INSTRUMENTAL ACOUSTICS STUDY ABOUT THE *GAITA HEMBRA*[1]

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In this paper, the results of an instrumental acoustics study about the *gaita hembra,* a Colombian traditional musical instrument, are presented. This study was performed with the purpose of deducing the behavior of the instrument in the frequency and time domains. Two instruments were recorded in order to be able to compare the results obtained with each one. The construction procedure and materials are explained, analyzing the way how the sound is produced, the acoustic properties of the tone holes and the tuning of the instrument. The power spectral density (PSD) of each note of the instrument is calculated. These data allow theorizing about the variation of the harmonic content of each note, depending on the initial conditions. Finally, the recorded samples are analyzed to propose a mathematical model of the envelope, also depending on the initial conditions.

INTRODUCTION

The acoustic features of musical instruments are determined by their construction procedure and materials. So, performing and instrumental acoustics study about the *gaita* allows deepening in the folklore studies, since the construction of the instrument determines its acoustic properties and, thus, determines its musical qualities (melodic, dynamic, timbre) and, therefore, affects the specific features of genres, rhythms and other instruments which accompany the *gaita*.
Though [1] has been of definitive importance to Colombian musicological research and, though there is a considerable amount of instrumental acoustic studies about occidental musical instruments [10, 11] like the piano, violin, clarinet and flute, there are not instrumental acoustic studies about Colombian traditional musical instruments.
The goal of this project is to arrive at determining conclusions about the acoustic behaviour of the instrument which allow the later development of a physical model of the sound source. Moreover, this research seeks to extend the present experience with the *gaita* to instrumental acoustics studies about other Colombian traditional sound sources.

1 GENERAL ACOUSTIC FEATURES OF THE *GAITA HEMBRA*

In this section are explained the parameters which determine the general acoustic behaviour of the *gaita hembra*.

1.1 Instrument construction

The *gaita hembra* is an air column musical instrument whose length is between 70 and 80 centimeters (traditionally, this length was defined by the arm length of the luthier), which is constructed from a cactus (*Selenicerus Grandiflorus*) which is bored and whose thorns are cut.
The center of the cactus stem is removed, first moistening and then boring with an iron stick. The cactus has a conical shape and is therefore thicker in one of its ends. The thicker end will go upside and will be coupled with the bee wax head which carries the duck feather mouth piece. The instrument has five tone holes, but only four of them are used when performing: the lower tone hole is rarely used, but when used, the upper tone hole is closed with wax. Though the instrument is slightly conic on the outside, its perforation is cylindrical.
The instrument's head is made with bee wax. The head has a characteristic black color because the wax is mixed with charcoal powder so it won't melt due to high temperatures. In this bee wax- charcoal head is encrusted the mouth piece which is made with a duck feather, with an angle and a distance to the edge of the air column which varies from instrument to instrument. The head and mouth piece of the instrument are shown in figure 1.

[1] Bachelor of Music Final Project. Pontificia Universidad Javeriana

Figure 1: Wax head and duck feather mouth piece

The construction is not serial so the only instrument which matches the tuning of a particular *gaita hembra* (female *gaita*) is the *gaita macho* (male *gaita*) constructed to accompany it. This *gaita macho* only has two tone holes, but the lower one is rarely used. Its length and the length of its corresponding *gaita hembra* are the same and the position of the two tone holes matches the position of the lower tone holes of the *gaita hembra.* A pair of *gaitas*, *hembra* and *macho,* is shown in figure 2.

Figure 2: *Gaita hembra* (left), *gaita macho* (right)

1.2 The air column

The air column is open in both ends so it produces harmonics in all integer multiples of the fundamental frequency.

1.2.1 Sound production

The sound is produced through a slit-edge system, shown in figure 3, coupled to the air column.

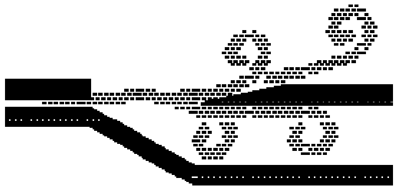

Figure 3: Slit-edge system [8]

When the air jet arrives at the edge vortices are formed inside and outside the air column. This way sound is produced in organ pipes and in the flute [8]. The frequency in the system (if it is not coupled to an air column) is calculated as [8]:

$$f = \frac{0.2 v_j}{d} \qquad (1)$$

Where f=frequency, v_j =air jet velocity and d=distance between slit and edge. When the system is coupled to an air column, the length of the air column determines the air jet velocity.

