Experimental Study of Attack Transients in Flute-like Instruments

A. Ernoult[a], B. Fabre[a], S. Terrien[b] and C. Vergez[b]
[a]LAM/d'Alembert, Sorbonne Universités, UPMC Univ. Paris 06, UMR CNRS 7190, 11, rue de Lourmel, 75015 Paris, France
[b]LMA - CNRS, 31, chemin Joseph Aiguier, 13009 Marseille, France
ernoult@lam.jussieu.fr

The stationary behavior of flute-like instruments is fairly well understood. Models and experimental studies allow to predict and to understand the influences of the principal parameters (flow velocity, position of the edge, etc) on the sound if these parameters stay constant in time. Depending on the instrument, these parameters can be fixed by the flute maker or by the musician. In musical playing, the musician plays on them to act on the sound. Some parameters can vary rapidly, like during the attack transients. The response of the instruments to these variations is crucial to determine their quality, in musical use. The target of this study is to understand the influences of these parameters on the characteristics of attack transients. The study presented is based on measurements on an actual recorder in musical context. Parameters of attack transient for acoustic and musician control are extracted from the data. Relations between these parameters are searched by taking into account the characteristics of the instruments. This study is a first step in the understanding of the possibilities of the musicians' control and of the physical limitations.

1 Introduction

Playing music using self-sustained oscillations allows the player to shape the sound, by modulating the control parameters. In recorder playing, the player gives each note or group of notes a specific time shape, according to the musical context and intention. Therefore, the sound is always changing, in a kind of "permanent transient".

In this work, we will consider as attack transient, the transition between no sound and well defined note. It starts when the musician starts to blow, moment at which there is not yet sound, and finishes when the amplitude of the acoustic pressure and the mouth pressure of the musician are quasi-static. The attack transients are know to be very important into the perception of the instrument. The understanding of phenomena involved and of the rules of the different parameters in the attack transients is important for the instrument makers and the players.

Some experimental works have already been carried on the attack transients of flute-like instrument (Nolle[1], Verge[2], Castellengo[3]). It appears that the typical duration of an attack transient is about 10 to 30 ms. It corresponds to a quick modification of the control parameters (like the mouth pressure) in comparison of the acoustic period (2ms for a oscillation at 500Hz). These studies used generally few data and are focus on a very specific aspect of the transient. The instruments used in the different studies being different, they are not easily comparable.

The most common model used for the flute-like instrument is the jet-drive model (Coltman[5]). This model assumed that the jet is split in two by the edge. This split can be described as a dipole of flux placed on both sides of the edge. This model leads to understanding the most of the stationary or quasi-static behaviors of flute-like instruments[7]. The jet-drive model is also used to study the regime change in these instruments (Terrien[6]). But this model, which assumed a well defined jet, can't be directly used to study the attack transients. Indeed there is no jet when the musician starts to blow. Some authors, already proposed models, sometimes in comparison to experimental studies (Fletcher[8], Nolle[1], Verge[2]). The models are not necessarily linked to an acoustical understanding of the transients (parameters are not linked with physical parameters, etc) or only a specific point of the attack transients is modeled.

As a first step in developing a model, it is important to characterize the attack transients. The aim of this first study is to explore the parameters of attack transients varied by the musicians in musical context and try to understand how the musicians control these parameters. Measurements are carried on a recorder played by a musician in a musical context. The parameters of the attack transients are extracted from these measurements. The behavior of the instrument for each fingering is characterized to normalize the parameters. Finally a global analysis is proposed to discuss the relations between the normalized parameters.

2 What does the recorder player do?

2.1 Experimental protocol

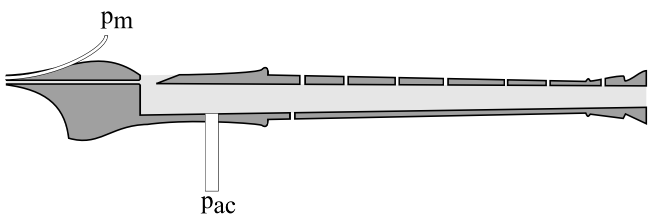

Figure 1: Sketch of the modified recorder that allows to measure the acoustic pressure inside the bore (p_{ac}) and the pressure inside the mouth (p_m).

