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Effects of Changes in the Bore Shape and the Labium Position in a Txistu

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Summary
The Basque txistu is a fipple flute with three finger holes. The sound produced by txistus depends on the physical characteristics of the instrument and the control exerted by the player. Cross fingering and half holing methods are used to play over two octaves. The effect of the horizontal position of the metal labium W, is experimentally measured in this paper. The studied notes are measured with a blowing machine, recording the radiated sound for a known input pressure and also with a musician playing them in mezzo forte dynamic. Data produced by a traditional and a new txistu prototype have been collected, analysed and compared. The internal bore shape of this new txistu is not pure cylindrical as that of the traditional txistu. Moreover the location, size and height of the holes have been changed. The analysis shows remarkable tuning differences between the two txistus.

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1. Introduction

The txistu is a straight fipple flute made out of African hardwood. Although historically the txistu has suffered some variations, in its modern form the one tuned in F is commonly used in music schools. It has a cylindrical bore of approximately 417 mm long and the internal diameter is 13 mm. The outside part of the instrument is cone shaped. Three finger holes are situated near the end of the bore: two on the upper part for the index and the middle fingers and one on the back, covered by the thumb. The player, "txistulari" in the Basque language, holds the instrument with the left hand introducing the ring finger into a metal ring that is placed at the end of the bore for this purpose as shown in Figure 1. The small finger can be used to half cover the main bore hole in some fingering and the right hand is used to play a drum or another kind of percussion. The instrument is commonly made out of three sections and supported by metallic rings that prevent the wood from expanding and cracking.

Many aspects of the acoustics of wind instruments are well understood [1, 2, 3] with flute acoustics having been studied in detail [4, 5, 6, 7, 8, 9, 10]. The sound of a txistu is produced when the player blows through the metal windway. At the windway exit, a free jet is formed by flow separation and travels until it hits the metal labium. The sound is the result of the coupling between the unstable flow and a resonant acoustic field in the pipe. The flow flips on both sides of the labium travelling inside and outside the instrument. The frequency of the flip is the same as that of the acoustic field. If the player maintains the flow, standing waves form at certain frequencies that depend on the geometry of the bore.



Figure 1. The txistu and the player, txistulari.

The distance between the windway and the labium is called W. A player can change W by moving the metal labium up or down the bore, being the value normally around 6 mm. The windway is 36 mm long and the flue exit height is called h. For the txistus studied in this work, the value of h is 1.4 mm. The edge of the metal labium is flat and it has a positive inclination of 5 degrees with

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the windway plane. The relative height between the central plane of the windway and the bottom of the labium is fixed by the maker. In measured instruments, the bottom of the labium is 0.8 mm lower than the central plane of the windway when W is 6 mm. Figure 2 shows the parameters of the mouthpiece and the holes of the txistu.

The musician controls several parameters simultaneously. The lungs modulate the air pressure to produce the desired air jet velocity. It is interesting to note that a professional player can play up to six notes on a txistu with the same finger position, so controlling the air jet is crucial to achieve the desired note. There are several different types of tonguing techniques. In each case, it is important not to touch the mouthpiece of the txistu with the tongue, as it distorts the sound and more saliva enters inside the windway.

In order to play more than two octaves with an instrument with three finger holes, the player has to excite high registers of the bore. Cross fingering configurations, in which one or more tone holes are closed below an open hole, and half holing techniques are used to correct the pitch and to play sharp and flat notes. In this study we will concentrate on the basic finger positions shown in Table I. With these positions the holes can be completely open (∘) or completely closed (●).

If a txistulari covers all the finger holes leaving the main bore hole open and blows with a low pressure, the first note will be G4, with a frequency near 392 Hz in the twelve tone equal temperament scale. With the next 2, 3 and 4 basic fingering positions, we will hear higher frequencies, with the intervals between notes being one tone, half a tone and a tone once again. This is the first register of the txistu, however, it is not very powerful and it is rarely used. Using overblowing, high registers can be excited. The highest note studied here will be the sixth register of the first position, with an approximated frequency of 2349 Hz.