In the *gaita hembra* the distance between slit and edge is constant. So to produce a nth harmonic in the *gaita hembra*, the air jet velocity has to be multiplied n times the air jet velocity necessary to produce the fundamental frequency. Therefore frequency and dynamics are proportional in the *gaita hembra*.

1.2.2 Tone holes

When all the tone holes are closed, the frequency of the sound produced, when the instrument is excited, corresponds to the fundamental resonant frequency of the air column. When the lower tone hole is opened, the length of the air column diminishes and is measured from the top of the instrument to the open lower tone hole and, then, being the air column length shorter, the frequency increases. When successively opening the tone holes, the frequency of the sound produced is progressively higher and the length of the air column is progressively shorter. The behavior of the tone holes can be modeled as:

$$v = \lambda f \qquad (2)$$

Where v= sound velocity, λ=wavelength and f= frequency.

1.2.3 Standing waves

The modes of vibration of an air column open in both sides and, therefore, the modes of vibration of the *gaita hembra* are shown in figure 4 [8].

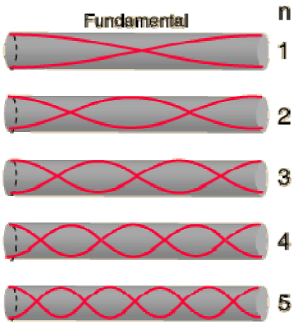

Figure 4: Modes of vibration of an air column open in both ends

The standing waves formed in the *gaita hembra* can be determined by:

$$L = n\frac{\lambda_n}{2} \qquad (4)$$

Where L= air column length, n= harmonic number, and λ=wavelength.
When performing the *gaita*, sounds are produced in the second, third and fourth modes; occasionally sound is produced in the sixth mode and rarely in the first mode. This is because the sounds produced in the first mode are too soft and wouldn't be heard when the instrument is accompanied by three drums (*llamador, alegre* and *tambora*).

1.3 Tuning

The tuning of the *gaita hembra* is defined by the cactus length and the distance between tone holes. An approximate notation of an A Dorian scale was used. The fingering, rather than the tuning, determines the note names. The intervals between the resultant frequencies were calculated as follows:

$$n = \log_2 (\frac{f n}{f_0}) \qquad (5)$$

Where n= number of semitones between f_0 and f_n. The differences between the Dorian intervals (in semitones) and the intervals in the scale of each *gaita* are shown in table 1.

Dorian interval	**Intervals *Gaita* 1**	**Intervals *Gaita* 2**
2	1,45	1,71
1	1,63	1,56
2	2,16	1,56
2	1,97	2,18
2	1,63	1,46
1	1,79	1,62
2	1,91	2,12
2	1,51	1,58
1	1,33	1,34
2	2,79	1,64
2	1,52	2,33
2	2,15	1,36

These results suggest that there is no fundamental reason to relate a scale with particular interval structure and the cultural tradition of the *gaitas* music, moreover, keeping in mind that many performers have played in instruments as different in tuning as the ones here presented.

2 HARMONIC ANALYSIS

The resultant waveform of a tone produced in a specific instrument can by analyzed from its harmonic content. This method for analyzing periodical signals is known as Fourier analysis after the French mathematician who developed it. This section deals with the Fourier analysis of the tones produced by the *gaita hembra.*

2.1 Fast Fourier Transform FFT

With the purpose of performing the harmonic analysis on the *gaita hembra* several tones of two different *gaitas* were recorded with a sampling frequency of 44.1 kHz and quantization rate of 16 bits. Four samples of each tone produced in each *gaita* were chosen after editing the whole track in Sound Forge 4.5. Of each one of these samples the sustained stable part was edited and analyzed using Matlab's Sptool. With the purpose of obtaining the frequency domain data from the waveform the Fast Fourier Transform (FFT) was calculated and the Power Spectral Density (PSD) graphic information was obtained. In the PSD graphic the average power in dB of each frequency can by observed.
The FFT allows obtaining the frequency domain data using and algorithm which performs faster if the size of the transform is a power of 2 number of samples. The frequency domain resolution is determined by the sampling Frequency to FFT size ratio:

$$\frac{F_s}{N_{FFT}} = \Delta f \qquad (6)$$

Δf is the bandwidth. The narrower each band is, the higher the frequency resolution. But, the higher the frequency resolution is, the lower the time resolution. Being the purpose of this section to establish general features of harmonic of the tones produced by the *gaita hembra* the main concern is to determine with accuracy the frequency components rather than assessing the evolution in time of each particular tone. For this reason a 131072 samples FFT size was defined. All samples analyzed in this section have a duration of 1 second.

