Influence of the fluctuations of the control pressure on the sound production in flute-like instruments

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In flutes and flue organ pipes, the blowing pressure is often considered as a control parameter at time scales lower than the acoustic time scales. For instance, the typical time of a rise of pressure represents an objective descriptor to analyse attacks (typical time about 20 ms for fast attacks). It has been observed that the blowing pressure is also prone to oscillate at time scales of the order of the acoustic time scales. This migth be due to the acoustic coupling between the instrument and the pressure reservoir. The present work investigates the influence of such a coupling on the sound production, and its pertinence from a musical point a view. In other words, can the ability of a musician (or an instrument maker) to control this coupling be regarded as a control parameter of the sound production ? This paper presents a preliminary experimental study focused on the effects of a pulsating blowing pressure on the sound production. The fluctuations of the blowing pressure are forced by using a loudspeaker within an artificial mouth. Different effects – such as modifications of the spectral enhancement or changes in the transients–, resulting from different supply and "coupling" conditions are presented.

1 Introduction

In flute like-instruments, the sound features are mainly conducted by the supply conditions. More precisely, since the jet is fundemental for the acoustic sources mechanisms, all the parameters that will change the jet behaviour are to be considered. It includes the geometry of the ducts that leads to the formation of the jet. For instance, a recent study [1] showed the importance of the shape of the flue exit : it changes the way the instabilities on the jet are initiated and how they are triggered by an acoustic field.

One other feature that has been observed is the fluctuation of the blowing pressure (in the mouth of the musician in the case of the flute) due to an acoustic coupling between the instrument and the blowing cavity [2]. Thanks to flow visualisations, Verge et al. showed the importance of the initial deflection of the jet during the attack transient [3]. The jet behaviour during the transient has been modelled by a coupling between the instrument and the blowing cavity through the framework of a Helmholtz resonator. Besides, using the same description, the authors concluded that the jet fluctuations constitute an important loss mechanism.

A more recent study, led by de la Cuadra et al. [4], revealed major differences between a novice and a confirmed flautist considering the blowing pressure, the jet length and height, the area of the outcoming flow. The authors noticed that the blowing pressure presents more high frequency components, close to the acoustic frequencies, for the experienced flautist than for the novice.

From this observation, a question naturally arises : can the ability of a musician (or an instrument maker) to control the coupling be regarded as a control parameter of the sound production ? This paper represents a preliminary experiments that "shunts" the loop of the interaction between the musician and the instrument. We opted for an electronically-based controlled coupling that will be described below. It makes possible the investigation of a wider range of coupling parameters than the one that we can ask to a musician. Besides the accuracy of the coupling parameters is ensured, first by the device itself, which enables a more reproducible execution than the human performance, and then by the repetition over several times, repetition that we cannot ask to a musician either. This experimental setup makes possible to relate some features of the sound to coupling parameters.

The article is structured as follow: section 2 presents a simplified description of the coupling based on work of Verge. Section 3 presents the experimental setup specifically created for this study. The results are presented in section 4 and discussed in section 5.

2 Description of the acoustic coupling

This section aims at giving the essential features of an acoustic coupling between the blowing cavity and the instrument. The model presented below is well know to acoustician since it is one physical representation of the Helmholtz resonator [5]. Besides it is the same model used by Verge et al. [3] in the case of an organ pipe.

The air jet is described by applying the instatianory law of Bernoulli between a cavity of volume V_0 supplied by a constant flux Q and a point just outside the channel:

$$\rho_0 l_e \frac{du_j}{dt} + \frac{1}{2}\rho_0 u_j^2 = p - p_{ac}, \tag{1}$$

where l_e is the equivalent length of the channel (see Verge 1994 for more details), u_j the jet velocity, ρ_0 the density of the air (took constant because the air is considered incompressible in the channel of length much smaller than the acoustic wavelength), p is the pressure in the cavity and p_{ac} is the pressure of the air surrounding the channel exit. Please note that the kinetic energy in the cavity has been neglected.

