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OPTIMIZED REDESING OF THE QUENA

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Abstract
The *quena* is a notched flute from South America. In southern and central Andes countless archeological specimens of notch flutes dating from prehispanic times have been found; they all share the same excitation technology but are different in several aspects such as the number of holes, the geometry of the notch and the size and shape of the tube. Today the quena is an instrument widely played in Latin America both in rural contexts, where they preserve a role and symbolism linked with the agricultural cycle, and in popular culture, where it adapted to tonal music. It is in the latter context that we propose to revise from an acoustic perspective the design of the bamboo quena, optimizing the position of the toneholes and modifying the geometry of the bore in order to obtain an instrument that is flexible and able to play tonal music as well as adapt to the chromatic needs of contemporary music. The analysis is based on a linear model of the acoustical propagation inside the instrument, which is numerically simulated and optimized in order to obtain a new design of the instrument, improving some of the limitations found in the original cylindrical quenas.

Keywords: musical acoustics, flutelike instrument, simulation, quena.

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1 Introduction

What is a notched flute?

The Grove Music Online describes the notched flute as a 'an end-blown flute (open or stopped) with a V- or U-shaped notch cut or burnt into its upper rim to facilitate tone production' [1]. Notched flutes are played widely and can be found in Africa, East Asia, the Pacific Islands and Central and South America. One of the most well known notched flutes is the Japanese *shakuhachi*. It is made traditionally out of bamboo and its most common form has four finger holes and one thumb hole. The *shakuhachi* has a range of two octaves and a fourth although the third octave is rarely used in the traditional repertoire. In China, the *xiao* or *dongxiao* is a notched flute also made out of bamboo [2][3]. Presenting a thinner bore, it commonly has five finger holes and one thumb hole although the *dongxiao* from Shanghai can have seven finger holes and one thumb hole. Variants of the notched flutes are found in Korea, Vietnam and Taiwan. In South America, the *quena* is another well-known notched flute. Like the other flutes, the *quena* is an ancient instrument, with a history of over 2000 years. The instrument is mainly found in Peru, Bolivia, northern Chile and northern Argentina and is less frequent in Ecuador, Venezuela, Columbia and the Guyanas [4]. It can be made out of cane, wood or reed and most instruments have six finger holes and one thumb hole [5].

Musical and cultural contexts

All these different flutes are used in specific musical and cultural contexts that determine the form and shape of the instrument. The *shakuhachi*, for instance, was initially part of the courtly *gagaku* ensemble when it was first imported from China in the eighth century. A thousand years later, Tsukitani Tsuneko explains, two different types of music emerged for the *shakuhachi*: *honkyoku* and *gaikyoku*. *Honkyoku* is a 'classical' repertoire with over 150 pieces composed specifically for the *shakuhachi* transmitted to generations of players, 'from temple to temple and region to region', becoming 'religious music for Zen practitioners' [6]. *Gaikyoku*, on the other hand, is composed of transcribed melodies played in small chamber ensembles (*sankyoku*) with other instruments. Initiated in the nineteenth century, this became the main repertoire of the instrument. It was played by professional musicians and led to changes in the manufacture of the *shakuhachi* as the instrument adjusted to the rest of the ensemble [7]. Indeed, *sankyoku* music required 'moderation in volume, exactness of pitch, soft timbre and rhythmic coordination with the strings' [8]. The *shakuhachi* was much experimented on over the years. Seven and nine-holed instruments were conceived, especially with Western music in mind, so that the twelve tones of the scale could be more easily produced. Despite such inventions and even one trial with a Boehm key-system [9], the new *shakuhachis* quickly declined. According to Tsuneko, however, finger holes on modern *shakuhachis* are strategically placed in order to be able to play major seconds and minor thirds and to adjust their tuning more easily to other instruments in the *sankyoku* ensemble [10].

