LabVIEW Simulation of a Flute Wind Musical Instrument Taking into Consideration the Fractional Behavior of Visco Thermal Losses in the Resonator

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LabVIEW Simulation of a Flute Wind Musical Instrument Taking into Consideration the Fractional Behavior of Visco Thermal Losses in the Resonator

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Abstract — The process of numerically synthesizing and designing musical instruments has been growing in the last few years. Many techniques such as modulation, digital wave guides and others, succeeded in mimicking the sound of a musical instrument using the computer system. However, still most of the instruments, especially wind musical instruments, are fabricated from a hobbyist perspective and not from a scientific manner. For that, the aim of this work is to analyse all the physical and mathematical parameters of a flute musical instrument, and to create a simulator using LabVIEW graphical user interface that allows the design of a flute to be based on scientific inputs such as the length, the width, the number and the size of holes, the distance between holes and many other features. The results represent all parameters needed to design a flute and they were simulated and verified numerically.
Keywords- ***LabVIEW Simulation; Flute Instrument; Acoustic Modelling; Resonator and holes***

I. INTRODUCTION

Most of the wind musical instruments are composed from three basic elements: an air pressure source, an exciter which stimulate and boost the vibrations , and a resonator, which carry the excited signals and leading to the final sound creation [1].

For the flute, the air pressure source is the musician's mouth where the player's breath is directed. When the air source (breath) hits the tip of the flute input, the air stream randomly fluctuates splitting the air into two parts where the first enters the hole of the exciter and the second diverge from it. This creates a rapid vibration at the input of the tube that is the resonator container, where the real resonator being the air inside the tube [2] [3].

The opened holes on the outside of the flute are for the purpose of changing the direction of the air flow inside the resonator and thus change the output sound frequencies. From an acoustic point of view, the resonator is considered to be open from both ends by considering the mouth hole as if it were an open end. So if we close all the note holes, the resonator-tube can be considered as a cylinder with two open ends that are affected by some visco thermal losses [4] [5].

In this study, we will simulate the fractional visco thermal effect in the resonator of the flute and try to verify that this fractional behavior is only valid for a very low frequency that is much below the normal functional frequency range of the flute musical instrument. We will show the frequency dominance of this behavior ending up with much less fractional effect with higher frequencies proofing that the visco thermal losses have miner effect on the quality of sound produced by the flute instruments.

Although all these technical details have been well defined, a very limited number of researchers have investigated in the physical modelling of the flute (as it is the case of most other musical instruments) [6]. Thus, the fabrication of such musical instruments is still based till present on the musical experience of the designer. This usually leads to not having the same musical instrument pattern in the design process. Moreover, additional efforts from the musician must be delivered to accurately play the instrument that will certainly differ from one flute to the other.

Thus, the aim of this work is to study and analyze the fractional acoustic and musical behavior of a flute instrument. This behavior will be simulated using the LabVIEW and MATLAB software and all the scientific parameters required for implementing the flute will be extracted in a report form, to be used by the instrument fabricator.

In order to be able to create an accurate simulator that delivers the desired results, many parameters have to be taken into consideration. These parameters are mainly the length, the width, the number and the size of holes, the distance between holes [7]. The relations that link all the previously mentioned parameters will be implemented within LabVIEW to produce the required outcome. The LabVIEW output will communicate with the wind synthesis MATLAB toolbox to produce an audio output along with a detailed report showing all information needed by the flute manufacturer. Furthermore, a graphical user interface, developed within LabVIEW, showing the flute length, holes positions, and holes width is created making the testing and tuning process very interactive and user friendly.

This work is divided into five sections. In section II, the acoustic behavior and modelling of the flute instrument will be discussed in details. In section III, the relation between resonator and frequency is presented. In section IV, the LabVIEW simulation will be conducted.

Then, the system testing will be discussed in section V. Section VI concludes this work and proposes some future works.

