Proceedings of 20th International Symposium on Music Acoustics (Associated Meeting of the International Congress on Acoustics)

25-31 August 2010, Sydney and Katoomba, Australia

Acoustics of the *Flautas de Chinos*

F. Blanc (1), P. de la Cuadra (2), B. Fabre (1), G. Castillo (3), C. Vergez (4)

(1) LAM - UPMC Univ Paris 06, UMR 7190, Institut Jean le Rond d'Alembert, 75005 Paris, France
(2) CITA, Centro de Investigación en Tecnologías de Audio, Pontificia Universidad Católica de Chile, Jaime Guzmán 3300, Santiago, Chile
(3) Instituto de Estética, Pontificia Universidad Católica de Chile, Jaime Guzmán 3300, Santiago, Chile
(4) Laboratoire de Mécanique et d'Acoustique, UPR 7051, 13402 Marseille, France

PACS: 43.75.Qr

ABSTRACT

In central Chile, a sacred musical ritual dated from pre-hispanic times, has survived centuries of segregation, misunderstanding and alienation, first from the european regard and later from their own mestizo compatriots. The ritual incorporates dance and music produced by bands of flutes whose sound is not conceived under any formal aesthetic paradigm but as an ingredient to stimulate and perturb their senses creating a sort of trance in performers and great excitation in the community. The ritual can last several hours and the sound can reach impressive loudness that can be heard from distances of hundreds of meters. Groups of about 20 musicians split in two teams and armed with flutes of different sizes, repetitively alter sound clusters that fill the space, time and frequency spectrum. The musicians are referred to as "chinos", a spanish deviation from a Quechua word which means servant. They are serving catholic divinities in a continuously evolving tradition that has adopted the overwhelming influence of christianity in Latin America. An anthropologic and ethnomusicologic study of the ritual is required to properly describe it but, for the moment, is beyond the scope of this article. Throughout the paper acoustical aspects of the instruments are described as well as some observations on the instrumental technique: the simplicity of their construction, materials and geometry, their acoustical impedance, the mechanisms of playing and their characteristic sound called *sonido rajado* (literally torn sound) are addressed. The complex resonator of the instrument, formed by two wooden cylindrical bore sections of different radius, no toneholes, and one closed end, is described in detail. An analytical model of its impedance is proposed and contrasted with measurements and spectrum analysis of field recorded sounds. Measurements of the control parameters show that the flow needed to produce the sound is about ten times larger than the one used on european transverse flute. High-speed visualizations of the air jet show its turbulent behaviors as well lips oscillations that could relate to the production of the *sonido rajado*.

INTRODUCTION

The flutes studied in this article are ritual flutes used by Chilean fraternities called *Bailes de Chinos*, that are involved in popular Catholic festivities in the central coast of Chile. The quality and manner of the execution of these flutes is inseparable from a set of expressive resources that engage, outside the instrumental sound, movement, choreography and singing.

Each *Baile* is formed by a variable number of performers arranged in two rows of 10 to 24 chinos dressed up in a uniform and ordered decreasingly according to the length of their flutes. From the leading flute, called *punteras*, measuring about 70 cm down to the smallest flute called *coleras* of about 30 cm length (de Arce 1998, Wright and Campbell 1998). The *Baile* is also formed by a *bombero*, responsible of marking the binary pulse that makes each row of flute players alternate; a drummer who shows the choreography movements (*mudanzas*) to be followed by the performers; and the *alferez* with a priestly mediation function through a devotional song and greeting *a lo divino* (to the divine), organized in quatrains and occasionally in tenths, both octosyllabic.

Except from the *alferez* chant, whose style is related to vernacular-religious music from the Hispano-arabic tradition, the collective performance of these flute rituals does not respond to any western musical reference, so we prefer to characterize it symbolically as an expressive completion power.

Both the design and execution of the *flautas de Chinos* seek to produce a sound that fills, in each breath, the sound spectrum of the instrument. The completion act is achieved in several ways simultaneously: as a cluster of frequencies, as a continuous sound in time domain and as a circular alternation of the two blowing rows where the attacks are marked and dissipated simultaneously.

We also note that the completion in acoustics terms, has a counterpart in the symbolic-expressive plane. The movements of the performers are not independent from the instrumental control. They relate to each other through the aerobic demand. The enormous amount of air required to properly blow the flutes produces hyperventilation, which is compensated by extreme physical demands: moving, rotating, and jumping for hours as in the Mapuchean *purrun*, or as in some dervishes or meditation dances. Moreover, the falling jump coincides with the exhalation, allowing for a sudden decompression of the diaphragm, which enhances the quality of the attack and determines sound envelopes.