2.2 Harmonic content

The harmonic content of each note of each *gaita* was obtained from the PSD graphic. In figure5 the PSD graphic for an A4 played in the *gaita* 1 is shown.

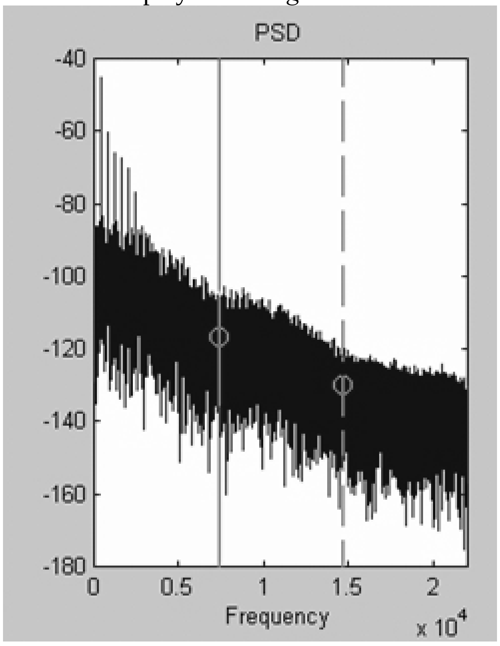

Figure 5: PSD graphic of an A4 played in the *gaita* 1

The sharp peaks in the graphic indicate where the harmonics of the analyzed note are. In table 2 the exact results of frequency and average power values are shown:

n	Frequency (Hz)	Average power (dB)
1	401,7	-45,3
2	802,1	-60,4
3	1203,8	-66,4
4	1604,2	-67,6
5	2001,2	-70,2
6	2406,0	-76,6

The variation of the power of each harmonic depending on the variation of the power of the note was analyzed. The results for a C5 are shown in figure 6.

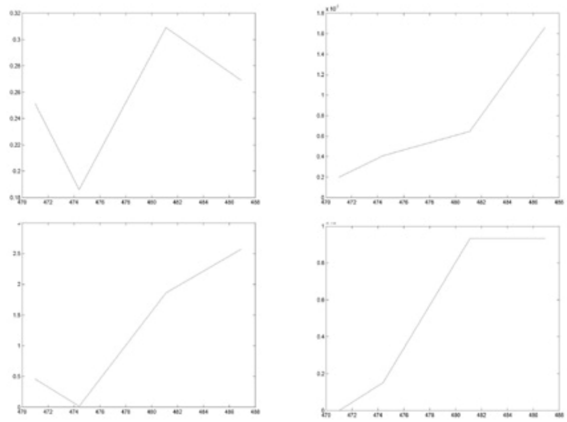

Figure 6: Harmonics 1 and 2 (up). Harmonics 3 and 5 (down)

In table 3 the exact values of power and frequency are shown.

Note	Sample	Power	Harmonic	Frequency	Power
C_5	1	-39,2		262,1	-80,7
			1	519,2	-46,8
			2	1039,3	-68,9
			3	1558,1	-82,0
	2	-39,1		258,4	-72,2
			1	508,7	-47,6
			2	1017,4	-70,2
			3	1526,8	-67,0
			4	2033,9	-80,8
	3	-34,8		280,1	-76,4
			1	519,5	-41,5
			2	1039,0	-63,1
			3	1558,5	-66,8
	4	-32,0		264,1	-76,0
			1	521,8	-37,6
			2	1043,7	-59,9
			3	1564,2	-68,2

Further analysis of these data can give clues which lead to the development of a spectral model to synthesize the sound of the *gaita*.

2.2.1 Harmonics tuning

The theory says that in an air column open in both ends the frequency of the second harmonic is exactly two times the fundamental. Nevertheless in [9] can be read that this does not exactly happen in a real air column. The fundamental frequency of the note shown in figure

5 is 401.7 Hz, thus, theoretically, the second harmonic frequency would be 803.4 Hz. The real frequency of the second harmonic is 802.1 Hz, though. The frequency of the second harmonic is almost, but not exactly, two times the fundamental frequency because of the irregularity of the air column and because its diameter is not infinitely thin, as in the theoretical case. This phenomenon can be seen in all real musical instruments, from wood wind to bowed strings, keyboard instruments and brass.
With the purpose of checking the tuning of the harmonics present in the notes played on each *gaita* a lineal regression was calculated. In table 4, the data corresponding to a B4 played in the *gaita* 1 is shown. As stated in the previous section, the notation does not correspond to the frequency value of each note, but to the fingering used.