Traditionally the txistu has been used for outdoor dances and popular songs. However, the introduction of regulated studies in music schools has made it usual to include this instrument in compositions with piano, accordions and other instruments. These instruments normally use the equal tempered scale and it is essential to have the same tuning between instruments playing together. It is possible to achieve this tempered tuning with the cylindrical txistu, however, lots of corrections are needed and this can be a problem even for an expert player. Problems in achieving tempered scale with a txistu prompted some txistu artisans in collaboration with scientists and txistu players to design a new instrument [11, 12]. From now on, we will refer to this new instrument as the modified txistu.

The changes in the modified txistu are centred on the holes and in the shape of the internal bore. The location and size of the holes have been modified as Table II shows. The location of the holes is measured from the mouthpiece to the centre of the hole and the height is the wall thickness of the hole. The cylindrical txistu has been enlarged by a 7.85 mm wooden ring in order to fix both instruments to

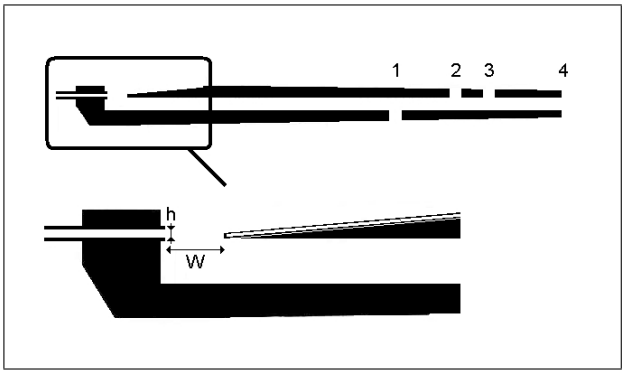

Figure 2. Longitudinal cross section of a traditional txistu.

Table I. Basic finger positions.

	Hole 1	Hole 2	Hole 3	Hole 4
Position 1	●	●	●	∘
Position 2	●	●	∘	∘
Position 3	●	∘	∘	∘
Position 4	∘	∘	●	∘

Table II. Hole location and dimensions in the cylindrical and modified txistus.

	Cylindrical Txistu (mm)			
Hole	1	2	3	4
Location	300.0	339.3	361.0	417.0
Diameter	9.3	8.4	10.0	13.0
Height	3.8	3.1	2.6	-
	Modified Txistu (mm)			
Hole	1	2	3	4
Location	299.0	336.8	358.3	417.0
Diameter	10.5	9.0	10.0	14.0
Height	2.3	2.5	2.1	-

the same length. This ring is made of the same material and has the same internal bore diameter as the instrument.

The holes and the internal bore diameter are bigger in the new instrument. It is known that a change in the geometry of the bore can change the frequency of a note: a decrease in the area at a pressure anti node produces an increase in frequency. Unlike the traditional model, the new bore is not cylindrical. The total volume is larger and it is composed of cylinders with different diameters.

The geometry of the upper part of the bore has several changes: in the first 40 mm near the mouthpiece it has a diameter of 13.5 mm. It widens, having a diameter of 14.0 mm in the next 18 mm of the bore. Next it has a diameter of 14.6 mm for 5 mm, 14.8 mm next 10 mm and back to 14.6 mm for another 5 mm length. In the rest of the instrument, the internal diameter changes several times to move the frequency of every note closer to the tempered scale. The minimum diameter along the bore is of 13.4 mm and the maximum 14.8 mm. At the end of the bore, located

at 417.0 mm from the mouthpiece, it has a 14.0 mm of diameter as it is showed in the Table II.

In this work, measurements from the two txistus, one with cylindrical bore and the other with modified bore, are analyzed and compared. The main objectives are to observe the effect of a change in the distance W, the effect of the jet pressure and to contrast the differences in tuning.

2. Experimental setup

The experiments are done in a room with a volume of 128 m^3 without any anechoic treatment trying to set as close as possible to the normal practice room and playing conditions. Measurements with a player and a blowing machine are taken. The sound of the txistu is recorded with a prepolarized free-field microphone 4189-A-021 and a PULSE 11 analyzer, both from Brüel&Kjær. The microphone is placed 50 cm in front of the txistu. The FFT spectra are taken for 6400 frequencies between 0 to 20 kHz. Frequency delta is 3.125 Hz, record length 320 ms and delta time 19.531 μs. The data are analyzed using Matlab.