Finally, body movements are not only a constitutive part of the sound production, but they also act as a completion gesture in their particular way. Their movements or *mudanzas* are structured as combination of horizontal and vertical movements, filling the last branch of this symbolic completion.

The rest of the article is structured as follows: next chapter is devoted to model the instrument's resonator and compare it with impedance measurements. Then field recorded of radiated sound are contrasted with the model. Finally, a description of the control parameters used by the performer are presented.

MODELING THE INSTRUMENT

Flautas de Chinos are made of a single piece of wood without toneholes. They produce a very strong beating sound called *Sonido Rajado* (literally torn sound) (de Arce 1998, Wright and Campbell 1998). They are sometimes ornamented by its owner (figure 1) following either the *baile* style or his own preferences. Inside the bore is porous and requires to be moistened before playing.

Figure 1: *Chinos* playing their *flautas* in a *Baile*. Some *flautas* are ornamented by their owners

But what makes the *flautas de Chinos* particular is the shape of their resonators, known as "complex tubes". Indeed, they are made of two cylindrical parts of different radius where the embouchure is located at the end of the wider cylinder. The narrower cylinder is sealed at the end of the instrument. Figure 2 presents a scheme of the geometry of the instruments.

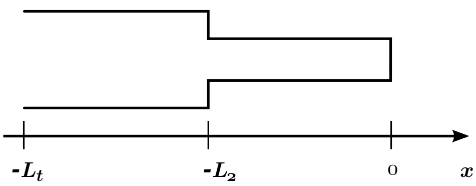

Figure 2: One-dimension model of the flute resonator. The embouchure is located at -L_t

Impedance model

To model the resonator, a one-dimension description of the instrument is used (Figure 2). At $x = 0$ a boundary condition of complete reflection is assumed. Therefore, viewed from $-L_2$ the reflection function of the narrow cylinder is a simple phase shift $R_2 = e^{-j2kL_2}$.

The normalized impedance of the narrow cylinder is then:

$$z_2 = \frac{Z_2}{\rho c} = \frac{1+e^{-j2kL_2}}{1-e^{-j2kL_2}}. \tag{1}$$

From the wide cylinder this impedance can be viewed as a reflection function, but flow conservation has to be carefully observed at the junction. This function combined with the delay due to the propagation in the wide cylinder leads to a reflection coefficient at $x = -L_2$, seen from $x = -L_t$, of the form :

$$R_1 = \frac{\frac{S_1}{S_2} z_2 - 1}{\frac{S_1}{S_2} z_2 + 1} e^{-j2kL_1}, \tag{2}$$

where $L_1 = L_t - L_2$ and S_1/S_2 ensure the flow conservation at the junction. With R_1, the impedance at the embouchure of the instrument ($x = -L_t$):

$$z_t = \frac{1+R_1}{1-R_1}. \tag{3}$$

Equation 3 can be computed easily. The visco-thermal losses are taken into account through the wave number k:

$$k = k_{ll} + \zeta \times (1-j)\alpha, \tag{4}$$

where k_{ll} is the wavenumber in the lossless case, and α is a coefficient computed with the mean section of the bore (Chaigne and Kergomard 2009) and corrected with the factor ζ in order to take into account the porosity of the resonator.

Comparison with measurements

Two *flautas* have been studied in details a *puntera* and a *catarra*. The former leads the *baile* and is designed to produce a very wide sound while the latter is designed to produce a wide beating sound. Their geometry measurements are detailed in Table 1.

Table 1: Total length L_T, narrow cylinder length L_2, diameter of the narrow cylinder $D1$ and the wide cylinder $D2$ measured on the studied flutes

	L_T (cm)	L_2 (cm)	D1 (mm)	D2 (mm)
puntera	55	27	9	19
catarra	25.5	13	9	19

Their impedances have been measured through the *capteur Z* impedance-meter developed at the Laboratoire d'Acoustique de l'Université du Maine, and computed with the model described in the previous section.

Figures 3 and 4 present the comparison between the impedances measured and predicted with the 1D model. They show a good agreement, despite the fact that it requires a fine tuning of the loss parameters. It is worth noting that the experimental device used to measure the impedances of the flautas does not allow to measure the radiation impedances or the extremity correction due to the player lips.