The case of the *quena*

Despite the wide variety of notched flutes around the world, we chose to use the Andean *quena* as a case study for notched flutes. Like the shakuhachi, the *quena* is also an instrument with an ancient history. Archeological finds testify that the notched flutes were played in Peru as far back as the Chavin era (900-200 BCE). Traditional repertoire is closely associated to the dry winter season and is still played in Aymara communities on the Bolivian altiplano [11]. The instruments used in these rural communities (*kena-kena*) are between 50 and 70 cm long, have six finger holes and are played as part of an ensemble. The *quena* was not solely confined to a rural environment. Solo playing developed within an urban setting, consolidated around the mid-twentieth century, when Andean music benefitted from a huge surge in popularity. Today, the standardized urban instrument is generally made out a single piece of cane, wood or even plastic and features six finger holes and a thumb hole at the back [12]. Some modern models are also in two parts, with a joint between the head and the body (Garcia, interview 30 May 2016, Paris). Folk music history in Latin America is complex. Reinvented several times through different national and political lenses [13], a cosmopolitan Andean music genre arrived in Chile from Paris, where several Argentinean, Chilean and Bolivian groups had recorded and gained popularity in the 1960s. Despite the fact that the music was not political, neither in its discourse nor in its texts, its close association with the revolutionary ideals from the continent where it came from was enough to associate 'flutes and revolution' [14].

Although Andean music was already played in Santiago de Chile in the 1950s, the genre boomed in the 1960s with the return of singer songwriter Violeta Parra from Paris and an increased interest from the music and media industries [15]. The *quena* and the *charango* were used extensively in left-wing Nueva Canción groups, identifying themselves with a pan-Andean revolutionary movement [16]. These instruments were so closely associated with this political movement that they were banned after the 1973 military coup, overthrowing Allende's democratically elected government [17]. One year later, however, traditional instruments were openly played by musicians who distanced themselves from the censored repertoire by playing European Early music. The group, Barroco Andino, was officially neutral but the simple fact that they were playing Andean instruments implicitly demonstrated resistance to the new regime. Patricio de la Cuadra, who joined the band in 1987, noted that the group had initially been formed so that its members could find a way of leaving the country during a tour (interview, 8 February 2016, Paris). This, however, did not occur as Barroco Andino became more and more popular and the musicians decided to stay in Chile. Other groups with traditional instruments were also formed in 1974 such as Kollahuara and Illapu, and, in 1975, Ortiga [18].

The new repertoire played by Barroco Andino (and later other groups) created different musical opportunities for the traditional instruments, including the *quena*. Through the performance of a European repertoire initially conceived for different instruments, the musicians pushed their instruments beyond their limits and started experimenting in order to meet the demands of the music. Musicians changed the instruments themselves. In the case of the *quena*, the instrument was tuned in order to play adequately in an ensemble, especially in the second octave (de la Cuadra, interview, 8 February 2016, Paris). To illustrate this, the first recording by Barroco Andino was compellingly called *La quena bien temperada* (the well-tempered *quena*). Thus, folk instruments were consciously removed from their previous musical frame. This had already happened once before as the rural *quenas* were transferred to urban, cosmopolitan folk music, shifting from ensemble to solo performances, from seasonal music to an imagined pan-Andean folk culture. In Chile, the *quena* was presently pushed even further as the instrument was introduced to new musical horizons for political reasons, decontextualized from its usual urban repertoire. Later, flautist Alejandro Lavanderos, student of Pierre-Yves Artaud, founded Ensamble Antara, a group gathering many different kinds of flute-type instruments including the *quena*. With a conscious effort to connect traditional sounds with contemporary music, Lavanderos approached both composers and instrument makers in order to be able to play a huge range of sounds and notes on the instruments. This led him to contact Jean-Yves Roosen, a Paris-based flute maker to create a chromatic instrument. Roosen created the first chromatic *quena* with a Boehm key mechanism. This, however, led to further questions as the identity of the instrument changed radically. It also led to different views from both parties as the musicians saw the new model as a type of vertical modern flute with a notched embouchure rather than an 'improved' *quena* arguing that it deprived musicians from the kinesthetic identity of the instrument associated to the keyless fingerings whereas the instrument maker clearly saw the instrument as a *quena*, bearing no resemblance to a flute.

For years, musicians have been experimenting and/or working with instrument makers in order to create an instrument that responds to their musical demands. Over the years, Chileans developed mechanisms to continue playing the *quena*. This led them to explore repertoires that were not conceived for the instrument, which in turn instigated research into the instrument's manufacture. As composers have taken an interest in these instruments thanks to their unique sound, musicians are trying to obtain models that will enable them to play music that pushes ever further the boundaries of their instruments.

2 Notched flute operation and control

Flute operation can be globally described as a coupling between the hydrodynamic modes of a jet with the acoustic modes of a resonator. The pipe resonances depend, among other things, on the characteristics of the pipe ends. The interaction of the jet with the notch takes place in one open end, which is also where part of the acoustic radiation of sound takes place.