II. ACOUSTIC BEHAVIOR AND MODELLING OF THE FLUTE

A- Block diagram of the flute

The flute musical instrument is mainly composed of three main parts that are the generator or the mouth piece acting as the main source of air pressure, the exciter that modifies the generated pressure in a nonlinear way and the resonator that carries the modified pressure in tube like container with an open end usually called the horn. Figure 1 shows the complete parts of the flute.

Figure 1 – Physical Illustration of the Flute parts

Since the air inside the tube is bounded by the tube shape, it acts like a rigid spring that is independent of the air surrounding it. When the air stream at the mouth input begins randomly oscillating in and out of the tube, this air-spring receives a rapid progression of small pushes ending up with a variable vibration not at the same rate as the vibration at the mouth hole input [8].

The force of the vibrations at the mouth hole are enough to start the air-spring moving, but not to control the repeated pattern of the air-spring's vibrations. Moreover, the air-stream uses the energy associated to it by these pushes to start vibrating in its own natural pattern. These vibrations are defined by the length of the air-spring [9] [10]. When this vibration starts, the movement of the air in the tube ends up with a series of expansions and compressions.

The compressed nature of the air-spring retains a part of the energy imparted to it leading to a grow in strength. It quickly overpowers the small fluctuations at the mouth input and synchronizes their timing with its own pattern. At this stage, the small pressure from the mouth hole fluctuations will occur simultaneously with each contraction of the air-spring. This is similar to a person pushing a swing. It makes the vibration build to a point at which it can vibrate the air around it, and a musical note with a certain frequency is generated.

B- Mathematical Modelling

B1- Exciter Modelling

The ability of the instrument to generate an acoustic wave from a static or partially static source of energy with respect to the acoustic variables in entitled the self-oscillation process. This process is strictly correlated with the non-linear nature of the instrument. Usually musical acoustics are represented by a nonlinear excitation system attached to a passive linear resonant system as shown in figure 2 [11].

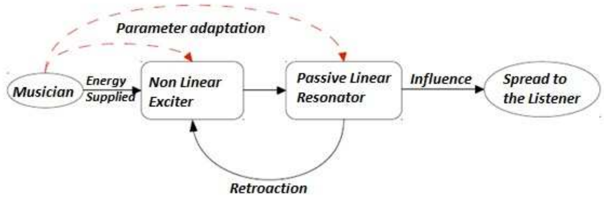

Figure 2 – Schematic representation of the mechanism of sound production in self-oscillating musical instruments

Modelling the exciter while being coupled to the resonator is considered a very difficult process due to its nonlinear behavior. This nonlinearity results from the naturally unstable air jet oscillation around a bevel (Figure 3). Therefore, the self-oscillation process highly depends on a synchronization between the oscillation of the air jet and the acoustic waves. So, it is necessary that the jet-bevel system triggers the resonator at the monotony of the acoustic field.

For further understanding of the concept and the numerical simulation, we start by a diagram modeling of the parameters of the different basic elements of the system. Moreover, a complete nonlinear model will be developed. However, after looking at the poor digital conditioning of such a model, a solution is proposed in order to be able to develop a digital simulator programmed in MATLAB/Simulink. A methodology is then defined for various values of the pressure at the input of the flute input. It is defined by respecting the domain of validity of the nonlinear model and the different pressure values that where experimentally recorded in the artificial mouth. The time response analysis makes it possible, in particular, to observe that the variations of several physical quantities (pressure at the input of the resonator, acoustic speed, etc.) are very small and around zero. Based on this observation, a linearization strategy is developed ending up with two linearized models, one for the analysis of the initial phase of the simulation, the other for the self-oscillations.