B_4 Sample 4		
Harmonic	*Frequency theoretical value*	*Remainder*
1	441,991613	
2	883,983226	-0,48322581
3	1325,97484	-0,67483871
4	1767,96645	2,13354839
5	2209,95806	2,24193548
6	2651,94968	2,35032258
7	3535,9329	-3,83290323

The remainder value corresponds to the deviation in Hz from the ideal theoretical value.
This procedure was implemented which each sample of each note of each *gaita*. Despite the handcraft origin of the *gaita*, there is, in general no significant difference between the theoretical frequency values of the harmonics of each note and the real values.

3 DYNAMICS BEHAVIOR

The goal of this section is to model each part of the envelope of a note played on the *gaita* calculating exponential or polynomial regression. From obtained data, the correlation coefficient between real data and the modeled data is calculated in order to decide which is the model which best characterizes the behavior.
The first task is to detect the envelope of a note from its waveform. In order to do this, the waveform is rectified calculating its absolute value. The envelope could then be defined as a line which connects the peaks of the rectified signal [4]. To decrease the amount of discrete values representing the signal and therefore to obtain a signal representation only from the peak values it is necessary to decrease the sampling frequency. At first, the frequency of sub sampling is defined as follows.

$$\frac{f_s}{5f_0} \qquad (7)$$

f_0 is the fundamental frequency of the analyzed note. Figure 7 shows the resultant envelope of an A4 played on the *gaita* 1. In each case, the sub sampling frequency is determined by the sampling frequency and the fundamental frequency of the analyzed note.

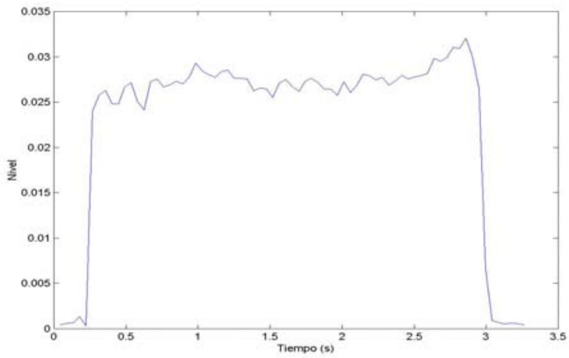

Figure 7: Signal of a recorded A4 rectified and sub sampled.

Each part of the envelope is analyzed in detail below.

3.1 Attack and Decay

The attack of the sound corresponds to the way and speed with which it begins. The decay is the transition from the peak value of the attack to the stable sustained value and is due to the interaction between the performer and the instrument. It happens often that the performer drives the instrument with a pressure level slightly higher than the needed to achieve the intensity he wants.
Traditionally, the *gaita* performer attacks the notes from the abdomen and it is precisely the case of the notes recorded and analyzed for this study. Although other attack possibilities are used by younger performers, they are not dealt with here.
Figure 8 shows the first 12560 samples of a rectified A4 note signal.

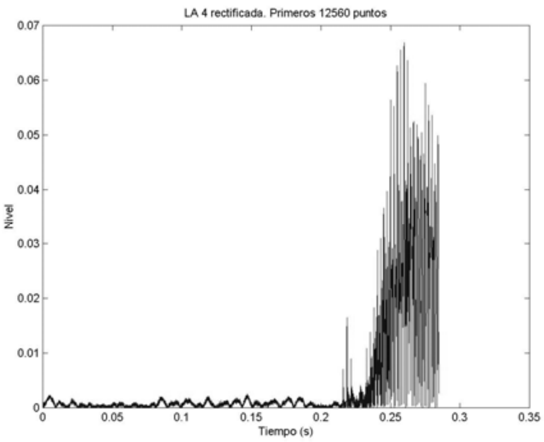

Figure 8: Rectified A4 note. First 12560 samples.

This rectified signal was sub sampled and edited to obtain the representation shown in figure 9.