The control exerted by the performer on the instrument can be of crucial importance in the quality of the sound produced. Indeed the sound of some instruments from the flute family, such as organ pipes, can be almost entirely the result of the manufactured object by instrument builder: the musician has little or no incidence on the sound produced. The other extreme is where the interaction of the performer has an enormous influence on the sound produced by the instrument. Such is the case of notched flute.

The *quena* player performs simultaneous and synchronized control over several parameters. The air pressure is modulated in the lungs to produce a desired air jet velocity. The tongue provides an exit valve that is used to produce the different types of attacks and, in combination with the velocity of the outgoing air jet, shape the global intention of musical phrases. The geometry of the opening created by the lips shapes the cross section of the air jet and by pushing the lips forward and backward, the quena player controls the distance the jet travels before reaching the sharp edge. This movement also alters the surface of the open extremity and therefore the input admittance of the tube [21]. Through years of practice an experienced musician learns refined control over those mechanisms.

The fact that the musician modifies the instrument's acoustical properties, in particular its admittance, while the performer interacts with it renders the design of the instrument very complex. The musician manipulates the jet speed and the closure of the pipe simultaneously and every musician develops his or her own control strategy in order to achieve his or her personal musical intentions.

Measuring the musicians' behavior is a complex task ([22][23]). An alternative approach has been utilized throughout this article: the passive impedance of a "good" instrument has been measured and its peaks of admittance noted; it is assumed that the difference from these peaks to a tempered scale are compensated by the musician and thus a description of the musician's modification of the bore is obtained.

3 Bamboo notched flutes

3.1 The knot

Notched flutes made out of bamboo use the knot at the end of the resonator to reduce the diameter of the cylinder. The acoustical consequence of this reduction is a misplacement of the resonances or inharmonicity, which impoverishes produced notes by decreasing their volume and brilliance. Why, then, is it systematically used in instruments like the *quena*? It is possible that by making the lowest note inharmonic, the harmonic structure of the other notes that result from carving toneholes in the bamboo benefit from an overall inharmonicity of the non-cylindrical bore. It is also possible that the reduction of the end facilitates the playability of notes in the third register of the instrument.

In order to develop an intuition on the effects of this reduction on the resonance structure of the bore, we have simulated, using the transfer matrix approach ([24][25]), cylindrical bores with a knot at the end of different diameters. Figure 1 shows the calculated resonances of a cylinder of 37 cm length and 19 mm of internal diameter ended with knots of diameters 7,9,11,13,15 and 17 [mm]. The resonances shown are the peaks of the input admittance. The first four resonances are shown. We observe that both the amplitude of the admittance peaks and their frequency positions change with the notch diameter.

A more informative view of the data is displayed in figure 1 right, with inharmonicity defined as:

$$Inhar_n = 1200 \log_2 \frac{f_n}{nf_0} \cdot \tag{1}$$

Where n is the number of the partial. Figure 1 right shows the inharmonicity for the first 4 resonances as a function of the knot diameter. We observe that the resonances become sharper, producing bigger octaves, as the diameter reduces.

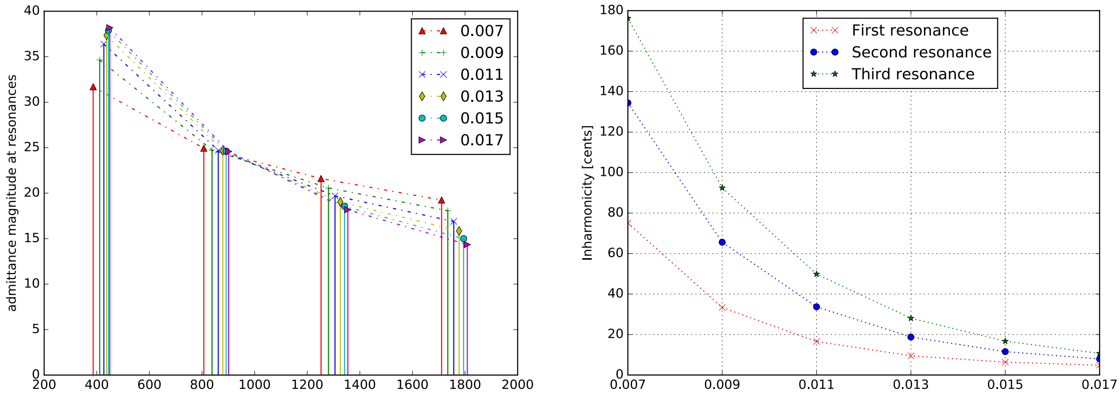

Figure 1 left: admittance peaks magnitude for knots of different diameters;

right: Inharmonicities for the three first resonances as function of the knot diameter