Two pressure sensors are mounted on four Aesthé recorders, made by the flute maker Jean-Luc Boudreau (figure 1). A bass (from F3 (175 Hz) to D6 (1175 Hz)), an alto (from F4 (350 Hz) to D7 (2350 Hz)), a soprano (from C5 (523 Hz) to A7 (3520 Hz)) and a sopranino recorder (from F5 (698 Hz) to D8 (4700 Hz)). The instruments used in this study are those used by Blanc[9]. Specific information on their geometries can be found in [9]. The first sensor is a B&K microphone model 4938 mounted through the wall and measures the inner acoustic pressure p_{ac} near the edge. The second sensor is a Honeywell pressure sensor model 176PC14HG1. It allows to measure the pressure p_m within the mouth of the player thanks to a capillary tube passing through the mouthpiece and ending in the mouth.

Measurements were made with an experimented recorder player. To explore all the types of attack transients used by this musician, the player was asked to execute two types of exercises with the four recorders: scales on all the range of the instrument repeated for the different typical attacks, and some musical extract chosen for their specificity and musical context. Due to the difficulty to play with the modified model of bass recorder, only scales have been measured.

2.2 Analysis of measurements

After segmentation, each note (or group of slurred notes) is analyzed to obtain information both on p_{ac} and p_m and try to understand the link between their features. We obtained

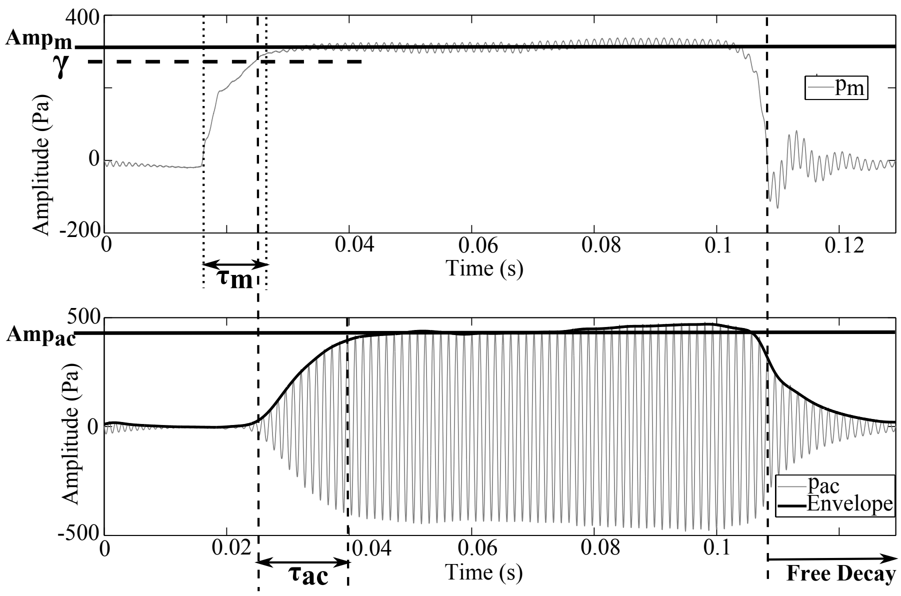

Figure 2: Typical representation of the different characteristics observed on the acoustic pressure and on the mouth pressure for an isolated note.

with this treatment: 153 notes for the bass, 985 notes for the alto, 1204 notes for the soprano and 457 notes for the sopranino recorder. The parameters extracted from the notes are represented in the figure (2). The characteristics observed on the acoustic pressure p_{ac} are:

- Amp_{ac} : The mean amplitude of the note at the end of the attack transient.
- τ_{ac} : The rise time of acoustic , which is the time for the acoustic pressure to move from 5 to 95 percent of the amplitude Amp_{ac}.
- f_0 : the fundamental frequency of the extract at the end of the attack transient.

The fundamental frequency (or pitch) of each played note, can be associated to a semitone of the equal-temperament scale (A4=440 Hz). The musician used a specific fingering to play this semitone. The characteristics observed on the mouth pressure p_m are:

- Amp_m : The mean amplitude of the mouth pressure at the end of the attack transient.
- τ_m : The rise time of the mouth pressure, which is the time for the mouth pressure to move from 5 to 95 percent of the amplitude Amp_m.
- γ : The value of the mouth pressure when the acoustic pressure equals 5% of the acoustic amplitude Amp_{ac}.It can be seen as a dynamic threshold of mouth pressure for the apparition of the acoustic oscillation.