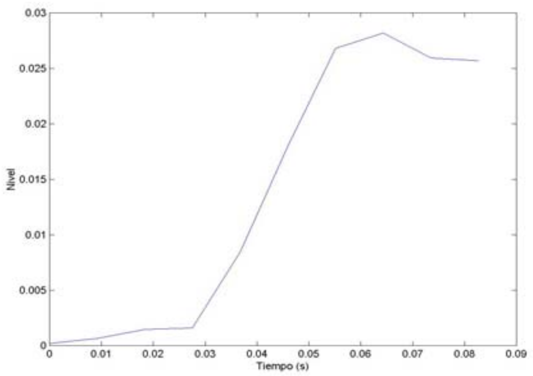

Figure 9: Rectified signal sub sampled at 111.65 Hz

To obtain a model from the data in figure 9 exponential and polynomial regressions were calculated. The correlation coefficients were higher for the polynomial regression. The attack and decay of this note, which was not played within any musical context but isolated, can be represented by this 5th grade polynomial:

$$y = 3{,}1251t^5 * 10^5 - 6{,}5879t^4 * 10^4 + 4{,}5923t^3 * 10^3 - 113{,}1208t^2 + 0{,}9008t \tag{8}$$

The correlation coefficient is 0.9981.

The same A4 note was analyzed within a musical context beginning a traditional musical piece in *porro* rhythm. Figure 10 shows the first samples of this note, rectified and sub sampled.

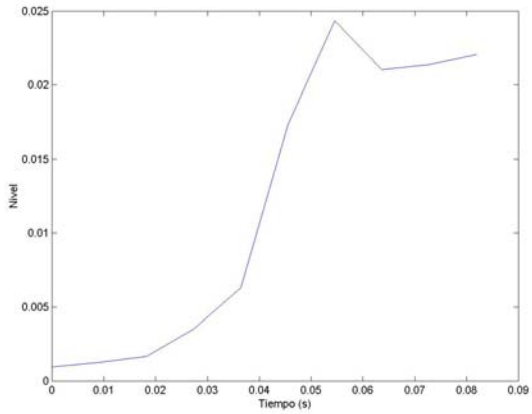

Figure 10: Attack and decay curve of an A4 played within a musical context at the beginning of a traditional Colombian musical piece.

In this case an 8th grade polynomial best represents the data in the graphic.

$$y = -3{,}4291t^8 * 10^{10} + 1{,}0567t^7 * 10^{10} - 1{,}3085t^6 * 10^9 + 8{,}3502t^5 * 10^7 - 2{,}9363t^4 * 10^6 + 5{,}6551t^3 * 10^4 + 544{,}4336t^2 + 2{,}0148t \tag{9}$$

This polynomial is valid just for the time and amplitude values of the specific note. From the equation which relates frequency and air jet speed can be obtained a generic polynomial. As stated above, due to the characteristics of the *gaita hembra* there is a direct proportionality between the frequency and the air jet speed, and, therefore, the intensity. It also can be deduced that the attack time is inversely proportional to the air jet speed and, therefore, to the frequency. The generic resultant polynomial, relating the A4 reference frequency with any note of frequency f is:

$$y = -3{,}4291t^8 * 10^{10} * \left(\frac{f}{la_4}\right)^9 + 1{,}0567 * 10^{10} * \left(\frac{f}{la_4}\right)^8 - 1{,}3085t^6 * 10^9 * \left(\frac{f}{la^4}\right)^7 + 8{,}3502t^5 * 10^7 * \left(\frac{f}{la_4}\right)^6 - 2{,}9363t^4 * 10^6 * \left(\frac{f}{la_4}\right)^5 + 5{,}6551t^3 * 10^4 * \left(\frac{f}{la_4}\right)^4 + 544{,}4336t^2 * \left(\frac{f}{la_4}\right)^3 + 2{,}0148t * \left(\frac{f}{la_4}\right)^2 \tag{10}$$

3.2 Release

After the attack and decay comes a sustained stable part. After this part usually named *sustain*, comes the *release* which refers to the way and speed with which the sound ends. Figure 11 shows the last samples of a rectified A4 note.

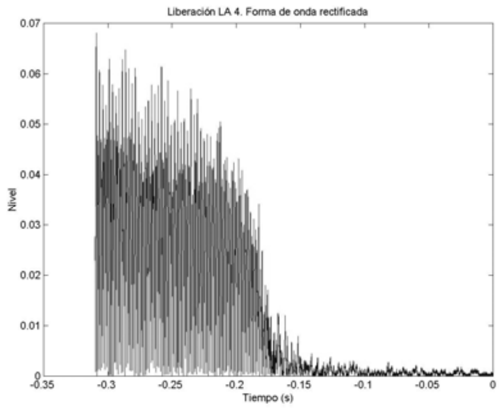

Figure 11: Last 13672 samples of an A4 note

The procedure is the same as with the attack and decay: rectifying, sub sampling and calculating polynomial regression. Figure 12 shows the signal in figure 11 now sub sampled.