3.2 Admittance measurements

In order to investigate the acoustical characteristics of the *quena*'s resonator, four real instruments were measured, all manufactured by Antonio Morales, a well-reputed Chilean flute maker who provides *quenas* for the group Barroco Andino and many others.

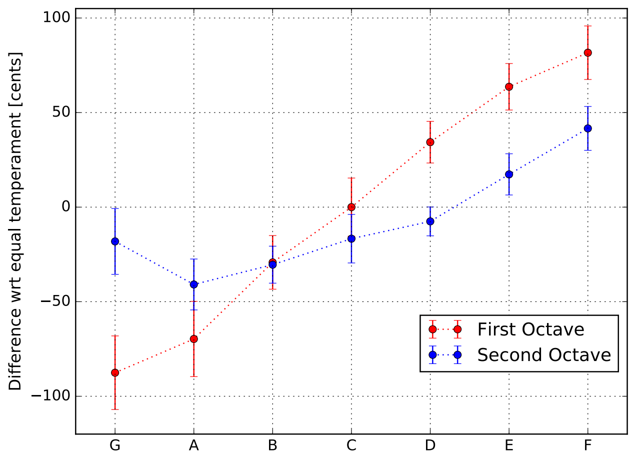

Figure 2: Frequency difference and variance of passive resonance peaks to equal temperament 4 *quenas* made by Antonio Morales.

The acoustical input admittance of the four instruments were measured and their passive resonance frequencies obtained. These *quenas* are expected to play almost three octaves; the first two octaves are obtained with the same fingerings. Figure 2 shows the position of the mean passive resonance and variance for the first and second octaves for all fingerings, as a difference with respect to equal temperament tuning. We observe that, in both octaves, resonances are sharper as they move up in the register. This tendency is more pronounced in the first octave than in the second one, which translates in a level of inharmonicity that decreases as the notes get higher.

3.3 Bore simulations

In bamboo flutes the shape of the bamboo determines the internal geometry of the resonator. With a new design, however, we have the opportunity to consider different bore shapes that could help to produce the inharmonicities desired for the instrument. Analytical models are available [24] but since we wish to compare many different shapes, we opted for a numerical simulation of the acoustical propagation in bores that combine cylindrical and conical sections.

As an example, Figure 3-below shows the structure of the resonant peaks for 6 cylinders of 37cm. length, in which the internal diameter grows gradually from 18 to 19 mm at various distances from the embouchure, as shown in Figure 3-above. We observe that important variations of the resonant structure can be obtained by adjusting the bore shape. In this example, the first resonance can be made 35 cents sharper or 35 cents lower simply by changing the position in which the geometry enlarges by 10 [cm] (from 0.1 to 0.2 meters). This is simply an example and many other bore shapes can be inspected in order to find one that collaborates with the harmonic modification researched in the instrument design.

In bamboo-made *quenas*, the cane imposes the internal geometry and the flute maker has to adjust the shape of the toneholes to compensate for the irregularities of the cane, while some canes simply won't permit the construction of a tuned instrument.