B2- Schematic and Configuration of the Exciter

Figure 5 displays a section of a flute, as well as a schematic of the exciter (formed from the interaction of an air jet with a bevel) with the following notations:

- **1**: outlet of the channel; **2**: bevel; **3**: resonator (air column); **4**: exciter;
- $R = \left(o\ ;\ \vec{x}\ ;\ \vec{y}\right)$: local reference associated with the jet;
- h: height of the spout channel;
- w: distance between the outlet of the channel and the tip of the bevel;
- x_0: tip offset of the bevel from the longitudinal $\vec{y}$ channel axis;
- $P_m(t) = P_m^e + p_m(t)$: input pressure generated at the mouthpiece, P_m^e is the operating point static component at the and $P_m(t)$ the variation around P_m^e.

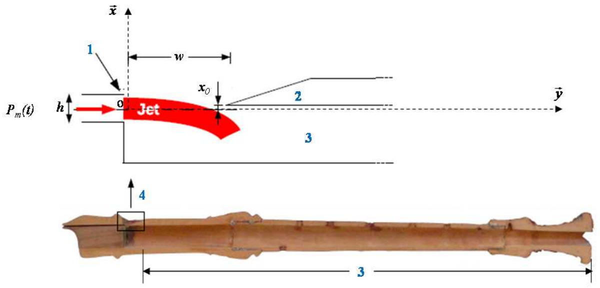

Figure 3 – Cross section of a flute and schematic representation of its exciter interaction of an air jet with a bevel with: 1: spout channel output; 2: bevel; 3: resonator (air column); 4: exciter

B3- Resonator Modelling

When a flute is blown, it can be considered as a vibrating resonant column of air with two open ends. There are two kinds of air-molecules; intelligent air-molecules and less educated air-molecules. When the flutist blows into the flute, air-molecules start to vibrate through the flute tube constantly (assuming constant blow). So, the intelligent air-molecules will be searching for the closest exit to get out of the dark humid tube whereas some less educated air-molecules will probably miss the opportunity to exit through the first closest open hole, so they will keep vibrating inside the tube and searching for the next open hole to exit through [12].

1) System Definition

The following is an acoustic pipe of length L and constant radius r triggered by an acoustic flow (volume flow) $Q_v(t)$ with $x=0$ where $x \in [0\ ;\ L]$ (Figure 4).

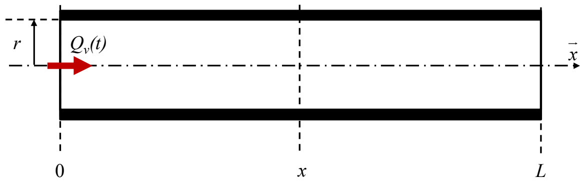

Figure 4 – Acoustic pipe of radius r = constant and of finite length L triggered by an acoustic flow $Q_v(t)$ with $x = 0$

As an acoustic wave propagates in the air, it sets the particles in motion which vibrate at a speed $v(t)$ around their equilibrium position. The acoustic flow $Q_v(t)$ then measures the flow [in m^3/s] of this speed through a surface with a scalar quantity [13] [14] [15] [16] [17].

The acoustic impedance $\boldsymbol{Z_{ac}}$ of a medium is defined in steady state as the ratio of the acoustic pressure [in Pa] and the speed [in m/s] of the related particle. If the medium is air, $\boldsymbol{Z_{ac}}$ is equal to the product between the speed of sound in air, c_a, and the air density ρ_a, thus $\boldsymbol{Z_{ac}} = \rho_a\, c_a$. These two parameters depend also on the air temperature T_a. Table 1 gives the values of the speed of the sound c_a, the density ρ_a and the characteristic acoustic impedance Z_{ac} as a function of the temperature T_a of the air.

