and the foot piece. The head is the responsible for the primary sound production. The player blows through the windway of the instrument and the resulting air jet travels until striking the lip labium, placed in the opening of the resonator, i.e. the body of the instrument. The interaction of the jet with the standing air and with the lip labium creates a *von Karman* vortex street that makes the standing air inside the pipe to vibrate at its corresponding resonant frequency [7], ultimately resulting into the sound pressure radiation perceived as sound.

Two main acoustic models try to explain the complex phenomena happening in flute-like instruments: the jet-drive model by Fletcher [6] and the discrete vortex model by Verge [14]. Although the former has been very useful for understanding the basic sound production mechanisms, it neglects many details of the flow at the lip labium which appear to be fundamental for the performance of the instrument [13]. The latter basically describes the timbre of the instrument as a function of the dimensionless velocity of the air jet and the mouth geometry, and throws a very important conclusion about the energy transformations that happen during the sound production process: from the pneumatic energy coming from the air jet developed by the player, 95% is dissipated in the *mixing region* (a concept introduced by Elder in 1973 which refers to the coupling zone at the exit of the windway and the lip labium), i.e. the shedding of vortices at the edge of the labium causes 95% of the energy to dissipate. From the remaining 5% that is transferred to the acoustic oscillation of the air in the pipe, around 3 or 4% is dissipated in viscous and thermal losses to the pipe walls, so that only about 1% of the initial pneumatic energy is radiated as sound. Therefore, we consider that aiming at extracting blowing pressure by measurements carried out after the mixing region would lead to less representative correlates of instrumental control.

With regard to the main instrumental gesture parameters modulating perceptual attributes of the produced sound, the blowing pressure and the fingering could be considered as the most important. Indeed, blowing pressure, as opposed to fingering, presents a continuous nature and allows the control of dynamics, timbre, and fundamental frequency. During performance, blowing pressure is exponentially related to fundamental frequency [9], and linearly related to the dynamics, although it has not been quantified in an empirical way [10]. Fingering allows the performer to alter fundamental frequency and, in combination with blowing pressure, may also help to modulate dynamics. The configuration of the mouth and the vocal tract is, conversely, a very controversial issue: on one hand some claim that the vocal tract is coupled to the recorder and has certain (limited) influence on the sound [2, 6]; on the other hand, others consider that the player only modulates his mouth pressure [10, 4, 5]. In this work, we focus on traditional performance techniques (articulation and dynamics), assuming a fixed fingering position for each of the analysis contexts.

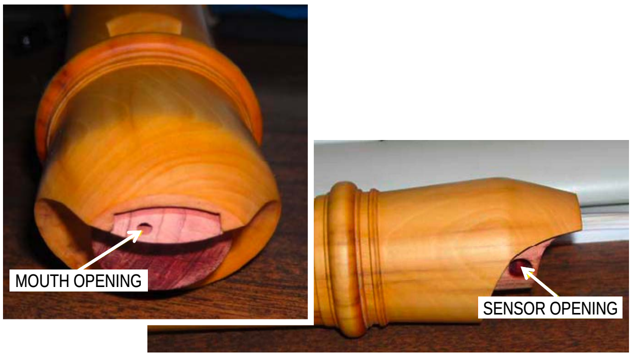

Figure 1: Detail of the openings in the mouthpiece.

In recorder practice, the performer can achieve a wide range of different articulations (from staccato to legato) by imitating nearly equivalent *consontant-vowel* syllables (e.g., "ta" and "da") in which the consonant describes the required tongue action, while the vowel indicates the continuation of breath required to maintain the note. This technique is usually called *tonguing*, and the syllables are in general treated as articulatory hints for the performer, but not as a prescription [9]: they indicate to the performer how to modulate the shape of the mouth, the motion and contact points of tongue, or even the amount of air coming from the lungs. In this work, we assume that the combination of these actions shapes the profile of blowing pressure.