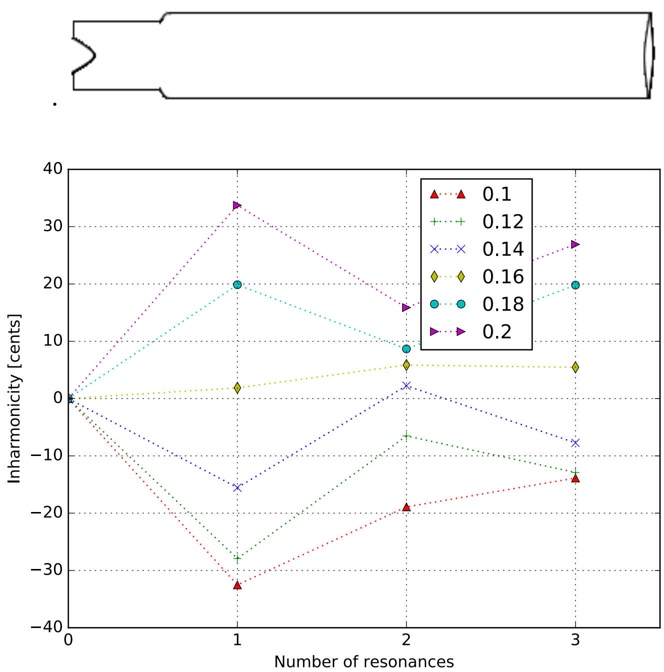

Figure 3: above: sketch of the instrument's shape to show the way the bore diameter is enlarged; below: Inharmonicities for various bore geometries. Each line corresponds to a bore with the enlargement at a different distance (in meters) from the embouchure.

3.4 Toneholes

While having a correct bore shape facilitates the tuning of a flute, the final pitch will be determined by the position and shape of the toneholes. Lateral toneholes are a way of modifying the acoustical length of the bore, a technical solution to a musical problem already present in Paleolithic flutes ([19][20]).

The musical interval (or the frequency distance) from a closed to an open tonehole depends on the distance of the tonehole to the active end or embouchure: the closer the tonehole to the embouchure, the larger the interval it will produce when it is opened. However, the interval also depends on the radius of the tonehole, as a larger tonehole will create a greater interval. Therefore, if we require a specific interval from a tonehole we can chose from many combinations of places and sizes that will satisfy the required interval. But the timbre that will sound out of a small hole is different from that of a big one, in other words the inharmonicity of the radiated sound depends on the tonehole size.

Figure 4 shows the input admittance of a simulated quena, we can observe the resonant structure of every tonehole. Simulated inharmonicities, toneholes position, internal profile and frequency of the resonances for every fingering are shown in Figure 5.