The blowing machine used is the 8MS11 from Air Control Industries (ACI) Ltd, Chard (United Kingdom). The air flows through a pipe that has a valve to change the air flow. The flow is directed to two identical tubes: one of them is attached to the mouthpiece of the instrument and the other to a Digitron manometer model 2021P. The temperature of the air at the exit of the windway is measured with a thermometer model CI-6605A from Pasco, being equal to the room temperature. Tone holes are closed using a latex glove full of plasticine.

The txistulari plays notes in a mezzoforte dynamic. These notes are recorded with the microphone. The temperature at the exit of the windway is measured and it is higher than the room temperature, as expected from human breath. In this case the player covers the tone holes.

Two different instruments are measured in these experiments: a traditional txistu with a cylindrical internal bore and a new design of txistu with modified internal bore and holes.

First, the distance W is fixed at 5.0 mm. Using four basic finger positions the first four registers of each position are played and measured. For the first position, up to six registers are measured. The same procedure is repeated with values for W of 6.0 and 7.0 mm (in the results and discussion we will refer to these distances simply as 5, 6 and 7 mm). In every case, the notes are recorded using the blowing machine and the txistulari.

Finally, the new instruments were given to professional players with an opinion poll.

3. Results and Discussion

3.1. Effects of W and jet pressure

In recorder like instruments, the ratio W/h is an important parameter since it determines, for a given value of the air jet height h, the distance travelled by the hydrodynamic perturbation on the jet and hence its oscillating mode [5]. It also determines the window surface to pipe cross-section ratio. In the case of the txistu, the distance W can be easily adjusted by the player moving the metal labium. Figure 3 shows the pitch of some notes played with different pressures for three different values of W.

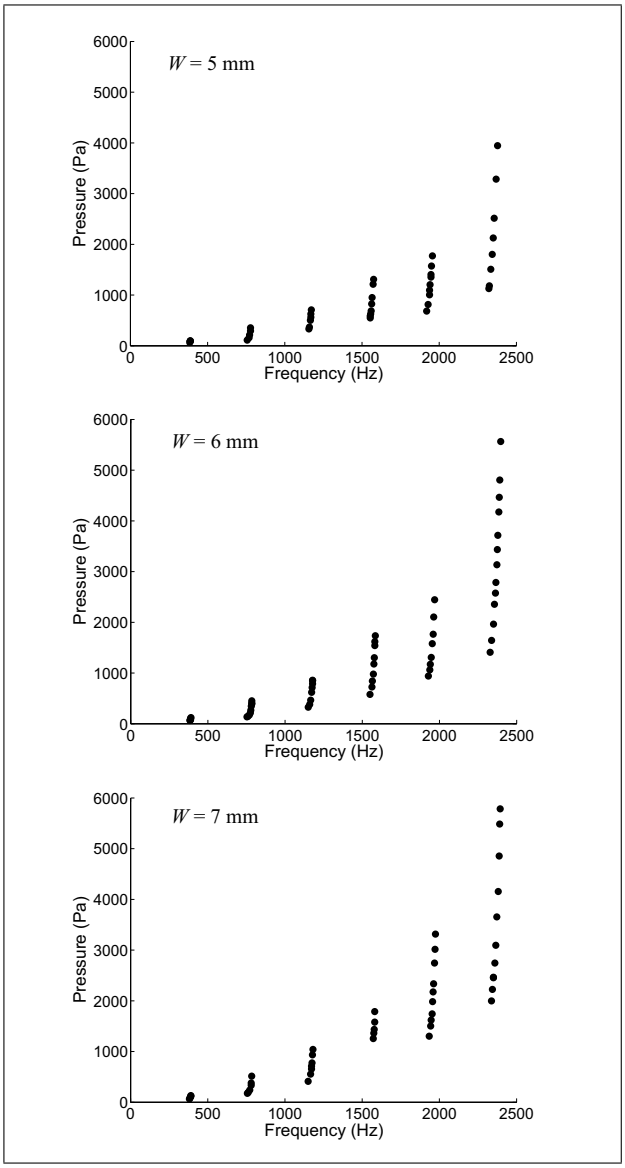

Figure 3. Fundamental frequency changing the air pressure for different values of W using position 1 in the modified txistu.