The relations between the parameters can't be observed directly. As a matter of fact, in the recorder, the different fingerings used to play the different semitones modify the instruments and their proprieties (the peaks of admittance, their quality factors, the quasi-static performance in function of the mouth pressure, etc). The parameters of the attack transients have to be studied by taking into account these characteristics for each semitone.

3 Characterization of the instruments

The behaviors of the recorders are characterized for each semitone, to lead to a normalization.

3.1 Preliminary analysis

A first specificity of the semitone already shown by Blanc[9], is the link between the amplitude of the mouth pressure and the fundamental frequency of the semitone. For one recorder the mouth pressure increases with the frequency of the semitones from 100 pa to 500 Pa. This range is more or less the same for the four recorders. Linked to this evolution, the mean acoustic amplitude increased from 50 Pa to 600 Pa with the frequency, until the change of regime (G5 (784 Hz) for the alto recorder), after which the acoustic level stays relatively constant.

All the notes of the four recorders are now analyzed together. In studying the rise times of the acoustic amplitude τ_{ac} in regard of the temporal period of oscillation $1/f_0$, a good correlation is found (coefficient correlation: 0.52). The rise time globally increases with the period. A linear relationship is obtained by fitting the dots (fig.3): $\tau_{ac} \approx h(1/f_0) = 6 \cdot 10^{-3} + 9.5/f_0$. In spite of this global relationship, the musician keeps a control of the rise times of the acoustic envelope. Indeed the normalized standard deviation of $(\tau_{ac} - h(1/f_0))$ stays $\sigma_{\tau_{ac}} \approx 37\%$.
Observing the mouth pressure's parameters, it appears that the rise times of mouth pressure are not correlated with the frequency (correlation coefficient: 0.2). But the musician used a large range of these rise times. Indeed the standard deviation of the rise times of the mouth pressure is $\sigma_{\tau_m} = 8ms$ which correspond to about 58% of the mean value.

To be independent of the characteristics of the instrument for each semitones and to lead a global analysis of these parameters, they have to be normalized by parameters specifics at each semitones. Two types of parameters are identified: the quality factor and the quasi-static thresholds.

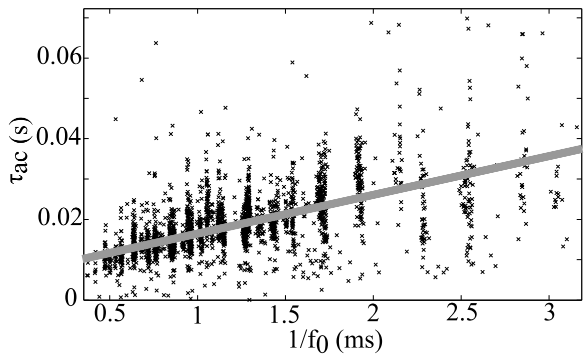

Figure 3: Rise time of acoustic τ_{ac} in function of the period $1/f_0$ (black cross). The grey line represents the linear regression: $h(x) = 6 \cdot 10^{-3} + 9.5x$.

3.2 Quality factor

Another parameter specific for each semitone is the quality factor of the resonator at the frequency of the semitone. The quality factor is very dependent on the way the musician closes the holes. Q-factors are estimated from the analysis of the notes played by the recorder player to have a value of the quality factors representative of the recorder played by the musician. Quality factors are estimated by the exponential fit of the decay of free oscillations at the end of the notes. Only the oscillations when the mouth pressure equals zero are considered (fig.(2)). The Q-factors are averaged over all the notes at a given semitone, taking the quadratic error of the exponential fit as weight. The mean values obtained for each semitone of the alto recorder are represented with the standard deviation in the figure (4). It appears that the Q-factors are globally around 20 for

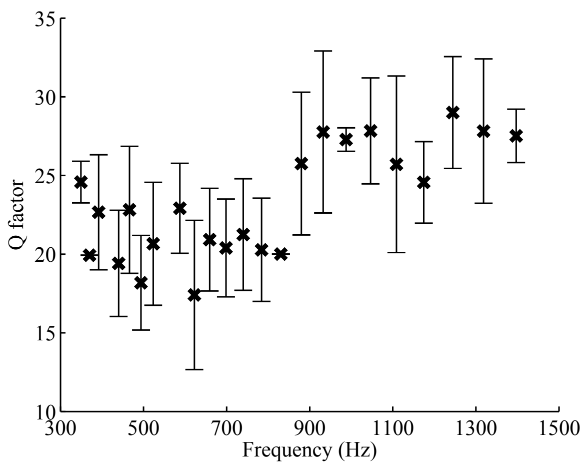

Figure 4: Mean Q factors and corresponding standard deviation of the alto recorder.

the semitones played on the first regime of the resonator (f_0 < 800 Hz) and around 27 for the semitones played on the second regime. The standard deviation is relatively important and homogeneous for all the semitones (the very low standard deviations for some frequencies are due to low occurrences of notes with free decay at these frequencies). This study is carried on the four recorders. The same kind of evolution is found for the other recorders. The Q-factors are around: 20 for the first octave and 35 for the second octave of the bass, 18 and 25 for the soprano and 15 and 20 for the sopranino.

