Proceedings of the International Symposium on Musical Acoustics, March 31st to April 3rd 2004 (ISMA2004), NARA, Japan

Flute-like instrument transients: An analytical study of mouth-tone production versus pressure rise time

Castellengo M.

Laboratoire d'Acoustique Musicale - CNRS, Université Paris 6, Ministère de la Culture. France
castel@ccr.jussieu.fr

Abstract

During starting transients, flute-like instruments may present inharmonic frequencies and blowing noises which are important for the perceived quality of the instrument. The amount, the intensity, and the frequencies of these tones are controlled by the rise time of the pressure build-up. The acoustical analysis of three different transients of an organ pipe is presented. We show that it is possible to anticipate the content and the temporal structure of a transient with the help of three groups of data: the edge-tone curves, the resonance frequencies of the pipe, and the pressure evolution during the transient.

The results also give an explanation to the paradoxical observation that a longer transient may seem more “precise” than a shorter one, found in the case where some mouth tones appear at the very beginning. Flute and shakuhachi tone analyses show, in addition, strong contributions of the transversal pipe mode to the transient.

1- Introduction

The acoustical phenomenon occurring during the onset of pipe mouth tones contains a large part of the information which contributes to perceptive sound quality. From the physical point of view, the mouth of the pipe is the main location of complex interactions between hydrodynamic and acoustic phenomena. In the literature one finds reference to two feedback paths act on the oscillation of the jet [1, 2, 3, 4]. Once the jet reaches the labium, a hydrodynamic feedback acts as a return; the jet oscillates following an "edge-tone" like behavior. With increasing transversal mouvement of the jet, the accumulated energy in the pipe forces the jet oscillation under frequency control of the first longitudinal modes of the pipe; the jet oscillations follow a "pipe-tone" like behavior. These phenomena are largely described by regarding the stages of the transient as being composed of many independent phases, though in reality the various stages overlap, giving rise to complex acoustic productions which provide the perceptively interesting character of the transients. We propose to give, using a time-frequency analysis of the transients of a flute and organ pipe, a phenomenological description of the actual transients combining the two types of feedback present.

2 – Progressive augmentation of pressure:

Air-jet labium system

This work utilized a circular organ pipe made of tin in which the excitation system (foot and mouth) can be separated from the remainder of the pipe. Principal dimensions of the pipe are: length = 312 mm; internal diameter = 27 mm; mouth dimensions lxL = 21x7 mm; flue width 0.2 <h <0.3. The first resonant mode of the pipe is 475 Hz.

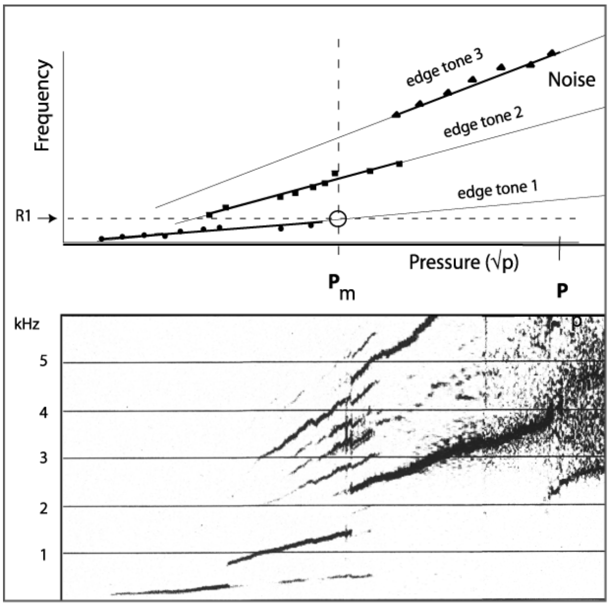

Figure 1 - The mouth system separated from the tube.
1a) Top. Edge-tone frequencies measured discretely (for fixed values of the air-pressure) are shown for the first three regimes. R1 is the first longitudinal pipe mode frequency. 1b) Bottom. Spectral analysis of the sound produced by the mouth system with increasing air-pressure.