Because of the compressibility of the air in the cavity, the mass conservation is written:

$$V_0 \frac{d\rho}{dt} = Q - \rho_{ac} S_j u_j, \tag{2}$$

where ρ is the density in the cavity, ρ_{ac} is the density of the air surrounding the channel exit and S_j is the outcoming area of the jet. Following Verge, each variable is split into a mean value and a time dependent term : $x = \langle x \rangle + x'$. As the mean value of the pressure near the channel exit $\langle p_{ac} \rangle$ is zero, Eqs. (1) and (2) lead to the stationary state:

$$\begin{cases} \langle u_j \rangle = Q/\rho_0 S_j \\ \langle p \rangle = \frac{1}{2}\rho_0 \langle u_j \rangle^2 \end{cases}, \tag{3}$$

because $\langle \rho_{ac} \rangle = \rho_0$. For small variation of the time dependent quantities, the dynamics is ruled by the equation obtained by combining Eqs. (1) and (2) linearized around the stationary state and using the constitutive equation $p' = c_0^2 \rho'$:

$$\frac{d^2 u_j'}{dt^2} + \gamma \frac{du_j'}{dt} + \omega_0^2 u_j' = -\frac{1}{\rho_0 l_e}\frac{dp_{ac}'}{dt} - \frac{\omega_0^2 \langle u_j \rangle}{\rho_0 c_0^2} p_{ac}', \tag{4}$$

with

$$\omega_0^2 = \frac{c_0^2 S_j}{V_0 l_e} \text{ and } \gamma = \frac{\langle u_j \rangle}{l_e}. \tag{5}$$

It corresponds to the harmonice oscillator describing the Helmholtz resonator. The "source" terms (right hand side in Eq. (4)) result from the existence of a time dependent pressure at the channel exit p_{ac}'. Finally Eq. (4) could be seen as a

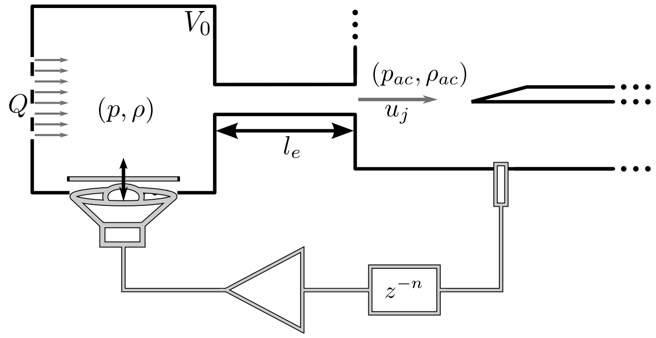

Figure 1: (black lines) Geometry of the simplified model. (gray lines) Simplified representation of the experimental modifications.

transfer function $H(\omega)$ between a source, the complex acoustic pressure $\widehat{p_{ac}}(\omega)$, and an output, the complex jet velocity $\widehat{u_j}(\omega)$:

$$H(\omega) = \frac{\widehat{u_j}(\omega)}{\widehat{p_{ac}}(\omega)} = -\frac{j\omega/\rho_0 l_e + \omega_0^2 \langle u_j \rangle / \rho_0 c_0^2}{\omega_0^2 - \omega^2 + j\gamma\omega}. \qquad (6)$$

From Eq. (4) (or Eq. (6)) arise three parameters that can be considered as control parameter:

- the length of the channel l_e tends to damp the oscillation while increasing ; meanwhile, it also reduces the natural frequency of the system and affects the source terms (right hand side in Eq. (4)),
- the ratio of the area of the jet over the volume of the cavity S_j/V_0 also affects the natural frequency,
- the mean value of the jet velocity $\langle u_j \rangle$ which gets involved in the damping coefficient γ and one of the source term.

For a given acoustic pressure, at a given frequency, changing one of the geometric parameters (l_e or S_j/V_0) only changes the *amplitude* or the *phase shift* of the jet velocity u_j'. The influence of the mean value of the jet velocity $\langle u_j \rangle$ is not so obvious since it also modifies the sound production mechanisms and thus the acoustic pressure.

The following section presents an experimental setup which permits to modify both amplitude and phase of a electronically simulated acoustic coupling.