The measurements are taken using a blowing machine and playing the first six registers of the position 1 with the new designed instrument. The height h can not be changed in measured instruments and it is 1.4 mm so, the ratio W/h moves from 3.6 to 5.0.

The pitch of a note changes when the air pressure changes. If the pressure gets higher, the frequency of the note becomes higher until it jumps, with hysteresis, to the next register. The range of pressures where a note sounds varies with the ratio W/h. When using values of W/h lower than 4, the pressure range where a note can be played is smaller. On the other hand, when W/h is near

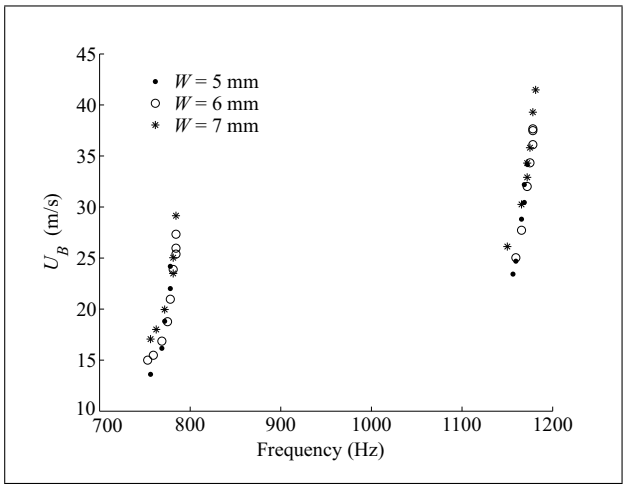

Figure 4. Fundamental frequency as a function of the maximum jet velocity U_B for different values of W in the modified txistu.

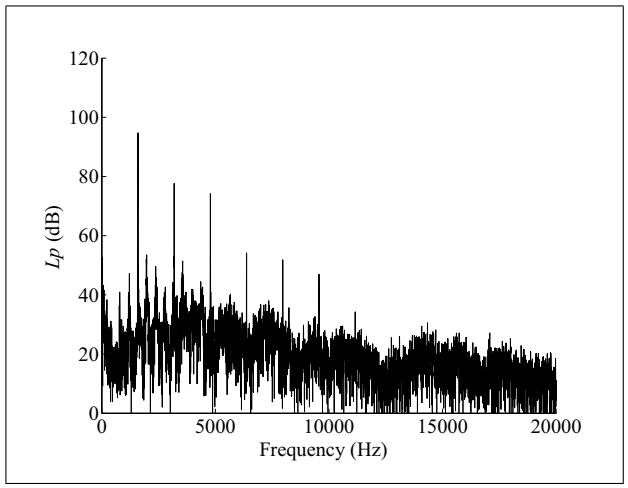

Figure 5. FFT of the fourth register played with the first finger position. The note has a fundamental frequency of 1593 Hz and it is played using an input pressure of 1302 Pa in the modified txistu. The value of W is fixed to 6 mm.

5, the higher registers demand bigger pressures and they sound very powerful, which often is not musically desirable. Moreover, when the fourth register is played with pressures below 1256 Pascal, multiphonic sounds appear. For a value of W=6 mm, the pressure range of each note and the pressure needed to play high registers are more desirable for the musician. In this case the value W/h is 4.3, as in recorders, where the ratio W/h is adjusted to a value close to 4. Similar results are obtained for the cylindrical instrument.

There are also differences in the threshold of vibrating modes when W is changed. Figure 4 shows the fundamental frequency of the second and the third oscillation modes as a function of the maximum jet velocity U_B for three different positions of the labium. The maximum jet velocity U_B is calculated using the pressure at the entrance of the windway, p_{in} in the Bernoulli's equation

$$U_B = \sqrt{2p_{in}/\rho_0}, \tag{1}$$

where ρ_0 is the air density. This equation is valid when the jet velocity profile at the exit of the windway reaches the Poiseuille profile. Following the method proposed by Sègoufin *et al.* [13] the critical value L_c and the Reynolds number are calculated with values of windway length l =36 mm and h=1.4 mm. The results show that L_c is of the same order than l in the first two registers, which is the condition to achieve the mentioned jet profile. The result agrees with their affirmation that in recorders, a Poiseuille velocity profile would always be reached if the windway had a uniform height.