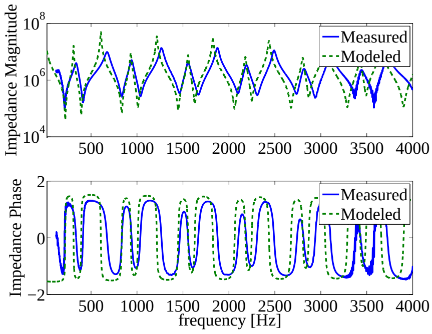

Figure 3: Comparison between the impedance measured and modeled for the *puntera*

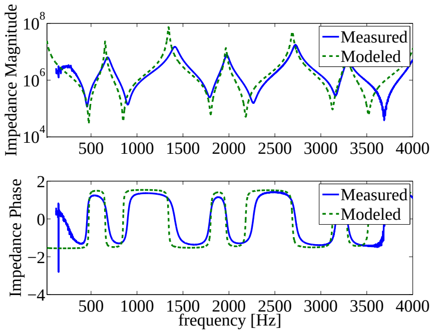

Figure 4: Comparison between the impedance measured and modeled for the *catarra*

Effect of humidity inside the bore The amplitude of the peaks in the admittance function is affected by the porosity of the inner wall of the instrument, due to increment of the visco-thermal losses experienced by acoustic waves while propagating inside the resonator. That's why flutes are moistened before being played, increasing the peak in the admittance function and facilitating the sound production of the instrument. Figure 5 shows the admittance measurements on a flute before and after moistening the inside bore.

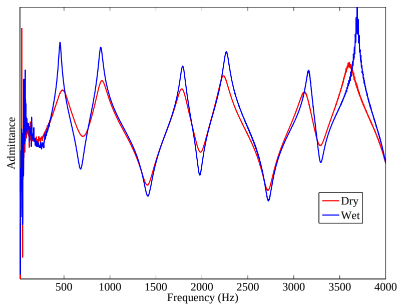

Figure 5: Measured input admittance comparison between a dry flauta (red) and a wet flute (blue). The larger amplitude observed in the wet pipe, due to the porosity reduction of the interior walls, allows for an easier sound production.

Estimation of the resonance frequencies

At a first approximation, the open end of the pipe imposes an acoustic pressure node. Considering the admittance $y_t = 1/z_t$, we can deduce from equation 3 the resonance condition :

$$R_1 = -1, \tag{5}$$

with R_1 defined with equation 2. Replacing R_1 by its expression in equation 5 leads to :

$$\frac{S_1}{S_2}z_2 + 1 = -\left(\frac{S_1}{S_2}z_2 - 1\right)e^{-2jkL_1}. \tag{6}$$

Multiplying the terms of the equation 6 with e^{jkL_1} leads to the expression :

$$2\frac{S_1}{S_2}z_2\cos(kL_1) = -2j\sin(kL_1). \tag{7}$$

Finally, by noting that equation 1 can be rewritten $z_2 = 1/j\tan kL_2$, we can express the resonance condition in equation 7 by writting :

$$\frac{S_1}{S_2} - \tan(kL_1)\tan(kL_2) = 0. \tag{8}$$

While the diameters of the flutes are similar, since most of them are drilled with the same tools, their lengths vary keeping the ratio between the length of the wide and narrow cylinders close to 1. Equation 8 then becomes:

$$\tan^2(kL) = \frac{S_1}{S_2}. \tag{9}$$

Where $L = L_t/2$. Which means that the admittance presents a series of double peaks around the resonances frequencies of a closed-open pipe of half the length. The space between consecutive peaks depends on the section ratio of the resonators. The effect of the lengths difference of the two parts of the complex resonator on the resonance frequencies is harder to predict. However the variations of length between the two parts of the resonators measured are less than five percent.

Figure 6 presents graphically the solutions of equation 9. The position of the resonance frequencies is driven by the ratio S_1/S_2. Remarkable values of this ratio are $S_1/S_2 = 1$, which corresponds to an open-closed pipe of length $2L = L_t$, and $S_1/S_2 \to \infty$, which corresponds to reducing the resonator to its wide cylinder.

The green dashed line represents the surface ratio (≈ 4.5) that corresponds to the measured *flautas*. With this ratio, the resonance frequencies are very close to the series $k_nL = 3\pi/8 + n\pi$ and $k_nL = 5\pi/8 + n\pi$, and are highly aligned with a harmonic relation.

FIELD RECORDINGS

In a *fiesta de Chinos*, dozens of *bailes* gather to play together. This provides the occasion to meet flautists from different parts of the country, with different instruments and playing techniques. It was an opportunity to record and measure flutes of different lengths.