F/√p curves, Figure 1a - The air-jet labium system is fed by a compressed air cylinder. The radiated frequencies are measured discretely allowing the presentation of three principal edge tone curves. By increasing the pressure, the system passes through the various behavior regimes [5]. The frequency of the first longitudinal mode of the pipe is indicated by *R1*.

Spectral Analyses, Figure 1b - Acoustic analysis of the sound captured at a distance of 20 cm represents the acoustic complexity of the radiated sound. Regimes 2 and 3 are rich in harmonics. Turbulence noise increases with the supply pressure.

Note: Low frequency sounds are extremely weak; noise reduction techniques have been used in order to obtain suitable data for presentation in Figure 1.

The organ pipe (normal configuration).

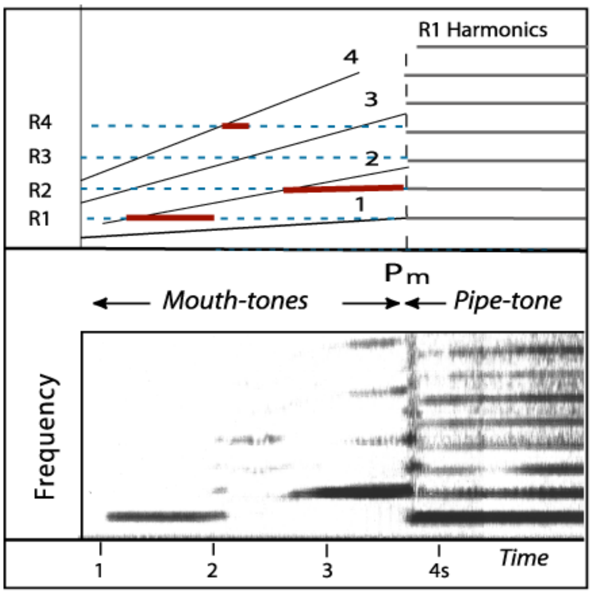

Figure 2 - The whole organ pipe excited with slowly increasing air-pressure. Top: Mouth tone data (red); Bottom: spectral analysis of the organ pipe sound.

Pipe mode frequencies - The pipe was reconnected to the mouth and excited by a noise source at the mouth. Spectral analysis of the resulting filtered noise received by a microphone placed at the far end provides the frequencies of the pipe modes. These modes are shown by dashed lines (blue) in Figure 2a (*R1, R2... RN*). The intersection between *R1* and *edge-tone 1* gives the pressure threshold value *Pm* at which the pipe passes into the pipe-tone feedback regime.

Through increasing pressure, the complete tube first produces a weak tone with a frequency of *R1*, then a quasi silence, a tone of frequency *F2*, then again *R1* accompanied by a continuous series of harmonics. By examining Figure 2a one notes that the sounds produced prior to the pipe tone regime corresponds to the intersection of the edge tone curves with the frequencies of normal modes of the tube (*R1, R2..RN*). These mouth-tones [6, 7] due to the interaction of an edge-tone by one of the pipe modes are more intense and preserve a certain stability while the pressure grows. The edge tone adheres to the pipe mode, rather than mounting progressively, until there is sufficient pressure to excite the subsequent pipe mode.

In summary: during a period of slowly increasing pressure, in this case over 4 seconds, the pipe passes successively from "mouth-tone" operation mode to "pipe-tone". The sound produced over this period commences with the emission of quasi pure tones, whose frequencies correspond to the eigen modes, then a more intense sound, rich in harmonics, at the frequency of the first longitudinal mode of the pipe.

Whistle-tones - It is rare that one desires to use the pipe in the "mouth-tone" operating regime. The mouth of an organ pipe or a recorder is well regulated for functioning in the pipe-tone regime, resulting in the mouth-tones being extremely weak and very difficult to stabilize. But a playing technique is possible with the flute because the musician has control of the parameters of the mouth. Using an increase in the flue-labium distance (mouth opened), the slope of the edge tone curves is decreased considerably, and at the same time, the pressure threshold of operation in the pipe-tone regime is moved back towards higher values [5, 8] In addition, as the normal modes of the flute are more aligned with the harmonics of the first mode, the musician can produce an interesting set of pure tones, quasi-harmonically related.