Table II – Speed of sound c_a, the density ρ_a and the characteristic acoustic impedance Z_{ac} as a function of the air temperature T_a

T_a (°C)	-10	-5	0	5	10	15	20	25	30
c_a (m/s)	325.4	328.5	331.5	334.5	337.5	340.5	343.4	346.3	349.2
ρ_a (kg/m^3)	1.341	1.316	1.293	1.269	1.247	1.225	1.204	1.184	1.164
Z_{ac} (Pa s/m)	436.5	432.4	428.3	424.5	420.7	417	413.5	410	406.6

The model adopted here is that of Webster-Lokshin [18]. It is a mono-spatial model that characterizes the linear propagation of acoustic waves in tubes with axial symmetry. This model caters for visco-thermal losses at the wall boundaries with the assumption of wide tubes [19]. Thus, in an axisymmetric tube of constant section $S = \pi\ r^2$, the acoustic pressure $P(x,t,L)$ and the acoustic flow $Q_v(x,t,L)$ are covered by the Webster-Lokshin, and Euler equation, represented by system (1):

$$\begin{cases} \dfrac{r}{c_a}\dfrac{\partial^2}{\partial t^2}P(x,t,L) + 2\varepsilon\dfrac{r}{c_a}\dfrac{\partial^{3/2}}{\partial t^{3/2}}P(x,t,L) - r\dfrac{\partial^2}{\partial x^2}P(x,t,L) = 0\ ,\ x\in[0\,;L]\ ,\ t>0 \\ \dfrac{\rho_a}{S}\dfrac{\partial}{\partial t}Q_v(x,t,L) + \dfrac{\partial}{\partial x}P(x,t,L) = 0 \end{cases} \tag{1}$$

where ε is a parameter associated with visco thermal losses and represented by the relation:

$$\varepsilon = \frac{K_0}{r}\ ,\quad \text{with}\quad K_0 = \sqrt{l_v} + (\gamma - 1)\sqrt{l_h} \tag{2}$$

Moreover, l_v and l_h represent the characteristic lengths of viscous (l_v = 4 x 10^{-8} m) and thermal (l_h = 6 x 10^{-8} m) effects, γ being the ratio of specific heats.

The concept of visco-thermal losses is a disperse effect at the wall of the pipe, which is due to the viscosity of the air and to the thermal conduction [19] [20]. For the case of wind musical instruments resonators, the assumption of wide tubes is used. This hypothesis is expressed by:

$$r \gg \max\,[\ r_v = (l_v\,\lambda)^{0.5};\ r_h = (l_h\,\lambda)^{0.5}], \tag{3}$$

where $\lambda = c_a/f$ represents the wavelength (in m) and f the frequency (in Hz).

Thus, for a speed of the sound c_a and a frequency f_{min} corresponding to the lower limit of the frequency domain of study of the model, it is possible to determine the minimum value of the radius r_{min} of the acoustic tube below which the model is not valid. As an illustration where l_v = 4 x 10^{-8} m, l_h = 6 x 10^{-8} m and c_a = 346.3 m/s (at a constant temperature T_a = 25°C), Figure 5 presents the curves of $r_v(f) = (l_v\, c_a/f)^{0.5}$ (in red) and $r_h(f) = (l_h\, c_a/f)^{0.5}$ (in blue) with respect to the frequency f.

If we consider that the frequency domain of study of the Webster-Lokshin model is that of the frequencies audible by the human ear, frequencies ranging between 20 Hz (most serious frequency) and 20 000 Hz (most acute frequency), then f_{min} = 20 Hz. For this value of f_{min}, the model is valid for acoustic tube radius greater than 1 mm as verified in Figure 5 [19] [20].

B4- Resonator and Frequency Relation

The musical note represented by the frequency produced in section II –Part A- can be modified very slightly by the breath and the adjustments of the lips, but to change it completely (short of changing octaves), the length of the air-spring itself must be altered. This is done by opening a new hole in the pipe. The hole allows the air flow to split allowing the air-spring to go as far as that open hole [21].