In spite of the large range of frequencies (from 175 Hz to 2500 Hz for the first two regimes of the four recorders), the quality factor doesn't have a large variation. This may be interpreted in terms of the maker's attempt to provide a homogeneous response of the different instruments of the family.

From linear analysis of damped oscillators, it is expected to follow a relation of the type of: "higher is the quality factor, faster is the rise time of acoustic". But no such trend is underlined with the measurements presented here. The rise time expressed in number of period does not either show any systematic relation. It can be due to the control of the musician which allows the rise time not to be dependent of the Q-factors. The lack of relation may also be a consequence of the low variation and the high standard deviation of the Q-factors.

3.3 Analyses using quasi-static thresholds

The study of bifurcation diagrams allows to characterize the behavior of the recorders for each semitone and to find quantities allowing to normalize the parameters defined in section 2.2. For this study, in a first step, the study of the bifurcation diagrams is carried only on the alto recorder. The recorder is equipped with the same pressure sensors than for the measurement with the musician. Fingering are produced by artificialy closing the holes. The thumb's hole has to be "half" closed from the A5 (880Hz) for the alto recorder. For these fingerings, the proportion of the hole which is closed influences a lot the bifurcation diagram. The recorder is supplied with a flux of a mix of N_2 and O_2 with similar proportions to air. The mouth pressure is controlled by a Mass Flow controller Brooks (5151S). The flow is increased slowly, over approximately 1 minute, to ensure a quasi-static evolution of the pressure. This study is focused on the attack transient, so the bifurcation diagram is explored only with a rising pressure.

Two types of bifurcation diagrams are obtained by plotting the acoustic amplitude or the frequency as function of the mouth pressure. Examples are given for the C5 (523 Hz) in the figure 5. To normalize the parameters related to the mouth pressure, it is chosen to used the mouth pressure with which the recorder has to be supplied to sound in tune according to the equal temperament (A4=440 Hz) ($f_0 = f_{semitone}$). One has to make sure to not take into account the whistle tones (around $p_m = 35Pa$ for C5 Fig.5). For C5, this threshold of mouth pressure is $T_p = 239Pa$ (Fig.5). They are no quantities easily measurable to normalize the rise time of mouth pressure. The mean value by semitone is chosen. The normalized parameters of mouth pressure used are:

$$\left\{ \begin{array}{lcl} \tau'_m & = & \frac{\tau_m - \langle \tau_m \rangle}{\langle \tau_m \rangle} \\ \gamma' & = & \frac{\gamma - T_p)}{T_p} \\ Amp'_m & = & \frac{Amp_m - T_p}{T_p} \end{array} \right. , \quad (1)$$

with $\langle \cdot \rangle$ the mean value for all the notes at one given semitone.

The amplitude of the acoustic pressure when the recorder is supplied by the pressure T_p, is chosen to normalize the mean acoustic amplitude Amp_{ac}. For C5, this "threshold" of

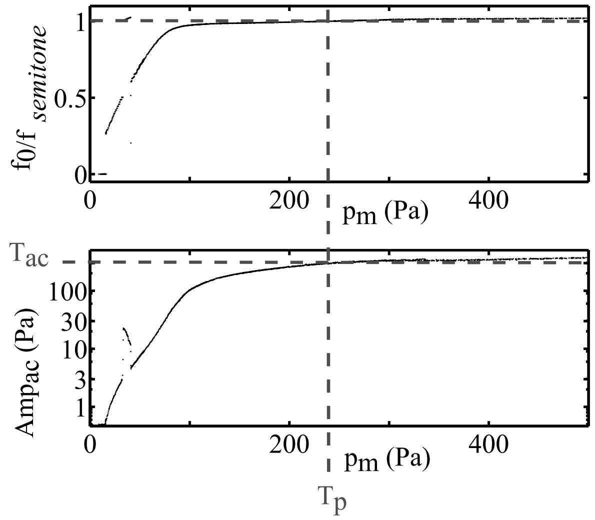

Figure 5: Bifurcation diagrams measured for a C5 (523Hz), with a duration of linear increasing of mouth pressure of 75s. Here $T_p \approx 239Pa$ and $T_{ac} \approx 298Pa$. The amplitude of acoustic pressure is plotted with a logarithm scale.