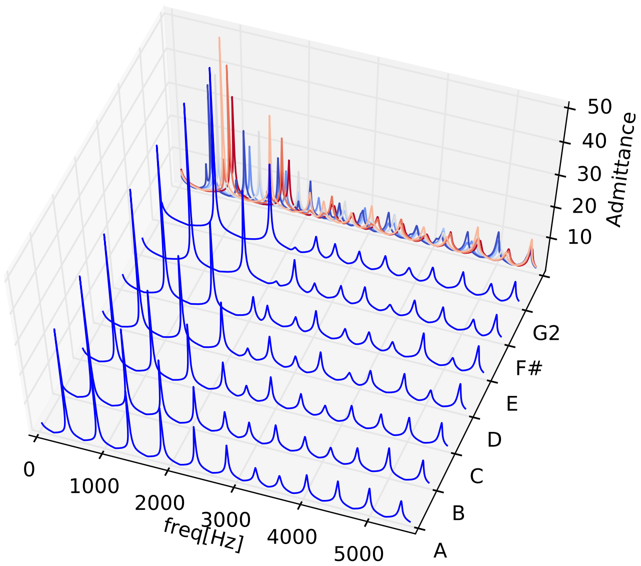

Figure 4: Input admittance of a complete *quena*

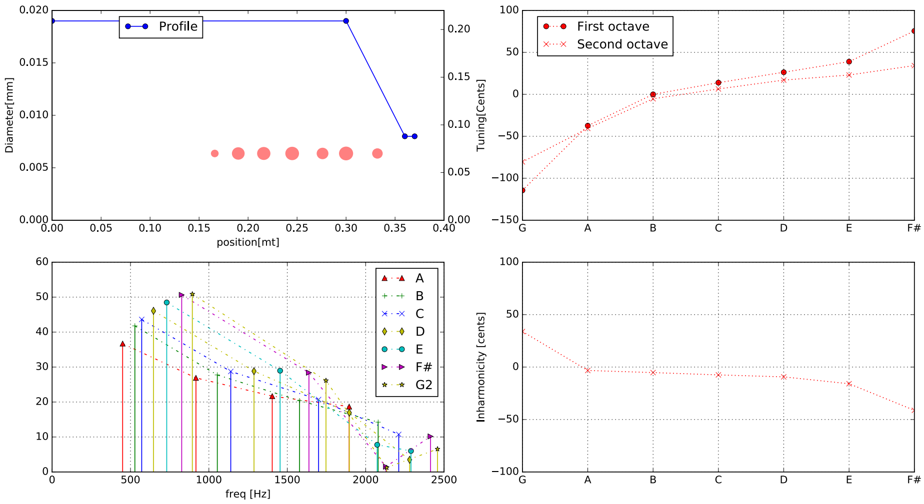

Figure 5: Simulated *quena* from real geometric measurements

3.5 Optimization

Thus, the design of a notched instrument can be approached as an optimization problem. The goal is to achieve a desired tuning profile both for the first and second registers. As for the controlled parameters, we have the internal geometry shape and the size and the position of the toneholes. An exhaustive search approach has been implemented, several bore profiles have been tested and toneholes have been adjusted to produce a desired tuning. One of the many possible optimization results is shown in Figure 6, where we observe that the tuning of both octaves is adequate and the error between the simulated and measured instruments lies within 20 cents. This solution is converted to a CAD model, shown in Figure 7, in order to be printed in a 3d printer and test the results.

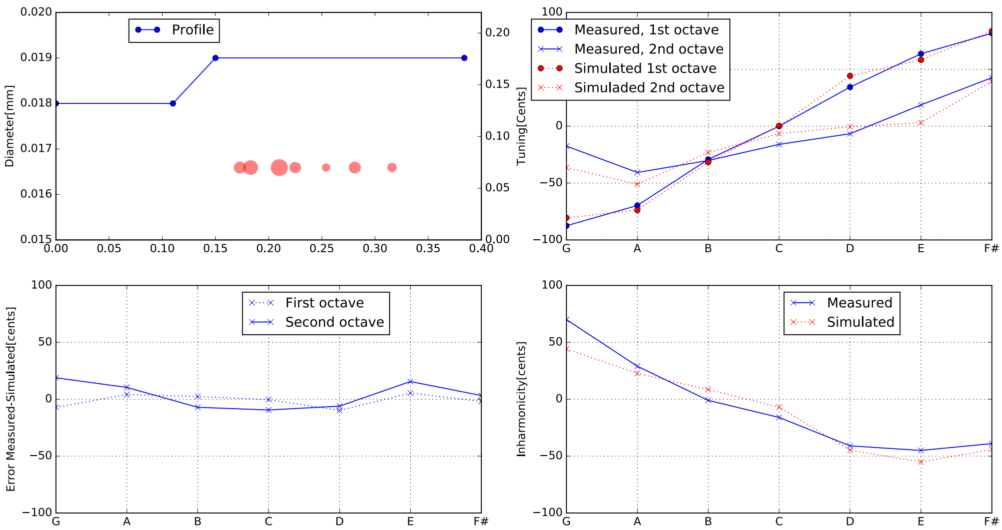

Figure 6: Simulation outcome

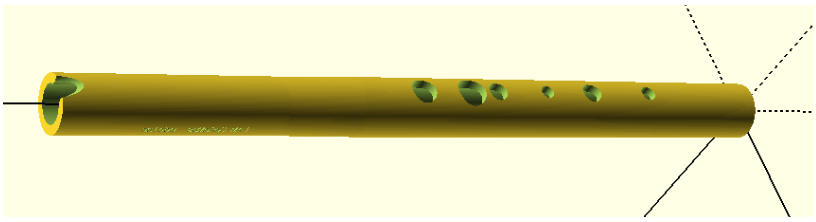

Figure 7: 3D model of the *quena*

4 Conclusions

The historical evolution of the *quena* has been determined by a set of constraints that include, amongst others, the musical and cultural contexts, the available technology and the physical limits of the bamboo cane. In this article, a first attempt to review the design of the instrument is proposed using a numeric simulation of the acoustical propagation in a tube with toneholes, with the Transfer Matrix approach, an optimization algorithm to determine de size and position of the toneholes for a given bore geometry and a 3D printer to produce the resulting instrument.

Several aspects of the proposed solution can be improved: a musical test of the proposed solution remains to be done; most wind instruments present undercut on the toneholes, a feature that certainly impacts the inharmonicity of the tonehole and can be used as a controlled parameter in future designs.

The musician adapts to the possibilities of the instrument, therefore it is conceivable that a new "way to play" the instrument can be proposed together with the design of the instrument. The proposed instrument also addresses the issue of the musician's relationship with his or her instrument, retaining the identity factors that seem to be important in order to play comfortably. The optimization of the *quena* and the quick production of different bores will allow musicians to experiment with different tonehole positions and bore shapes, neither which seem to interfere with the inherent identity of the instrument.