Variations in dynamics are achieved through a change in the blowing pressure, although this phenomenon also causes the pitch to slightly change. The pitch of the instrument is correlated to the blowing pressure through an exponential relationship as it was claimed by Bak [9]. A similar correlation has been found for the transverse flute and it follows the relationship $P = 0.8 \times f$, as demonstrated by previous works [6, 10]. In fact, dynamics modulations are achieved through a combined effect of alternative fingerings and blowing pressure. Montgermont [10] studied this relationship between dynamics and blowing pressure for the transverse flute. For a given pitch, the amount of blowing pressure needed for achieving a higher dynamic is obviously higher. Basically, we can affirm that blowing pressure, fundamental frequency, and dynamics are highly correlated in recorder practice, as we will demonstrate in the next sections.

3. DATA ACQUISITION

Blowing pressure and radiated sound are synchronously acquired from real practice by means of a novel, low-intrusiveness measurement setup based on a modified recorder and

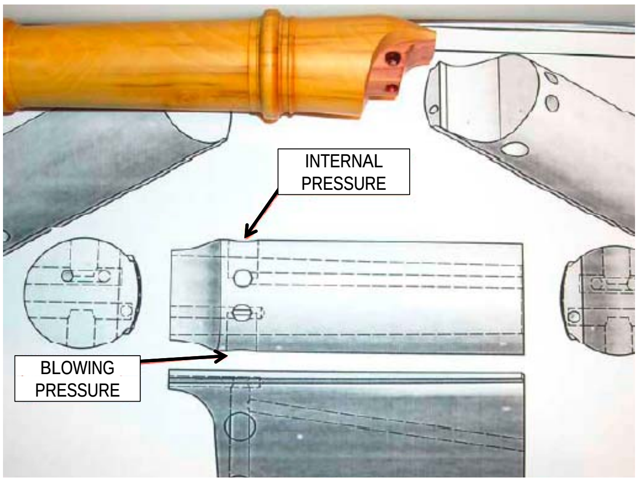

Figure 2: Further detail of the modified mouthpiece, where both ducts can be observed.

a close-field microphone. A set of scripts was designed in order cover a number of performance contexts when constructing a multi-modal database for posterior analysis of blowing pressure profiles.

3.1 Acquisition of blowing pressure

Special mechanical alterations were carried out in the mouthpiece block of an alto recorder that allowed the connection of two pressure sensors without altering the timbre of the original instrument: the intrusiveness was significantly reduced as compared to using a plastic catheter in the mouth of the musician, i.e. the performer could play the instrument naturally. The instrument was designed by the catalan luthier Josep Tubau, who carried out the modifications and tests with the aim of establishing two measurement points: (i) pressure in the mouth of the performer (or *blowing* pressure), and (ii) pressure at the closer end of the resonator pipe (or *internal* pressure).

The first measurement is achieved by means of a connecting duct that joins a hole at the mouth opening (i.e. the beginning of the windway) and another hole at one side of the mouthpiece, as it is shown in Figures 1 and 2. In this way, the air coming from the lunges of the performer flows through the windway and at the same time, the pressure is transfered to the sensor connected to the outer hole of the duct, outside the instrument. The second measurement is carried out thanks to an analogous technique, this time relying on a connecting duct with one of its openings at the closer end of the resonator pipe, as it is also shown by Figure 2. The second measurement, while very useful for studying sound production mechanisms, is not used in this work.

As for the pressure sensors, which had to provide a dynamic range of approximately $3000Pa$, we selected a model based on a piezoresistive transducer (attached to a silicon membrane whose deflection results almost proportional to the pressure applied) because of a great accuracy together with a small size. The model chose was the Honeywell© ACSX01DN[1].