acoustic amplitude is $T_ac = 298Pa$ (Fig.5). The deviation of the frequency from the expected frequency of the semitone $f_{semitone}$, is used as normalized frequency. The acoustic rise time is normalized by the linear relationship with the oscillation period found in section 3.1. The normalized acoustic parameters obtained are:

$$\begin{cases} \tau'_{ac} = \frac{\tau_{ac}-h(1/f_0)}{h(1/f_0)} \\ Amp'_{ac} = \frac{Amp_{ac}-T_{ac}}{T_{ac}} \\ f'_0 = \frac{f_0-f_{semitone}}{f_{semitone}} \end{cases} \quad (2)$$

4 Toward an understanding of the musician's control

With these normalized parameters it is now possible to study together all the notes of the alto recorder. The correlation coefficients between the normalized parameters are calculated on the 985 notes of the alto recorder.

Table 1: Correlation Coefficients between the normalized acoustic parameters.

	f'_0	Amp'_{ac}
τ'_{ac}	0.29	**0.39**
Amp'_{ac}	**0.63**	1

By observing the correlations between the acoustic parameters, it appears that the normalized frequency is correlated with the normalized acoustic amplitude. For a given fingering, pitch gets sharper when the musician plays louder. This is in line with the results presented by Auvray[7], who shows that it can be interprets in terms of jet-drive model. Table 1 indicates that the musician doesn't correct the pitch of the sound in musical context by closing less or more the holes as can be observed in some cases like slow movements and harmonic context. Indeed, the attention of the player was focused was focused on attack transients rather than intonation.

A slight correlation between the rise times of acoustic and the mean amplitudes targeted is underlined. It means that the attack transients are globally longer when the musical dynamic is higher. The correlation coefficients obtained between the normalized parameters of the mouth pressure are represented in the table 2. A relation between the target mouth pressure and the dynamic threshold is here underlined. As plotted in figure 6, it appears that the dots are closed but higher than the line $y = x$. Globally $Amp'_m \geq \gamma'$ which means that the acoustic starts during the rise of the mouth pressure and that the musician doesn't use an overshoot to do a special attack.

Table 2: Correlation Coefficients between the normalized parameters of the mouth pressure.

	Amp'_m	γ'
τ'_m	0.25	-0.14
γ'	**0.75**	1

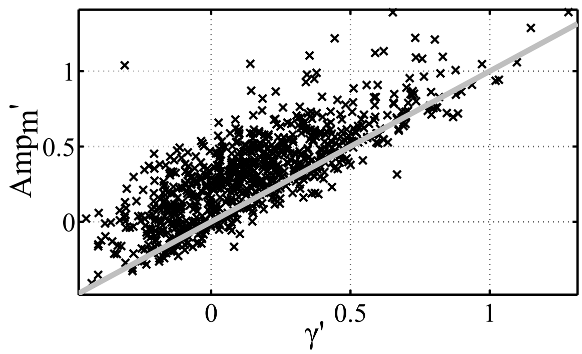

Figure 6: Normalized dynamic threshold γ' in function of normalized mouth pressure amplitude Amp'_m(black cross). The grey line is the line $y = x$.

Table 3: Correlation Coefficients between the normalized parameters of the mouth pressure and the ones of the acoustic amplitude.

	τ'_{ac}	Amp'_{ac}	f'_0
γ'	0.05	**0.51**	**0.48**
τ'_m	0.04	0.03	0.02
Amp'_m	0.13	**0.50**	**0.50**

Now correlations between the mouth pressure parameters and the acoustic pressure parameters are studied with the coefficient of table 3. The coefficient between the acoustic amplitude and the mouth pressure is relatively high. It indicates that when the musician blows stronger, the musical dynamic is higher. Combining the relation between the dynamic threshold and the mouth pressure amplitude (table2) and the relation between the acoustic rise time an the acoustic amplitude (table1), the other high correlation coefficients can easily understood.

But it appears that the rise time of acoustic is not correlated with the parameters of the mouth pressure observed in this study. This parameters, which is the only one specific of the acoustic attack transient, seems to be only dependent on the acoustic characteristics (amplitude and frequency).