3 Experiments

3.1 Setup

The same modified recorder as used in [6] is pluged on an artificial mouth. The artificial mouth is a small cavity of diameter 44mm, of height 55mm and of resulting volume V_0 = 5.6e-5m^3. This volume is close to one of the author's mouth volume measured by the well known method of Coltman [7]. Compressed air is sent to the cavity through a hole of diameter 8 mm. The pressure in the artificial mouth is measured by means of a differential dynamical pressure sensor Endevco 8507C-5. The pressure is controlled by a digital PID feedback loop based on a dSpace controler [8]. This enables different types of blowing condition that will be described below.

The "acoustic" coupling is forced through a feedback loop between the acoustic pressure p_{ac} within the recorder and an Aurasound NSW2 loudspeaker (resonance frequency = 200 Hz and resistance = 6 Ω) placed within the artificial mouth. The acoustic pressure is measured in the bore of the recorder close to the labium (see [6] for more details) with a Endevco 8507C-2 microphone. The feedback loop is controled by the same dSpace controler as used in for pressure regulation [8], where the signal is numerically amplified and delayed. The modified signal is then sent into an audio amplifier (Pioneer stero amplifier A107 with a constant gain) to finally supply the loudspeaker. The artificial mouth and the loudspeaker are hold by a larger cavity (volume 2.2e-2m^3) whose purpose is to damp the backward wave created by the loudspeaker. The presence of a high frequency component in the blowing pressure does not affect the feedback control of the slow variations.

The action of the loudspeaker is modelled as follow. At frequencies above the resonance frequency of the loaded loudspeaker, the motion of the diaphragm is ruled by [9]

$$M\frac{d^2x}{dt^2} = f_{Bl}, \qquad (7)$$

where x denotes the transverse motion of the diaphragm, M the mass of the moving part and $f_{Bl} = Bli$ the electromagnetic coupling force with Bl the coupling constant and i the current. The electrical voltage delivered by the dSpace controler is amplified and applied to the loudspeaker. The driving force f_{Bl} then depends on the electric impedance of the loudspeaker. As the analysis of the experiment is based on a phase detection between the pressure signals as described below, the additional phase shift brought by the complex loudspeaker impedance is included as a total delay τ brought by the feedback loop: Eq. (7) is rewritten as

$$Md^2x/dt^2 = Gp_{ac}(t-\tau), \qquad (8)$$

where G represents the total gain of the loop. The motion of the diaphragm leads to a variation of the cavity volume:

$$V = V_0 \pm Sx, \qquad (9)$$

where V_0 is the initial volume and S = 13.2 cm^2 the section of the one dimension approximation of the diaphragm. A ± sign depends on the polarity of the loudspeaker wiring. Finally, conducting the same derivation as in section 2, but considering a new mass conservation equation with a varying volume

$$\rho\frac{dV}{dt} + V\frac{d\rho}{dt} = Q - \rho_{ac}S_j u_j, \qquad (10)$$

and neglecting the natural coupling yields:

$$\frac{d^2p'}{dt^2} + \gamma\frac{dp'}{dt} + \omega_0^2 p' = -\frac{\rho_0 c_0^2}{V_0}\frac{d^2V'}{dt^2} - \frac{\langle u_j \rangle \omega_0}{S_j}\frac{dV'}{dt}. \qquad (11)$$

The response in phase and amplitude of the system depends on the eletrical impedance of the loudspeaker and the natural filtering of the cavity. In order to get rid of these additional modifications of the coupling, the analysis of the measurements is directly led on the signals of pressures in the cavity and in the recorder. The phase shift between the two signals is dectected thanks to a "Costas loop based algorithm" described by the three following steps:

1. detection of the fundamental frequency f_0 by computing a FFT on the first 100 ms of the acoustic signal

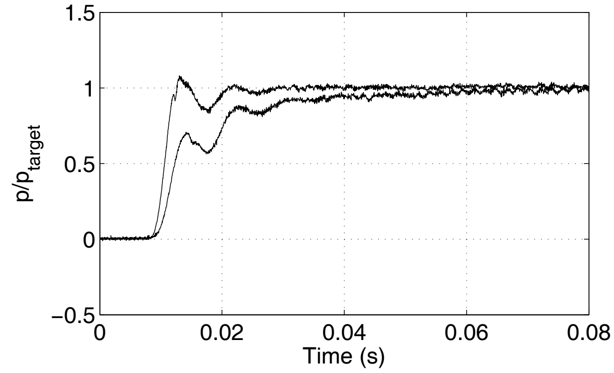

Figure 2: Progressive and overshoot rise of pressure generated by the electrovalve. Even if the slope is not uniform, the response of the electrovalve is reproducible.