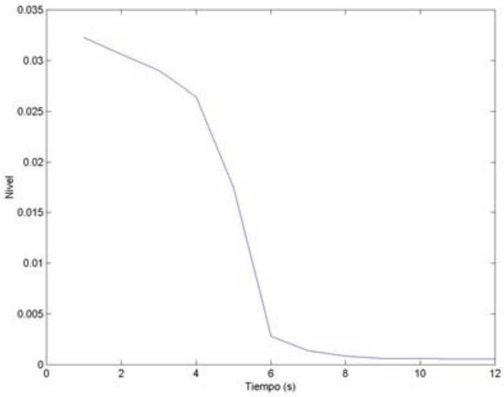

Figure 12: A4 note release

This curve is best represented with the next 9th grade polynomial:

$$8{,}1953t^9 * 10^6 + 1{,}0747t^8 * 10^7 + 5{,}8107t^7 * 10^6 + 1{,}6759t^6 * 10^6 + 2{,}7920t^5 * 10^5 +,.7249t^4 * 10^4 + 1{,}5056t^3 * 10^3 + 42{,}5529t^2 + 0{,}4633t \tag{11}$$

A similar procedure to the one applied with the attack and decay, in order to obtain a generic polynomial can be applied here; only keeping in mind that in this case, the release time is proportional to the intensity, and therefore, to the air jet speed and the frequency. The resultant polynomial is:

$$y = 8{,}1953t^9 * 10^6 * \left(\frac{f}{la_4}\right)^{-8} + 1{,}0747t^8 * 10^7 * \left(\frac{f}{la_4}\right)^{-7} + 5{,}8107t^7 * 10^6 * \left(\frac{f}{la_4}\right)^{-6} + 1{,}6759t^6 * 10^6 * \left(\frac{f}{la_4}\right)^{-5} + 2{,}7920t^5 * 10^5 * \left(\frac{f}{la_4}\right)^{-4} +,.7249t^4 * 10^4 * \left(\frac{f}{la_4}\right)^{-3} + 1{,}5056t^3 * 10^3 * \left(\frac{f}{la_4}\right)^{-2} + 42{,}5529t^2 * \left(\frac{f}{la_4}\right)^{-1} + 0{,}4633t \tag{12}$$

4 CONCLUSIONS

The *gaita hembra* is an air column open in both ends and, therefore, has all harmonics, odd and even.

The sound is produced by an air jet driven to a sharp edge. The distance between the lower end of the duck feather mouthpiece and the edge of the air column is constant so there is a direct proportionality between the frequency and the air jet speed which musically means that higher notes are played louder. Since the *gaita hembra* is accompanied by instruments with a high sound pressure level, the notes are rarely produced in the first mode of vibration because the performer must drive the instrument with a very weak air jet and the resultant intensity is very soft.

The tone holes allow modifying the air column length which relates with the wavelength by

$$\lambda = \frac{2L}{n}$$

measuring the air column length from the upper end, to the first open tone hole.

The tuning of the instrument is determined by the air column length and the distance between tone holes. The intervals obtained with each of the two analyzed instruments demonstrate that because of their traditional handcraft construction, it is difficult to find two instruments with similar tuning. From these results it can be concluded that there is no reason to relate a particular scale with the cultural tradition of *gaitas* music.

Keeping the same fingering, different sounds can be produced. In an air column, standing waves can be produced in several modes of vibration. The higher modes of vibration are approximate multiples of the first. To produce a sound in a mode of vibration different than the fundamental it is necessary to increase the air jet speed.

In an infinitely thin air column, the frequency values of the harmonics are exactly integer multiples of the fundamental frequency value. In a real air column of finite diameter this does not exactly happen. The harmonics slightly deviate from the ideal values. The deviation of these values in the *gaita hembra* is not significant.
To detect the envelope of a specific sound this must by initially rectified calculating its absolute value. When rectified, the envelope can be obtained sub sampling the original signal.
The attack and decay curve depends significantly of the conditions in which a sound is produced. In the case of a musical instrument, it depends significantly on whether the sound was produced within a musical context or isolated.

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