5 Discussion

This study is the first one about the transients in flute-like instruments including a wide number of notes over a wide tessitura, in musical context. It underlined some relations between parameters varied by the musician in musical context. Some relations were already printed in the literature like the one between the amplitude of the mouth pressure and the acoustic amplitude, or the one between the frequency and the acoustic amplitude. The rise time of acoustic, which is the only parameter studied here which is specific to the attack transients, appears to be only related to the other acoustic parameters: the acoustic amplitude and the frequency(table1). These two parameters are imposed by the musical context to the musician. It seems that the musician is not free to change the attack transients. Other relations could be underlined by observing other parameters of the mouth pressure transients. The over-shoot or the regularity of the rise are examples of other parameters. Another parameters of the acoustic transients, maybe more characteristic of the musical attack, could be observed: for example the spectral evolution during the transients.

The results presented here can be analyzed from another point of view. For some parameters, the musician is submitted to some physical limitation of the instrument. For example, the musician can't totally avoid the dependence between the rise time of acoustic and the frequency (fig.3) which is found to be $\tau_{ac} \approx 10/f_0$. In the same manner, the mechanism of acoustic source forces the frequency to evolve with the amplitude of acoustic. The musician can't totally avoid this dependence (table1). For other parameters, the musician seems to be totally free, like for the rise time of mouth pressure (tables 2 and 3). The musician doesn't seem to be submitted to the Q-factors of the different semitones.

In this study, the correlation coefficients are globally low due to the large number of samples included in the study. Even if a relation between two parameters is clearly highlighted by the distribution of dots (like in the fig.6), the large dispersion of the parameters leads to a low coefficient. The data are acquired in a musical context with a musician. This leads to a big variation of the shapes of the notes obtained from the segmentation. The automatic acquisition of the different parameters is sometimes really dependent of the value of thresholds used. For example, the value of the mean amplitudes Amp_m and Amp_{ac} are relatively arbitrarily when no stage can be found in their evolution during the note.

This low values can be also due to the low range explored by the parameters. In a musical context, the musician doesn't use extreme value of parameters which could correspond to exotic attack transients without musical interest. Laboratory measurements with a controlled mouth pressure should help to explore larger ranges of parameters and make the analysis easier. It should lead to a clearer understanding of the relation between the parameters. By carrying the studies of section 3.3 on the other recorders, the relation between the parameters should be confirmed. If the relations are confirmed, by both laboratory measurements and studies of other recorders, it would be interesting to propose a physical model allowing to understand these relations.

Acknowledgments

The authors would like to thank the musician Sarah Lefeuvre, who agreed to participate in the experiment, and who made this study possible.

References

[1] A. W. Nolle, T. L. Finch, "Starting transients of flue organ pipes in relation to pressure", *J. Acoust. Soc. Am.* **91**(4), 2190-2202 (1992)

[2] M. P. Verge, "Aeroacoustics of confined jets", *Phd thesis*, Technische Universiteit Eindhoven , (1995)

[3] M. Castellengo, "Acoustical analysis of initial transients in flute like instruments", *Acta Acustica united with Acustica* **85**, 387-400 (1999)

[4] C. Ségoufin, B. Fabre, M. P. Verge, "Experimental study of the influence of the mouth geometry on sound production in a recorder-like instrument: windway length and chamfers.", *Acta Acustica united with Acustica* **86**, 649-661 (2000)

[5] J. W. Coltman, "Sounding mechanism of the flute and organ pipe", *J. Acoust. Soc. Am.* **44**(4), 983-992 (1968)

[6] S. Terrien, R. Blandin, C. Vergez, B. Fabre "Regime change thresholds in flute-like instruments: influence of the mouth pressure dynamics", *Acta Acustica united with Acustica*, to appear.

[7] R. Auvray, B. Fabre, P. Y. Lagrée, "Regime change and oscillation thresholds in recorder-like instruments", *J. Acoust. Soc. Am.* **131**, 1574-1585 (2012)

[8] N. H. Fletcher, "Transients in the speech of organ pipes - A theoritical study", *Acustica* **34**, 224-233 (1976)

[9] F. Blanc, B. Fabre, N. Montgermont, P. De La Cuadra, A. Almeida "Scaling of flute like instrument: an analysis from the point of view of the hydrodynamic instability of the jet.", *Acta Acustica united with Acustica* **96**, 642-653 (2010)