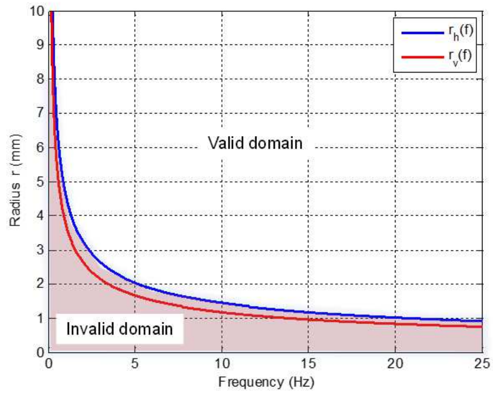

Figure 5 – Curves $r_v(f) = (l_v\, c_a/f)^{0.5}$ (in red) and $r_h(f) = (l_h\, c_a/f)^{0.5}$ (in blue) with respect to the frequency f

When the air jet produced by the flute player reaches the edge of the embouchure hole (hole in the exciter) it is scattered into and out of the hole. This deflection pushes the air already inside the flute, and, at the same time, the pipe vibration feeds the jet alternation of going in and out the hole. Thus, the vibration excites the air inside the pipe and makes it work as an open pipe in both ends. As a result, standing waves are produced and oscillate along the pipe which creates regions with high and low pressure. The regions with low pressure let the air molecules displace along the pipe, while the air molecules within high pressure regions are not able to move at all. The points with the highest displacement are called pressure nodes and the points with lowest displacement are called pressure antinode [22].

If another hole is opened close to the mouth hole, the air-spring will end there instead. The vibrating portion of the tube will always be (at least on the first octave) between the mouth hole and the first open hole beneath it. The shorter the air-spring, the faster its natural rhythm and the higher the note (thus the frequency) it will produce. To go up the first octave of the flute, then, the flutist opens one hole at a time from the bottom, shortening the air-spring a little with each hole opened [9] [21].

A number of parameters affect the sounding pitch of a note played on a flute [23].

- As the first open hole is closer to the mouth piece, the higher the pitch (refer to equations 4 and 5).
- The larger the open hole, the smaller the pitch. (refer to equations 6 and 7)
- A larger hole in a thicker barrel is similar to a smaller hole in a thinner barrel. The depth of the hole affects the pitch.
- Additional open holes below the first open tone hole will raise the pitch. The smaller the first open tone hole is, the more it will be affected by the open holes below it.
- Closed holes above the first open tone hole can affect the pitch played, however they can either raise or lower the pitch.

When constructing the flute, one needs to decide where to put finger holes. The following equation approximately describes a relation between length and frequency of the fundamental tone [24]. Thus,

$$f_1 * L_1 = f_0 * L_0 \quad , \tag{4}$$

where:
- L_o is the length of the flute from the exciter till the horn (the end of the resonator);
- f_o is the fundamental frequency measured when all the holes of the flute are closed;
- L_1 is the length of the flute from the exciter to the first open hole;
- f_1 is the recorded frequency measured at the first open hole of distance L_1 from the exciter.

Any specific frequency at a given hole can also be defined with respect to the length between the exciter and this hole as shown in the below equation:

$$f_0 = \frac{c}{2*L_0}, \tag{5}$$

where c is the speed of sound in vacuum taken to be 345 m/s.

A real flute is not precisely a narrow cylindrical pipe with two open ends. For that, equations 4 and 5 are not accurate estimators of tones produced by the flute. The end correction is when an end of a cylindrical tube functions as if it were slightly longer than its length. So a better approximation to the actual fundamental frequencies of a tube with two open ends can be made as follows:

$$f_0 = \frac{c}{2*L_e}, \tag{6}$$

where Le is the effective length of the pipe. For each end, the pipe is effectively about 0.6*R longer where R is the radius of the pipe resonator. Le is defined as follows:

$$L_e = L_0 + 1.2 * R. \tag{7}$$

The above two equations still won't estimate exactly the frequencies of a tube with multiple holes in it. A hole drilled on the side of a pipe changes the effective acoustic length of the pipe. The larger the hole, the closer the acoustic length will be to the hole position.