References

[1] Cooke, Peter and John M. Schechter. Notched flute, *Grove Music Online. Oxford Music Online*. Oxford University Press, accessed April 5, 2016,

http://www.oxfordmusiconline.com/subscriber/article/grove/music/20120

[2] Picard, Francois. *La musique chinoise*, Paris: Minerve, 1991, 132.

[3] Thrasher, Alan R. Xiao, *Grove Music Online. Oxford Music Online*. Oxford University Press, accessed April 5, 2016, http://www.oxfordmusiconline.com/subscriber/article/grove/music/45374.

[4] Stobart, Henry. Kena. *Grove Music Online. Oxford Music Online*. Oxford University Press, accessed April 5, 2016, http://www.oxfordmusiconline.com/subscriber/article/grove/music/22682.

[5] Paraíso, Raquel. Quena, *Encyclopedia of Latin American Popular Music*, ed. George Torres, Oxford: Greenwood, 321.

[6] Tsuneko, Tsukitani. The shakuhachi and its music, translated by Charles Rowe, *The Ashgate research companion to Japanese music*, eds. Alison McQueen Tokita and David Hughes: 145-168. Aldershot: Ashgate Publishing Limited, 2008, 155-159.

[7] Ibid. 158-159.

[8] Ibid. 160.

[9] Seyama, Toru. 'The Re-contextualisation of the Shakuhachi (Syakuhati) and its Music from Traditional/Classical into Modern/Popular'. *The World of Music,* 40 (2), 1998, 75.

[10] Tsuneko, Tsukitani. The shakuhachi and its music, translated by Charles Rowe, *The Ashgate research companion to Japanese music*, eds. Alison McQueen Tokita and David Hughes: 145-168. Aldershot: Ashgate Publishing Limited, 2008, 153.

[11] Stobart, Henry. Quena. *Continuum Encyclopedia of Popular Music of the World, Volume 2: Performance and Production*, eds. John Shepherd, David Horn, Dave Laing, Paul Oliver, Peter Wicke: 491-492, New York: Continuum, 2003, 491.

[12] Ibid. 492.

[13] González, Juan Pablo. 'Música chilena andina 1970-1975: construcción de una identidad doblemente desplazada'. *Cuadernos de música iberoamericana* 24: 175-186, 2012.

[14] Ibid. 180.

[15] Ibid. 180.

[16] Mularski, Jedrek. *Music, politics and nationalism in Latin America: Chile during the Cold War Era*. New York: Cambria Press, 2014.

[17] Jordán, Laura. Music and "clandestinidad" during the time of the Chilean dictatorship: repression and the circulation of music of resistance and clandestine cassettes, *Revista Musical Chilena* 212, 2009, 81-82.

[18] González, Juan Pablo. 'Música chilena andina 1970-1975: construcción de una identidad doblemente desplazada'. *Cuadernos de música iberoamericana* 24: 175-186, 2012, 183.

[19] M. Dauvois, B. Fabre, 1999. 'Instruments à vent paléolithique', Colloque Acoustique et Instruments Anciens: Factures, Musiques et Science, Cité de la Musique, Paris.

[20] M. Dauvois, X. Boutillon, B. Fabre, M. P. Verge, 'Sons et musique au paléolithique', *Pour la Science* 253, (November 1998)

[21] J.W. Coltman. Resonance and sounding frequencies of the flute. J. Acoust. Soc. Am., 40:99–107, 1966.

[22] P. de la Cuadra, B. Fabre, N. Montgermont, and C. Chafe, "Analysis of flute control parameters: A comparison between a novice and an experienced flautist," *Acta Acustica united with Acustica*, vol. 94, no. 5, pp. 740–749, 2008.

[23] Vauthrin, Camille; Fabre, Benoît; Cossette, Isabelle, "How Does a Flute Player Adapt His Breathing and Playing to Musical Tasks?" *Acta Acustica united with Acustica*, vol. 101, no. 2, pp. 224–237, 2015.

[24] A. Chaigne and J. Kergomard, *Acoustique des instruments de musique*, ser. Collection Echelles. Belin, 2008.

[25] Kinsler, Lawrence E.; Frey, Austin R.; Coopens, Alan B. y James V. Sanders. *Fundamentals of Acoustics*. U.S.A.: John Wiley & Sons, Inc., 2000.