In the second register, the threshold changes from 13.6 m/s when W=5 mm to 17.1 m/s if W=7 mm, which is 16.8% higher. When W=5 mm, the hysteresis between the second and the third registers is very narrow. When W increases, the hysteresis becomes larger. In this two registers the range of pressures where a note can be played is bigger when the distance between the windway exit and the labium is larger.

A general overview of the FFTs obtained for position 1 shows little bumps when the third register is played at high frequencies. The Reynolds number calculated for this register goes from 1604 with the lowest pressure when W = 5 mm to 3052 which is found when the pressure is the maximum and W = 7 mm. The transition from laminar to turbulent jet happens between Re = 2500–3000 [14, 15]. These bumps are produced by the turbulent structure of the jet flow and they are located at the passive resonance frequencies of the pipe [16]. This effect is clearer in higher registers. With higher Reynolds numbers the jet is more turbulent and the noise increases. Figure 5 shows a FFT of the fourth register with position 1 and a blowing pressure of 1302 Pa in the modified txistu. The fundamental frequency is near 1593 Hz. This turbulence noise influences the timbre of the instrument.

3.2. Tuning differences between cylindrical and modified bores

In order to investigate the tuning of the instruments, value of W has been fixed to 6 mm for both txistus.

In Figure 6 the studied notes are shown changing the pressure of the air, at 23 °C, with the blowing machine in the cylindrical txistu. The deviation of each note from its theoretical value in cents as a function of the fundamental frequency is shown. The reference scale is the twelve tone equal temperament with $A4$ =440 Hz. Different markers have been used for each position.

Tuning of one note can vary more than 70 cents between the minimum and the maximum pressures. This figure is not representative of the tuning of the instrument for two reasons: the first one is that the blowing machine can blow at higher pressures than a player would: the sixth register of the first position uses pressures up to 5500 Pa. The second reason is that the hysteresis makes it almost impossible for a player to start a note with its minimum value of pressure. Using that initial pressure, probably a lower reg-

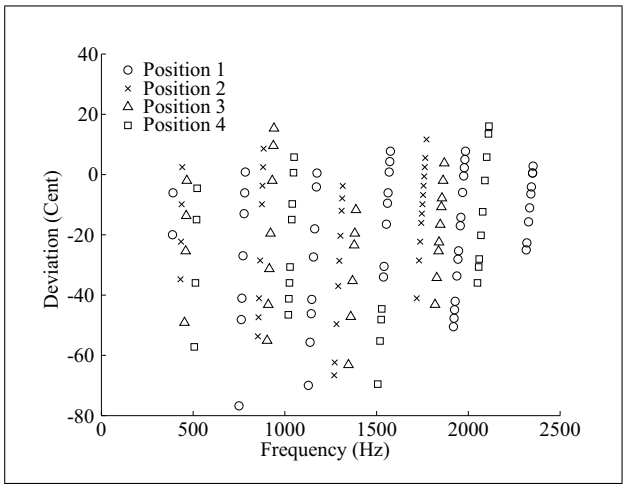

Figure 6. Deviation from the tempered scale of the notes using basic finger positions. The pressure is changed using a blowing machine in the cylindrical txistu.

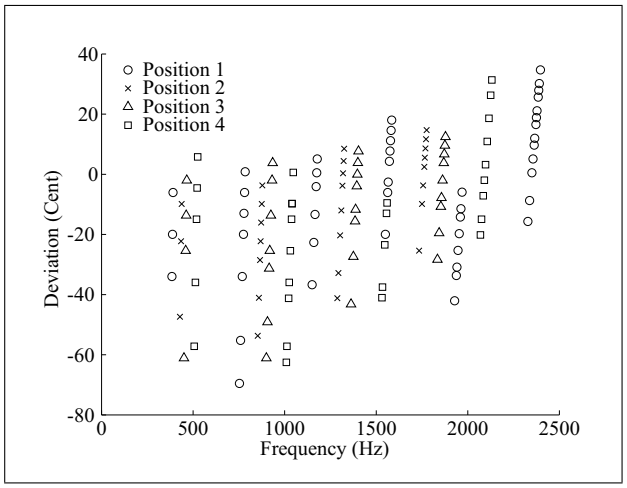

Figure 7. Deviation from the tempered scale of the notes using basic finger positions. The pressure is changed using a blowing machine in the modified txistu.

ister will sound. If the musician wants to play at the minimum pressure of one note he or she would have to lower the pressure once the note is sounding, which is not very usual in txistu music.