Radiated sound

The *puntera* is the first flute in the *baile*, and the flautist is very often considered to be the most skilled performer.

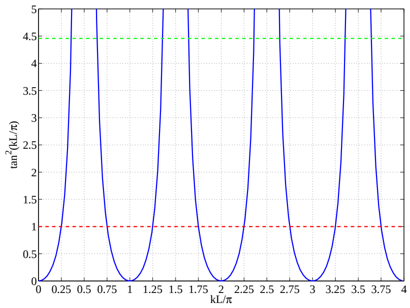

Figure 6: Position of the resonance frequencies in a graphical resolution of equation 9

Figure 7 presents a comparison between the model predicted admittance feed with bore measurements and the radiated spectrum when played by a *flauta puntera*. Although the sounds were recorded during the *fiesta* contained ambience noise, it is observed that the radiated spectrum peaks at each resonance of the instrument admittance.

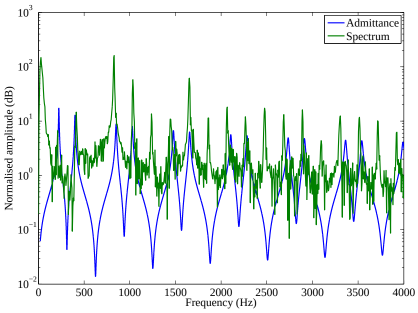

Figure 7: Comparison between the admittance model and the radiated spectrum for a *flauta puntera*). The spectrum and the admittance are both normalized in order to display them on the same figure

Depending on the way the player blows, the peaks of the radiated spectrum can be double. The frequency gap of the double peaks is of the order of magnitude of 10 Hz, which is corresponding to the characteristic beating of the *sonido rajado*, as observed in (Wright and Campbell 1998).

It appears also that there is an evolution on the harmonic content during the sound. As an example Figure 8 shows the sonogram from a *segundera* (second in the line) where it can be observed that the sound begins with an excitation of the third resonance and later other resonances appear. In the case of the *puntera* (Figure 9), the excitation of the whole spectrum occurs together.

Spectrum completion

Given the good agreement between model and measurements, an attempt to show the spectrum completion has been done. An ensemble of 10 pairs of flutes has been modeled. Their lengths vary between 30 and 70 cm, as shown in Figure 10. In it every couple of flutes of similar length is represented by a color[1]. When generating sound, each pair of flutes injects energy in spectrum areas that coincide with the peak of its admittance function, and because of their shift in frequency, the ensemble fills with energy much of the audible spectrum.

[1] For clarity of the representation, only a subset of the ensemble has been modeled and displayed. The admittance function of the flutes not shown can easily be sketched by interpolating their neighbors.

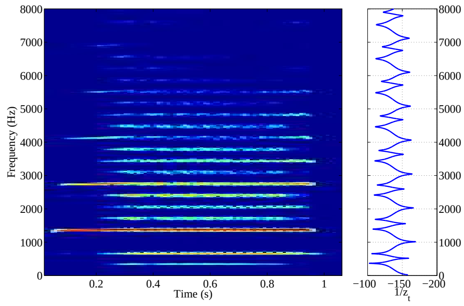

Figure 8: Spectrogram of the radiated sound from a *segundera*

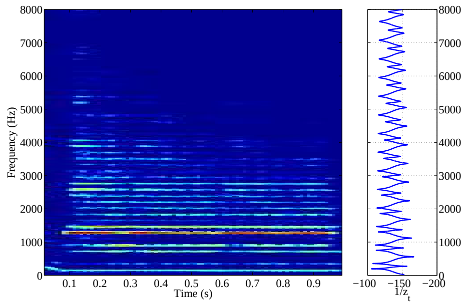

Figure 9: Spectrogram of the radiated sound from a *puntera*

CONTROL PARAMETERS

Control parameters have been measured. Experienced flautists (non *Chinos*) have been asked to play the instruments, while their mouth pressure was measured with a Honeywell 176PC14HG1 pressure sensor. The lips of the players where filmed (at 12 images per second) while playing in order to measure the lips opening surface with image processing. The radiated pressure is measured as well, with a Schoeps mk6 microphones couple. For a detailed discussion on the experimental setup see (de la Cuadra et al. 2008)

Jet velocity and flow

Jet central velocity can be estimated from the pressure inside the player's mouth cavity, using Bernoulli's equation. The *flauta de Chinos* are played with intense and short blowed bursts. When trying to produce the *rajado* sound, the mouth pressure reach values up to 3500 Pa, which leads to jet velocities of approximately $U_j \approx 75$ m/s.