The signal coming from the pressure signal was acquired using a National Instruments© [2] USB-6009 acquisition card, which provides a sampling rate of $48000Hz$ to be multiplexed among the number of signals to be acquired. In our case, two signals were acquired: the blowing pressure signal, and an audio metronome signal later used for synchronization with the sound signal acquired with the microphone (see below).

[1] http://sensing.honeywell.com/index.cfm/ci_id/154366/la_id/1.htm

[2] http://www.ni.com/

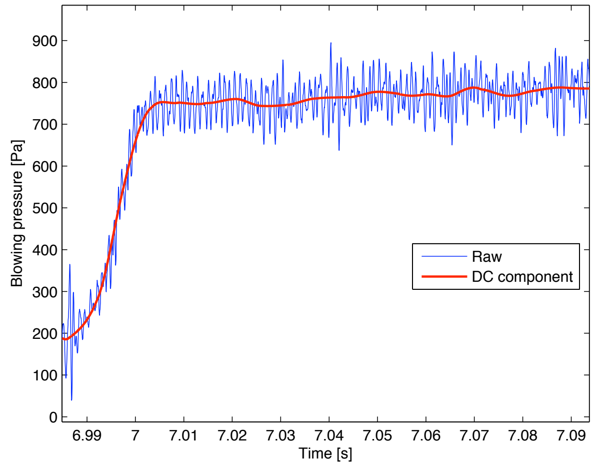

Figure 3: Raw and smoothed blowing pressure signals obtained from a note-to-note legato articulation played fortissimo.

3.2 Data pre-processing

Because of different sampling rates and time-propagated sample period inaccuracies (due both to hardware and software typical issues), the audio signal coming from the microphone and the pressure signal coming from the acquisition card had to be re-synchronized. For that purpose, a external audio metronome click signal was recorded both by the audio acquisition device and by one of the channels of the USB-6009 analog acquisition card. By means of a pulse detection algorithm devised for this purpose, metronome clicks were correctly detected from both metronome signals, and the obtained time stamps were used for resampling and synchronizing both signals [12].

The second step consisted on removing the higher-frequency component (at a frequency equal to that of the note being played) of the acquired pressure signal. The measured blowing pressure (as it happens with the pressure at the mouth) presents a coupling (resonant) frequency component (around which it oscillates) strongly depending on the effective length of the resonator pipe, i.e. it depends on the fingering of the performer. Filtering of this higher-frequency pressure (see Figure 3) component was achieved by means of numerical smoothing, using a quadratic-regression filter conveniently applied to the signal in order to avoid blurring pressure onsets and offsets.

The final step consisted in segmenting blowing pressure signals into single notes. For that purpose, a two-stage automatic segmentation technique was developed. First, onset candidates are generated for each note, mostly based on the absolute values of blowing pressure and its first three derivatives. Then an adaptive algorithm, making use of the nominal score and taking into account a maximum deviation of the performer, evaluates which of the generated onset candidates best matches a real onset. Resulting segmentations were manually revised in order to avoid errors in further analyses.

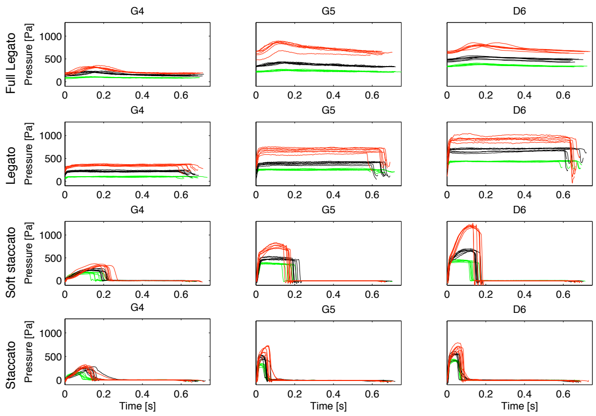

Figure 4: Blowing pressure profiles for different articulations (rows), fundamental frequency (columns) and dynamics (GREEN: pp, BLACK: mf, RED: ff); nominal note duration was 0.66 seconds.