3 – Analyses of three transient attacks of an organ pipe.

During musical performance, the rise of the pressure during the attack is considerably faster than that which was studied in section 2 above. The question arises whether one finds in the transient the same phenomena time compressed, or if the pipe behaves differently.

For the subsequent study, the pipe is placed on a "small organ chest". It is played by means of a pallet through which one controls the opening rate. Pressure variations in the pipe foot are recorded during the transient.

Three different pressure build-up rates were tested: “slow,” “short,” and “impulsive”. The pressure profiles are presented in the central part of Figure 3. The horizontal dashed line corresponds to the pressure threshold for "pipe-tone" regime onset in static condition. A vertical line indicates, on the time axis and on the spectral analysis (*Pmin*), the moment during the transient when the threshold value is crossed. All sections of the figure have identical time scales; the square bar scale is graduated in units of 6 periods (6T) corresponding to 12.5 ms.

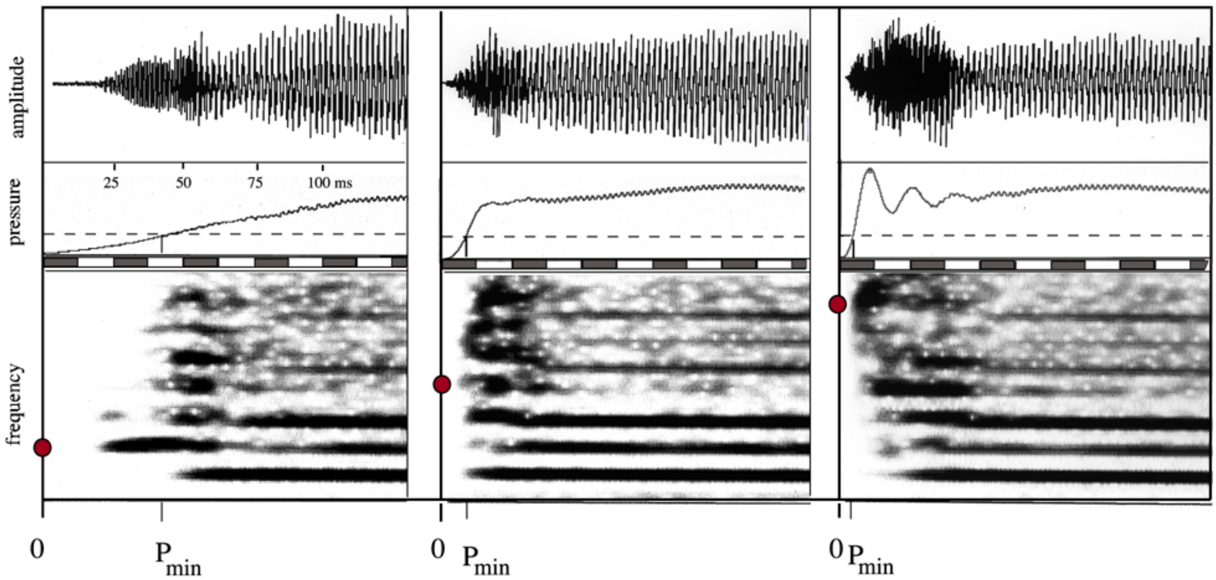

Figure 3 – Analyses of three attack transients: wave form (top); pressure transient (middle); spectrogram (bottom). From left to right: (A) "slow", (B) "short", (C) "impulsive" transient.

Analyses of the various characteristic parameters of the transient.

Duration - From the beginning of the opening of the pallet until a steady-state pressure of 360 Pa is achieved at the pipe foot, the total duration of the transient for the three attack types is 160 ms, 45 ms, and 26 ms respectively. The pressure threshold (125 Pa) is crossed at 40 ms (20T), 9 ms (4T), and 4ms (2T). Note that the initial slope of the impulsive type of transient is followed by oscillations due to the normal modes of the air supply chest [9]. Perceptually, the quicker transient, the one which gives a more precise sensation is B rather than C [10]. As seen on the sonagram analyses of this transient, the fundamental frequency of the pipe tone grows somewhat simultaneously with the two first mouth tones.