2. numerical estimation of $S_i = \langle p_i(t)\sin(2\pi f_0 t)\rangle_t$ and $C_i = \langle p_i(t)\cos(2\pi f_0 t)\rangle_t$, where $\langle\cdot\rangle_t$ denotes averaging over one period, for both cases $i = \emptyset$ (pressure in the cavity) and $i = ac$ (acous tic pressure)

3. computation of the phase shift φ between the pressure in the cavity and the acoustic pressure (took as reference):

$$\varphi = \tan^{-1}\left(\frac{S}{C}\right) - \tan^{-1}\left(\frac{S_{ac}}{C_{ac}}\right). \quad (12)$$

The amplitude of coupling is characterized by the ratio p/p_{ac} estimated by computing a FFT. Typical values go from p/p_{ac} = 0.1 to 0.9.

3.2 Protocols

Two different protocols are presented in this paper, corresponding to different coupling and supply conditions.

The first one investigates the effect of the coupling conditions during the steady state. The artificial mouth is supplied with a constant flux. The delay is slowly increased such as the corresponding phase shift varies from $-\pi$ to π over 30 seconds. The procedure is repeated for different value of amplitude of coupling.

The second one investigates the effect of the coupling conditions on the attack transient. Two types of transient are obtained by sending two types of command in the electrovalve: a progressive one (characteristic time = 30ms) and an overshoot (characteristic time = 10ms). The shapes of the blowing pressure during the transient are shown on figure 2. The procedure is repeated for different amplitude and delay of coupling, corresponding to different phase shift for the target frequency.

4 Results

4.1 Steady state

To the authors' feelings, the main modification brought by the coupling during a steady note concerns the timbre. As it is a notion extremely hard to define, the analysis of the coupling is reduced to the analysis of the spectral enhancement using a basic spectral descriptor: the dimensionless spectral

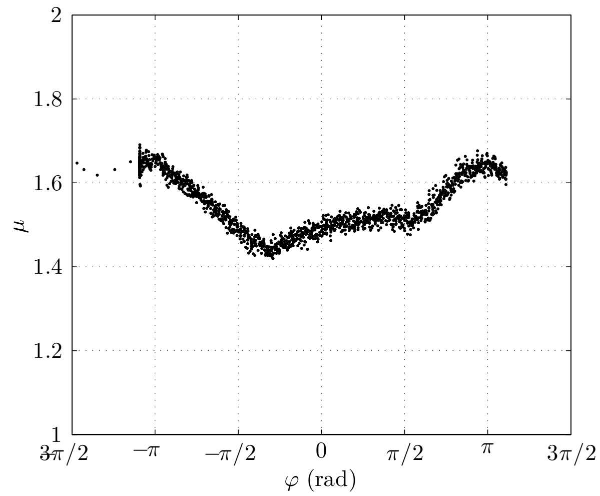

Figure 3: Spectral centroid μ versus phase for one amplitude of coupling (p/p_{ac} =0.5).

centroid of the inner acoustic pressure calculated as

$$\mu = \frac{1}{f_{osc}}\frac{\sum_n a_n f_n}{\sum_n a_n}, \quad (13)$$

where f_{osc} is the oscillating frequency, a_n and f_n are the amplitude and the frequency of indice n of a FFT computed over $M = 4096$ ($\simeq$ 82 ms) with $N_{fft} = 2^{17}$, respectively. This procedure is repeated over the time samples with an overlap of 75% ($\simeq$ 61 ms). Please note that, due to radiation, the outer acoustic pressure may present greater spectral modifications that the inner acoustic pressure.