3.3 Database structure

A multi-modal database, including aligned and segmented pressure signals and produced sound, was constructed after carrying data acquisition and processing from a number of recordings with a professional recorder player. A set of recording scripts (mainly musical exercises in the shape of repetitions and scales) was designed so that a balanced set of performance techniques is covered. Four main dimensions (or *performance context* parameters) were taken into account, leading to a total of around 10000 notes:

- **Pitch**. The recordings covered the whole tessitura of the instrument, in jumps of 2 or 3 semitones, for each combination of the other dimensions. Each pitch was performed by using a unique (the most common, according to the performer) fingering position.
- **Dynamics**. Each of the recording scripts is performed with three different dynamics: pianissimo (pp), mezzo-forte (mf), and fortissimo (ff).
- **Note duration.** Five different note durations were re-corded. These durations correspond to the duration of a quarter, eighth and sixteenth note at 90 BPM, and a eighth and sixteenth note at 120 BPM, respectively.
- **Articulation.** Four articulations (primarily regarded as 'tonguings' by the musician) were considered and labeled as *full legato* (no tonguing, but just diaphragm-driven blowing pressure oscillations), *legato*, *soft staccato*, and *staccato*.

4. DATA ANALYSIS

Data analysis first consisted in the observation of segmented blowing pressure profiles, and the identification of a number of envelope features as a basis of further systematic analysis and modeling in different performance contexts.

4.1 General considerations: towards an articulation-independent envelope model

In order to devise an envelope model able to consistently represent profiles in different performance contexts, the first step was to observe the blowing pressure envelopes. Figure 4 shows a general picture of the acquired envelopes: three different dynamics for each given articulation and pitch, all of them for the same note duration (also, only three different pitch values -one per octave- are shown). As a first clear observation, each articulation presents a characteristic shape, as a result of different tonguing (when existing). Secondly, the maximum value of blowing pressure reached within each note is positive-correlated with fundamental frequency and dynamics, as it happened for the transverse flute [10]. For the case of legato articulation (uninterrupted air jet, no tonguing) one can observe how the blowing pressure never falls down to the bottom line of 0Pa, as opposed to what happens with the rest articulation types, for which the air pressure gets interrupted during note-to-note articulations (tonguing effect). In fact, as it can be observed from the plots, one could interpret that in the staccato articulation notes are detached from each another by shortening the blowing pressure "pulses" (indeed corresponding to notes) and forcing a "silence" between consecutive notes. This makes clear an important difference between pressure profiles of staccato-like and legato-like note-to-note articulations. Moreover, the difference between the full legato and the legato is also substantial, but not in the case of the staccatos whose profiles have a more similar shape. Moreover, the attack and decrease blowing pressure slopes are softer for legato types than for staccato types.

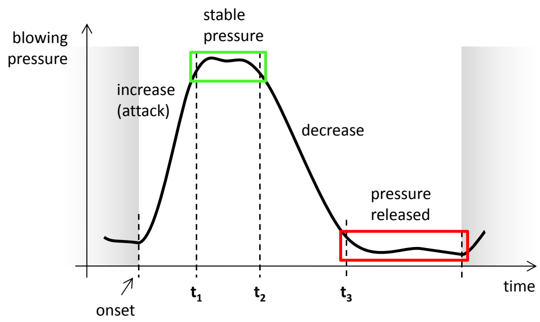

Figure 5: Schematic representation of the envelope model used in this work.