The same experiment is shown in the Figure 7 for the modified txistu and the main difference between the instruments can be appreciated looking at each finger position separately. With the first position, for the cylindrical txistu, the difference in the deviation between registers is not as big as in other positions. For the third position, looking at the maximum deviation value, there are gaps of over 20 cents between registers. This is not the case in the modified txistu. Especially in the low registers, the maximum deviation stays in a region of 15 cents wide. The higher registers of the instruments seem to have a large deviation but, as has been mentioned before, a player can not achieve pressures of that level.

The next Figure 8 shows the deviation of the cylindrical txistu played by a txistulari. The notes are played in the

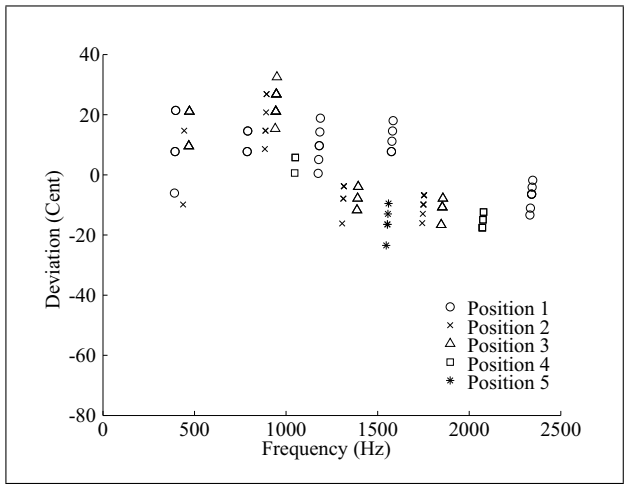

Figure 8. Deviation from the tempered scale of the notes using basic finger positions. The cylindrical txistu is played by a musician.

pressure range of the mezzo forte dynamics. Each note is recorded 10 times over and the delta frequency of the measured FFT is 3.125 Hz. Several notes with the same fundamental frequency are shown as one unique marker. This is an indicator of the reproducibility of the experiment. The frequency of the notes is higher with a musician because the temperature of the air at the exit of the windway is 31 °C instead of 23 °C.

Not all of the notes with basic finger positions are used by musicians. The fifth register of the position 1 is not used because in cylindrical txistus the corrected position is easier to achieve. This note is out of the figures 8 and 9 for that reason. A new position is introduced in these figures: position 5 is played with all holes open. The note with a frequency near 1568 Hz can be played with positions 1, 4 or 5. However, txistularis always use the first or the fifth positions, because they are easier and they have a closer pitch from each other.

Once again the first position is more balanced than the rest in the cylindrical txistu. There are considerable gaps between registers. These differences can make an interval of an octave, 25 cents lower than what it should be, what is half of a semitone. There is a considerable tuning difference when playing the same note with the first or the fifth position.

The results obtained with the same txistulari playing the modified txistu are shown in Figure 9.

The tuning of the new txistu is clearly more approximated to the tempered scale using basic finger positions. Deviation of notes is above zero, however, the length of the bore can be increased introducing wooden rings and the tuning of the instrument will decrease. The actual length of the bore has been selected because the txistu is often tuned with $A4 = 442$ Hz and because it is possible to make the bore longer to play in tune with a flatter instrument, though it is not possible to make the txistu shorter to put it in tune with a sharper instrument.