Figure 3 shows the dimensionless spectral centroid for one amplitude of coupling (p/p_{ac} = 0.5) as a function of the phase shift between the pressure in the cavity and the acoustic pressure. It varies from 1.7 to 1.4 while the coupling signal is phase shifted. As expected, after a phase shift of 2π, it comes back to its initial value. Note that the change is not symmetrical with respect to zero. This calls for a more precise analysis of the signal with a specific attention to the phase shift between the harmonic components.

The comparison between the different amplitudes of coupling is made by using the complex quantity:

$$c = \mu e^{i\varphi}, \quad (14)$$

where φ is the phase of coupling estimated with Eq. (12). This complex spectral centroid is plotted in the complex plane for different amplitude of coupling on figure 4. For the non coupled case, as the phase does not vary, the complex concentroid is located at one angle corresponding to the acoustic coupling phase shift. For low amplitudes of coupling, the spectral content is not modified: the complex spectral centroid c looks like a circle. For larger amplitudes of coupling, the spectral centroid reaches its maximum value for phase shifts close to π.

Note also on figure 4 a straight line at angle $\varphi \sim 7\pi/8$ corresponding to the initial phase shift. It includes the latence of the dSpace controller, the phase shift due to the loudspeaker eletrical impedance and the response of the Helmholtz system.

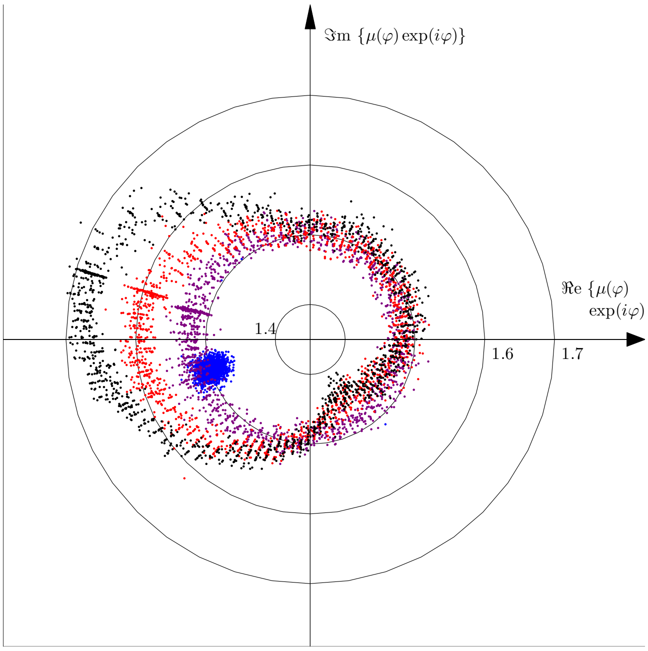

Figure 4: Circular representation ot the spectral centroid μ as a function of the phase φ for different amplitudes of coupling: p/p_{ac} = 0.015 (blue, natural coupling), 0.1 (purple), 0.4 (red), 0.6 (black).

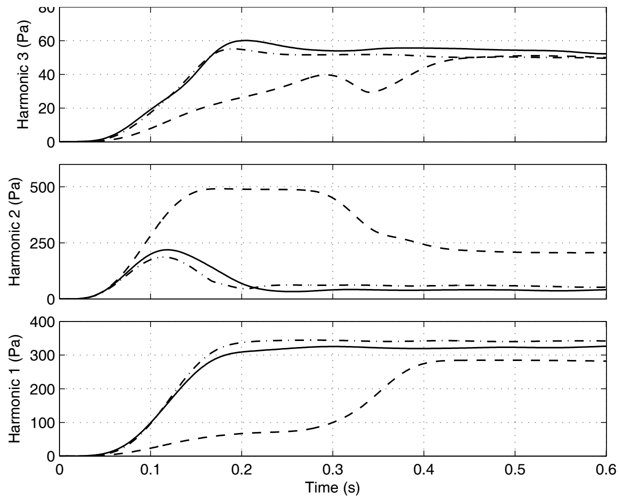

Figure 5: Amplitude of the three first harmonics versus time during a fast attack for one amplitude of coupling (p/p_{ac} = 0.6) for phases: (solid line) reference signal without coupling, (dashed line) $\varphi = \pi$, (dot-dashed line) $\varphi = -\pi/4$. The main differences occur for a phase coupling close to π.