The envelope model used for quantitatively represent blowing pressure profiles is depicted in Figure 5. The model is used for all four articulation types, and is based on dividing the pressure signal into four different phases or segments. The first segment corresponds to the pressure attack, and it is characteristic to all four articulation types. In a second phase (after t_1 in the figure) the pressure reaches its maximum value. In all but the *full legato* articulation, t_1 defines the beginning of a stability with a higher pressure, during which most of the energy is transferred to the instrument. The third segment, defined between t_2 and t_3 corresponds to a decrease of the blowing pressure, and its pressence is equally common to all articulations, as it happened (obviously) with the attack segment. Finally, the blowing pressure is released, and a state of stability at its minimum value is reached (between t_3 and the onset of the following note. In staccato articulations, the last state is significanly long, and the pressure stays at 0Pa (the tongue interrupts the air flow). Conversely, the duration of this phase results extremely short for the case of legato articulations (as expected), mainly cause by the fact that yet blowing pressure is lowered, the air flow does not get completely interrupted.

The estimation of the segment durations (defined by t_1,

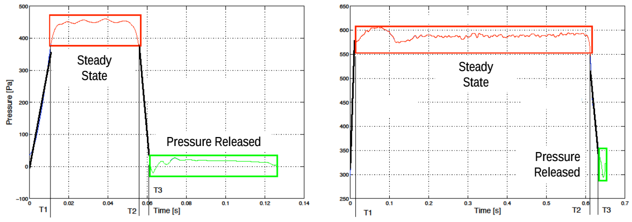

Figure 6: Examples of pressure envelope segmentation: staccato (left) and legato (right).

t_2, and t_3) is carried out automatically for all notes in the database. The limits of the second state are estimated by looking at how the instantaneous blowing pressure compares with a parameter $\Delta P = P_{max} - P_{min}$ that is computed for each note as the pressure dynamic range along its execution. The limits t_1 and t_2 are computed by by considering that pressure excurion during the steady state segment must be within 90% of ΔP. Analogously, the time limit t_4 is defined by considering that the pressure excursion during the last state must be within 10% of ΔP. Figure 6 shows two examples of envelope segmentation. Once the profiles are segmented, durations and slopes are computed for each segment, with the idea of analysing the role of performance context parameters (dynamics, articulation, etc.) in shaping the envelopes of blowing pressure.

4.2 Observations on dynamics and fingering

A straighforward analysis was first carried out by looking at the averaged value of blowing pressure of the steady state segment (see Figure 5) of notes. For that purpose, and with the aim of validating our findings in comparision with previous studies on the transverse flute [10, 6], computed pressure values were compared for different finguerings (pitch values) and articulations by averaging all corresponding notes in the database. The results are displayed in Figure 7, clearly showing how blowing pressure is related to pitch (fingering) and dynamics. The pitch-exponential nature of the relationships, being independent upon the articulation used, corresponds with what had been shown in literature for transverse flute.

4.3 Attack times

By comparing the averaged attack time for each different articulation, an interesting observation can be made. For the case of *full legato*, in which the air flow is uninterrumped from note to note, the attack time appears as independent on the fingering (a similar behavior is observed for *legato* articulation). Differently, for those articulations in which the tonguing effect interrupts the blowing pressure right before the note onset, the attack time is negative-correlated to the fingering. These two different behaviors can be seen in Figure 8 for the cases of *full legato* and *staccato* articulations. This reason for this difference can be hypothesized as follows. Since the he maximum blowing pressure before reaching a change of oscillation mode is in general lower (as it is the 'normal' range of pressure) for lower pitch fingerings, the performer risks entering an undesired second oscialla-tion mode more easily. Thus, limiting the rate of increase of blowing pressure helps the performer to avoid entering in chaotic transitional states before reaching higher modes of oscillation. Within each type of these two articulatio subgroups, it remains clear by looking at Figure 8 that attack times are shorter for *legato* than for *full legato*, and also shorter for *soft staccato* than for *staccato*. Concentrating