As in other woodwind instruments, air pressure is an essential factor in the tuning of the instrument. The into-

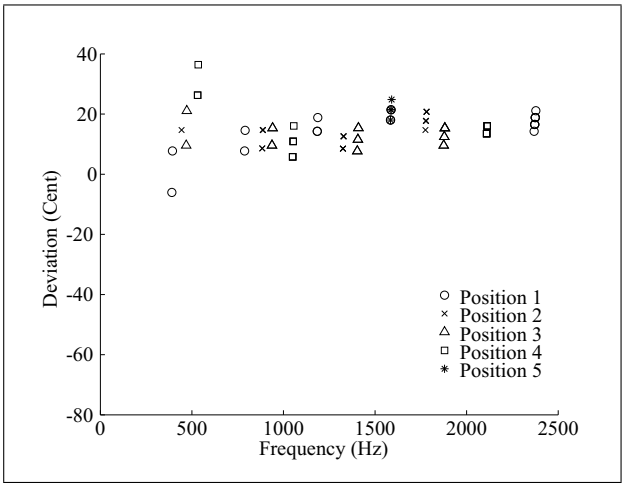

Figure 9. Deviation from the tempered scale of the notes using basic finger positions. The modified txistu is played by a musician.

nation is influenced by the extent of variations in blowing pressure required over the range of the instrument [17]. The decision about which pressure a note must be in tune with basic finger positions, is subjective. The first register of the instrument has the biggest deviations, however, this register is not normally used and the player can easily decrease the frequency of these notes by slightly covering the main bore hole with the pinkie. The note that can be played with two different finger positions, located near 1568 Hz, has nearly the same tuning with both positions. Globally, the pitch of every note is now closer to the tempered scale and none of the intervals between notes have worsened with the modification of the bore.

Comparing the results of the txistu when it is played by a machine or by a musician, it seems like the musician plays in the high pressure region for the low registers and in the middle or low pressure region when playing high registers. This will maintain the balance in the sonority between notes of the entire spectrum.

3.3. The musicians opinion

Six instruments were built following the principles of this study and they were given to six professional txistu players. These are some of the most interesting opinions of their experience after some weeks of playing the txistus regularly.

Using basic finger positions, the tuning of the new txistu is closer to the tempered scale than their older instruments. The sound is more powerful than that from their txistus. In cylindrical txistus low registers seem weaker comparing with the high register's louder sound, but all in all registers are more balanced in the modified txistu. The articulation can be made softer and the connection between some notes has become easier. The player has to partially close some holes to play some notes and they believe that these positions are now easier and the notes have a higher sound level.

Some notes can be played only with one finger position in the cylindrical txistu, but with the modified txistu it is possible to play certain notes with more than one finger position.

Txistularis feel that the modified txistu makes it easier in playing the higher registers, giving them confidence.

4. Conclusions

The Basque txistu is a fipple flute with three finger holes. Due to this, the same finger position is used for several notes in order to play more than two octaves, exciting high registers.

The flue exit height (h) is fixed by the maker in measured txistus, but the player can change the distance between the air windway and the metal labium, called W. The values measured for W are 5.0, 6.0 and 7.0 mm. With the smallest value, the starting pressure of a note is smaller and the system will jump easily to the next register. Hysteresis is also smaller between the second and the third registers when W is small. When the distance W is large, higher pressures are required to play higher registers and multiphonic sounds appear in certain notes. The more balanced distance for W seems to be around 6 mm, giving a ratio of W/h of 4.3. This value is close to the one recommended for recorders.

With values for the length of the windway of 36 mm and 1.4 mm for the height h, the flow reaches a Poiseuille profile in first two registers of the position 1. When the jet becomes turbulent, noise at the passive modes of the pipe can be noticed. This turbulence noise influences the timbre of the instrument.

Deviation from the twelve tone equal temperament scale is measured for a cylindrical and a modified txistu. It is possible to play in tune with a cylindrical txistu, however, lots of corrections and control over slightly opening the holes is needed. Using basic finger positions, with holes completely open or close, the cylindrical txistu gives some intervals half a semitone shorter according to the measurements. A new instrument was designed with changes in the holes and in the shape of the bore in order to change the frequency of some notes. Measurements made with a txistu player and a blowing machine show that the approximation to the tempered scale with this new instrument is better achieved using basic finger positions.

This new instrument was given to professional txistu players. The txistularis found the instrument closer to the tempered scale and they liked the powerful sound and other characteristics of the instrument.

The work is still open and the evolution of the instrument continues.

Acknowledgement

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