4.2 Attack transient

No significant modifications has been observed for the progressive attack. For the overshoot attack, the amplitudes of the three first harmonics during the transient are detected using a short time Fourier transform (window M=4096, N_{fft}=M, overlapping 99%) and are plotted on figure 5 for one amplitude of coupling. Although for a phase shift close to zero ($\phi = -\pi/4$) the behaviour is the same as the non-coupled case, for a phase shift close to π some differences arise.

For the case $\phi = \pi$, a strong transient predominated by the second harmonic occurs, after which the system returns to a first register sound. As observed for the steady case, at the end of the transient, when the system reaches a steady oscillation, the harmonic content is modified with respect to the non-coupled case. Figure 5 also highlights the non-uniform modification of the spectral content: the amplitude of the second harmonic is strongly increased whereas the amplitude of the third is almost unchanged.

In a Attack-Decay-Steady-Release view, the times of attack and decay also increase with the amplitude of coupling and when the phase gets close to π.

5 Discussion

The experimental setup presented in this paper highlights interesting behaviours in spite of two main shortages.

Firstly, the natural acoustic coupling represents an amount of energy which is taken from the instrument and somehow converted into oscillation in the cavity. This loss of energy is actually restored to the system via the jet fluctuations, even if these fluctuations could have a negative work on the acoustic production for short channel lengths [3]. It is slightly different from the forced coupling which adds energy in the system.

Besides, the whole system {pipe+electronic feedback} constitutes a new auto-oscillating system with its natural frequency. More precisely, when the delay is set to correspond to a phase shift of π with respect to the first resonance frequency of the pipe f_1, it also corresponds to a phase shift of 2π for the second frequency of the pipe $f_2 \simeq 2f_1$. Thus, for high amplitude of excitation, it is expected that the system almost locks on the second harmonic of the pipe as shown on figure 5.

However, in spite of these two observations, this experimental setup still provides informations on the influence of the coupling condition on the sound production. The phase shift between the acoustic pressure and the blowing pressure does have an effect on the spectral content. It seems that rather than a “basic” enhancement of the spectrum, it is more a modification of the energy distribution between the harmonics. For a phase shift close to π, when important modifications occur, even harmonics seem to be increased. Moreover, during the transient, which is fundamental for the perception of musical sound, the phase shift seems to have an important effect.

In both cases, it is when the blowing pressure is out of phase with the acoustic pressure that the modifications are more obvious. In other words, it is when the jet fluctuations are amplified by the two opposite sign variations of pressure in the cavity and the pipe. Conversely, when the phase shift between both pressures is smaller, as it is expected for small channel lengths, the coupling seems to have only a small impact on the spectral content and on the attack transient. This observation calls for a more refine study of the consequences of jet velocity fluctuations.

6 Conclusion and perspectives

The acoustic coupling between the instrument and the blowing cavity acts as a filter whose amplitude and phase vary with geometrical configurations and jet mean velocity. For small channel lengths such as found on organ pipes, the phase shift between both pressures is expected to be small and the resulting jet fluctuations have a damping effect on the oscillation [3]. For larger channel lengths, the phase shift between the acoustic pressure and the blowing pressure may vary up to π.

The electronical forced coupling extends the range of coupling parameters experimentaly investigated. Important effects have been identified for phase shifts between the acoustic pressure and the blowing pressure close to π. A fine tuning of the resonance of the supply system exerted by the musician could modify important features of the radiated sound. This study gives substantial informations that should feed a forthcoming experimental study led on flute players.

Besides, in organ pipes, the supply system can bring nonrelated fluctuations considered as "pollution" by organ builder. Further works should focus on the hydrodynamic and the aeroacoustic of fluctuating jets with and without acoustic coupling. For such jets, it is expected to observe both sinuous (antisymmetric) and varicose (symmetric) modes of instabilities which migth be associated with different sound production mechanisms.

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