The ***closed correction for tone hole n*** is when the length of the vibrating air column is effectively increased by each closed tone hole which exists above the first open tone hole.

$$closed\ hole\ correction = 0.25 * walW * \left(\frac{fhDs\,(n)}{borD}\right)^2. \tag{8}$$

The ***end correction*** is the distance from physical open end of flute to effective end of vibrating air column. The vibrating air column ends after the end of the flute.

$$end\ correction = 0.3 * borD. \tag{9}$$

The ***embouchure correction*** is the distance from the begining of air column to the center of embouchure hole; the air column effectively extends beyond the blow hole center by this same distance.

$$embouchure\ correction = \left(\frac{borD}{adjEmbD}\right)^2 * \left(walW + 0.6 * \frac{adjEmbD}{2}\right). \tag{10}$$

The ***effective thickness*** is the height of air column at open finger holes; air column extends out past end of hole a fraction of the hole diameter.

$$effective\ \ thickness\ of\ pipe = walW * FhDs(n). \tag{11}$$

The ***first hole distance*** is the effective distance from the first tone hole to the end of the vibrating air column when this hole is open.

$$first\ hole\ distance = \left(endX - fhXs(n)\right) * \left(\frac{borD}{fhDs}\right)^2 \tag{12}$$

The ***effective length*** of the tone hole could be calculated by the following equation.

$$L_H = l_H + d_H - \frac{0.45*(d_H)^2}{d_1}. \qquad (13)$$

In equation 10 l_H is the bore thickness at the tone hole, d_H is the tone hole diameter, and d_I is the bore diameter at the tone hole [25]. With the effective length, going back to equations 2 and 3 we can find the frequency and width relation.

III. Relation Between Frequency and Musical Notes

Musical frequencies are commonly measured with reference to the tempered scale with a musical note (A) of 440Hz. This frequency represents the fundamental frequency f_0. It could be other than 440Hz, and every pitch represents a particular type of a flute. The different frequencies along with their musical notes are listed in Figure 6 [26].

	semitone	octave						
Do	C#	34.6	69.2	138.5	277.1	554.3	1108.7	2217.4
Re	D	36.7	73.4	146.8	293.6	587.3	1174.6	2349.3
Re	D#	38.8	77.7	155.5	311.1	622.2	1244.5	2489.0
Mi	E	41.2	82.4	164.8	329.6	659.2	1318.5	2637.0
Fa	F	43.6	87.3	174.6	349.2	698.4	1396.9	2793.8
Fa	F#	46.2	92.4	184.9	369.9	739.9	1479.9	2959.9
Sol	G	48.9	97.9	195.9	391.9	783.9	1567.9	3135.9
Sol	G#	51.9	103.8	207.6	415.3	830.6	1661.2	3322.4
La	A	55.0	110.0	220.0	**440.0**	880.0	1760.0	3520.0
La	A#	58.2	116.5	233.0	466.1	932.3	1864.6	3729.3
Si	B	61.7	123.4	246.9	493.8	987.7	1975.5	3951.0
Do	C	65.4	130.8	261.6	523.2	1046.5	2093.0	4186.0

Figure 6 - Musical notes with their corresponding frequencies

Tuners usually give the approximate note on the tempered scale and the difference with respect to the one played. This difference is given in cents that are calculated as follows: in each half tone there are 100 cents, and in an octave there are twelve half tones, thus in an octave we can find 1200 cents. An octave corresponds to a double frequency change of a factor of two. In other words, a second note that is an octave above a first note has double the frequency of the first. Furthermore, 1 cent corresponds to a factor of $2^{\frac{1}{1200}}$. As an example, if you are sharp by +20 cents, you multiply the frequency of the nearest tempered scale note by $2^{\frac{+20}{1200}}$ to calculate the actual frequency of the musical note. If you are flat by 15 cents, you would multiply the nearest tempered scale note by a factor of $2^{\frac{-15}{1200}}$ [27] [28].