A good indicator of the state of a flue instrument is the jet dimensionless velocity (Blanc et al. 2010, Verge et al. 1997) $\theta = U_j/fW$, where f is the frequency of the oscillation and W the distance travelled by the jet. Considering the perturbation convection velocity on the jet and the optimal phase of the perturbation to sustain the oscillation (Coltman 1968), one can derive an optimal dimensionless velocity $\theta_{opt} \approx 6$.

From the films of the player's lips on the *puntera*, we estimate the distance W between the lips of the player

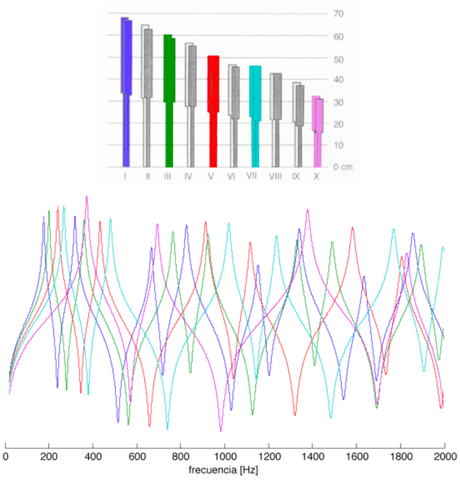

Figure 10: Ensemble of flutes with the detail of the complex tube geometry (top, from (de Arce 1998)) and the admittance of entry (below). For clarity of the representation, the plot includes the admittance of a subset of the flutes, which are individualized using a similar color in both graphs. Note how the sound of the ensemble fills much of the spectrum.

and the labium to be 10 mm $\leq$ W $\leq$ 15 mm. Assuming that the instrument is in a state such as $\theta \simeq \theta_{opt}$, leads to an oscillating frequency $f \approx 1000$ Hz. This indicates that the *sonido rajado* implies an excitation of the instrument on higher registers.

The flow estimation indicates that the flow blowed to play the instruments can reach values such as 6 L/s. Considering that the average lungs capacity of a human male is about 4 liters of air, the duration of each sound can not be greater than 0.7 seconds, which undoubtedly affects the pulse of the march.

Estimations of the air flow used to play the modern flute with the same setup and player, lead to flows ten times smaller. Considering the high flow range used to blow the instrument, turbulent jet behavior is expected. The operational jet can be observed using smoke and high-speed video recording as shown in Figure 11.

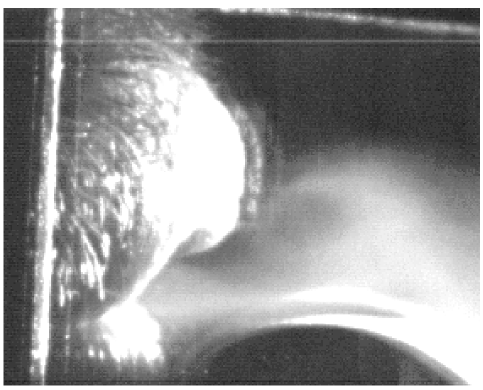

Figure 11: Lateral view from the lips of a flutist playing a flauta de chinos. It shows the characteristic openness of the lips and the turbulent structure of the air jet, which has been stained with smoke for visualization.

CONCLUSIONS AND FUTURE WORK

This paper presented a first attempt to measure and model acoustical properties of Chilean *flautas de Chinos*. The sound produced by the instruments is not intended to be musical under any known aesthetic paradigm, therefore a multidisciplinary approach is required to provide a comprehensive description of it. Flutes are performed as part of ancestral rituals that include dance, singing, religious and tradition, and the acoustical description of the instrument provides only a limited approximation to the ritual.

A simple model of admittance of the resonator is proposed that provides reasonable results when compared to measurements on real instruments. Although the model does not consider the radiation of the pipe and the extremity correction due to the player lips, it also correctly predicts most peaks in the radiated sound spectrum.

The spectrum peaks appear to be slightly detuned, which could be responsible of the characteristic beating of the *sonido rajado*.

More detailed measurement of control parameters on experienced flute performer are required to identify how the *rajado* sound is produced, and in particular how the lips of the player affects the tuning of the resonator. A better model of turbulent jets could also help us understand the non-linear behavior of this an many prehispanic Latin American instruments that use similar techniques for their ritual and expressive requirements.

ACKNOWLEDGEMENT

This research was possible due to the support from ECOS-CONICYT, Fondos de Fomento de la Música Nacional and Fondecyt (grant# 11090142), Conicyt, Government of Chile.

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