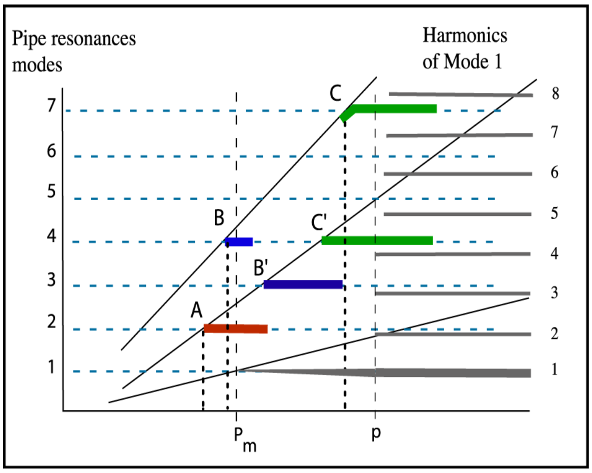

Figure 4 – Analyses of mouth tones of three attack transients of an organ pipe.

Mouth tone transients - The first component appearing at the time of the transient is indicated by a circle on the frequency axis of the sonograms: it moves towards the higher frequencies with increasing slope of the transient. Based on the data presented above - three edge tone curves (ET) and seven pipe resonance modes (R) - it is possible to analyze the inharmonic components of the transient and to interpret them within the framework of mouth tone operation. Component *A* is due to intersection *R1-ET2*. Component *B* comes from intersection *R4-ET3* and is followed by *B'* (*R3-ET2*). For impulsive transients, one initially finds component *C* (*R7-ET3*) then *C'* (*R4-ET2*) which starts following a lower pressure value ocurring after the first pressure maximum.

Mouth tones and pressure threshold - It is noted that only transient *A*, which is long in duration, produces mouth tones at pressures lower than the pressure threshold. The mouth tones of transients *B* and *C* develop for pressure values ranging between *Pm* and *P0*. We have consciously limited our analysis to 4 kHz. Higher frequencies can be produced when the high pressures are achieved in a very short time, as in the case during an attack with "tonguing".

4 – Mouth tones and transverse pipe modes -

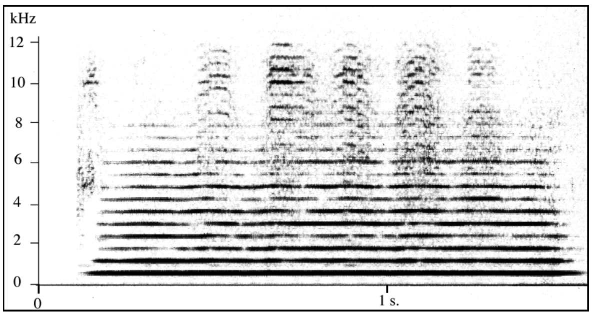

Figure 5 - Sonagram of a note played on the flute (E5 = 660 Hz) showing the role of the transversal mode.

When analyzing the higher regions of the flute spectrum, noise and noticeable variations in tone are observed. Figure 5 shows a stable note (E5 = 660 Hz) played by a flutist. Two high tones are present in the transient at approximately 5 and 10 kHz and, throughout the note, as well as a variable reinforcement of the high end of the spectrum, synchronized on the vibrato.

According to Pierce, the first transversal mode of a 19 mm diameter tube is at approximately 10.5 kHz. Similar phenomena occur in shakuhachi playing.