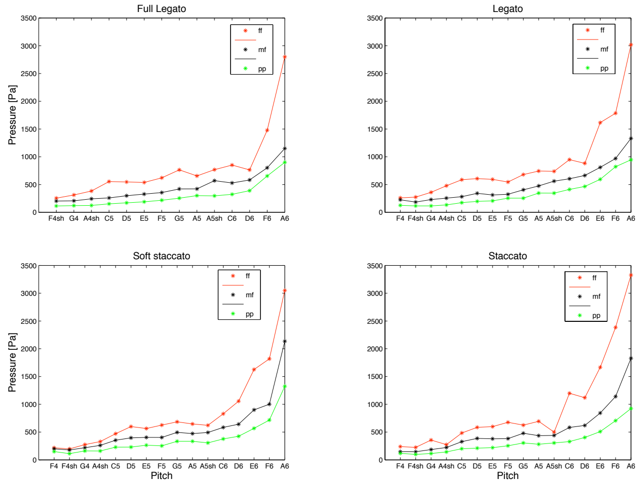

Figure 7: Average blowing pressure for different articulations versus pitch (fingering) for different articulations.

on one articulation type at a time, no significant differences were found when comparing the durations of the attack segments for different dynamics.

4.4 Temporal ratio of tonguing

We have used here the term "tonguing ratio" for referring to the ratio between the time the air is flowing (blowing pressure is different from zero) and the time the airflow is interrupted by the action of the tong. In other words and attending to our envelope model, this feature is computed as the ratio between the duration of the steady state and the nominal duration of the note. Of course, for the case of *full legato* articulation it does not make as much sense as for the other articulations. It was found that this ratio is independent of the pitch, but slightly dependent on the note nominal duration: shorter notes present a higher ratio than the longer nominal durations. With respect to articulation, we found an approximate values of 0.75 for *legato*, 0.40 for *soft staccato*, and 0.25 for the case of *staccato*.

5. CONCLUSION

In this paper we have presented a study of blowing pressure profiles acquired from recorder playing. We have used a low-intrussive acquisition system based on a mechanically modified recorder, enabling us to synchronously acquire sound and blowing pressure from real recorder practice. We have constructed a multi-modal database including aligned blowing pressure and sound signals, covering different fingerings, dynamics, articulations and note durations. Blowing pressure signals have been semi-automatically segmented first into notes by taking into account to the performed score. Then, by attending to an envelope model devised from obervations of the acquired signals, blowing pressure profiles are automatically segmented into characteristic intra-note segments. From those envelope segments, a number of features, mainly related to the attack times, the amount of blowing pressure, and the rate of tonguing, have been extracted and systematically analysed for different articulations, dynamics, fingerings and note durations.

The main contribution of this paper is the acquisition and systematic analysis of blowing pressure signals from real performance in recorder playing. While previous studies had been mostly focused on the transverse flute, here we

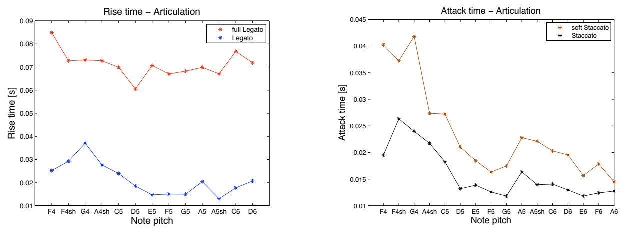

Figure 8: Comparison of attack times: (left) *full legato* **versus** *legato*, **(right)** *soft staccato* **versus** *staccato*.

worked on the recorder and, most importantly, towards a parameterization of blowing pressure that would allows the reconstruction of profiles with certain ease.

With respect to the analysis of profile features, we have successfully reproduced some of the previous studies on transverse flute, and extended them by extracting and analysing articulation-specific features.

We will continue using the multi-modal database for approaching further challenges, like it is the case of building a generative model for synthesizing blowing pressure from an annotated score (possibly using more elaborate contour models (e.g. concatenated Bézier curves), studying mappings between blowing pressure and sound perceptual attributes, or driving physical models from recorded or synthetic blowing pressure signals.

6. ACKNOWLEDGMENTS

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