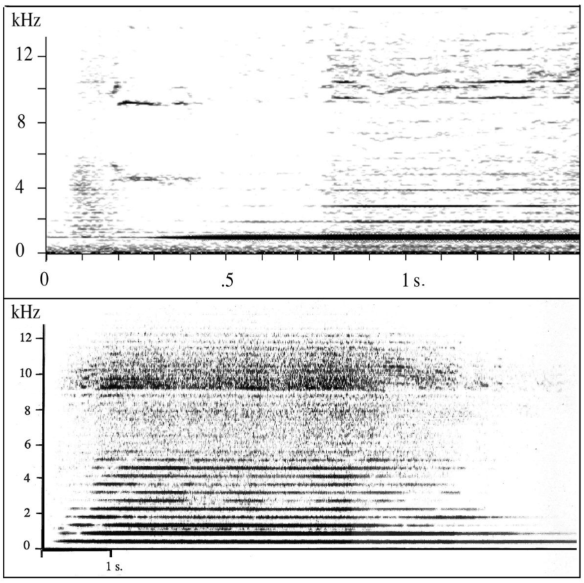

Figure 6 –Shakuhachi: excitation of the transversal pipe mode by the mouth tone (top, soft playing) and by blowing noise (bottom, loud playing).

The musical style emphasizes breathing noise, which is well pronounced around 9 kHz, the corresponding transverse mode frequency for a standard pitch shakuhachi. Figure 6 shows two examples produced by a professional player, M. Iwamoto, playing in the traditional style [11]. The beginning of the first sound is relatively soft, and then increases in intensity.

5 - Conclusions

The role of two different jet oscillation control processus have been presented: edge-tone feedback and pipe-tone feedback, during onset of the attack transient of a flute like pipe. The mouth tones, due to the interaction of an edge-tone with one of the normal modes of the instrument, play a major part in the spectral variability of the transient. Very sensitive to the initial slope of the transient and having little inertia, the mouth tones precede the onset through pipe-tone behavior, delaying the arrival of it, and are superimposed on it. Perceptively, the shortest transient does not necessarily correspond to the strongest initial slope.

To account for the complexity of the acoustic phenomena, it is advisable to take into account multiple edge-tone modes with their productive regions and to consider all the normal modes of the pipe: longitudinal and transversal.

Through their inharmonic character, the mouth tones play a major role in the acoustic quality of the instruments with fixed mouths (*i.e.* organ and recorder) where they make it possible to obtain subtle variations at the time of the attack due to variable tonguing. Their content is regulated through the construction of the instrument. In instruments with "human mouths," the musician has the latitude to use mouth tones (whistle tones), to neglect them, or to give a specific character to the attack (using transveral modes).

Acknowledgements

The author would like to thank Avraham Hirschberg and Benoit Fabre for their assistance in the final versions of the paper. Also, Brian Katz for asssitance in the english translation of the text.

References

[1] Coltman J.; (1968), Sounding mechanism of the flute and organ pipe. *J.A.S.A.*, **44**, 983-992.

[2] Fabre B.,Hirschberg A.,; (2000), Physical modeling of flue instruments : a review of lumped models. *Acta acustica* **86;** 599-610.

[3] Yoshikawa S., Saneyoshi J.; (1980), Feedback excitation mechanism in organ pipes. *J. Acoust. Soc. Japan (E),* **1**, 175-191.

[4] Verge M.P., Hirschberg A., Caussé R. (1997), Sound production in recorderlike instruments. Part II. A simulation model., *J.A.S.A.*, **101** (5) pp 2925-2939.

[5] Powell A.; (1961), On the edgetone, *J.A.S.A,*. **33**, 395-409.

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

[7] Fabre B., Castellengo M.,; (2001), Experiments on mouth-tones during transients and steady-state oscillations in a flue organ pipe. *Proc. 17th ICA, Rome.*

[8] Fletcher N.H.; (1976), Sound production by organ flue pipes, *J.A.S.A.*, **60** (4), 926-936.

[9] Finch T.L., Nolle A.W.; (1986), Pressure wave reflections in an organ note channel, *J.A.S.A.*, **79**, 5, 1584-1591

[10] Nolle A.W., Finch T.L.; (1992), Starting transients of flue organ pipes in relation to pressure rise time, *J.A.S.A,*. **91**(4) 2190-2202.

[11] Castellengo M., Fabre B.,; (1994), The contemporary transverse flute and the shakuhachi: analysis of performance techniques. *Contemporary Music Review*, **8**, 217-237