IV. LabVIEW Simulations

Variables shown in equations (4) to (13) are defined as follows:

- *maxHoleCount*: Number of flute finger holes
- *fhDs*: Finger diameters for hole *n* (in mm)
- *actEmbD*: Physical embouchure hole diameter mm
- *adjEmbD*: Embouchure hole diameter, adjusted for lip cover (in mm)
- *borD*: Inside diameter of tube (in mm)
- *walW*: Wall thickness of tube (in mm)
- *fhFs*: Finger hole note frequencies in Hz
- *endF*: All-holes-closed end-of-flute
- *endX*: Effective location of end of flute (in mm)
- *fhXs*: Location of finger holes (in mm)
- *embX*: Location of embouchure (in mm)

Figure 7 represents the GUI of the simulator created using LabVIEW with all the detailed parameters and variables.

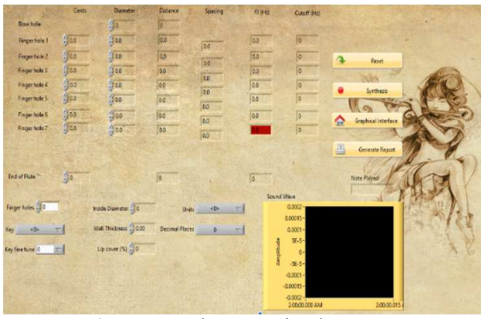

Figure 7 - LabVIEW Simulator GUI

The user interface displays as inputs, hole widths, base key (flute type), number of holes and other more intricate customization options for the creation of the flute. It consists of indicators for all the calculated values, a waveform for the played wav file, an indicator for the note played, and links to report generation, graphical interface, and sound synthesis.

Hovering over the frequencies will cause their respective (*.wav* file) to automatically play (although synthesizing has to be triggered manually for changes to be reflected since it is a processor consuming thread and could not be automated to reflect them in real time). The whole GUI consists of a state machine with an event structure to handle changes in input in real-time. The application also delivers the main calculations to fabricate a flute. The welcome screen of the LabVIEW application looks as shown in Figure 8.

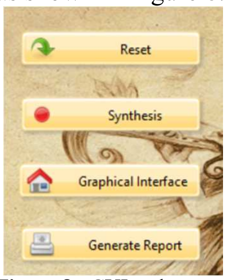

Figure 8 - GUI and report links

Two main features exist in the developed application:

- The manual entry mode, where the user sets the input parameters manually as the number of holes, their widths, and the cutoff frequency;
- The graphical synthesis mode, where the parameters are generated based on the size and position of the holes that are placed graphically by the end user.

Both features will be presented in the following section.

V- System Testing

A- Manual Entry Mode

After embedding all the required parameters in the simulator, it is now the turn for testing. The user can choose the number of holes, their diameter, wall thickness of the flute, and the fundamental frequency as shown in Figure 9.

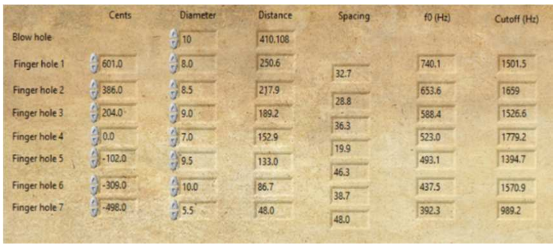

Figure 9 - Manual parameters entry

When running the application, and hovering over the frequency of each hole, a single tone sound will be produced and plotted. As an example, this is the output of the 440 Hz which represents the (A4) or (La) musical note.

Using the Matlab wind instrument toolbox, we interpreted the demos of music synthesis and created a custom score file creation script using LabVIEW, freqtowav.vi which creates the score files with the exact arguments to create the notes in Matlab. The files are coma separated spread sheets including time, frequency, reverb and other arguments corresponding to the sound synthesis. The LabVIEW application also connects to a MATLAB script node that synthesizes the wave files. The output of this node is created in a test folder subdirectory.

The developed Freqtowav.vi is used to create score files for note synthesis, using, as template, the available examples in the wind_synthesis_toolbox. It writes the score file to an excel file. The score files created are then sent to MATLAB for processing via a MATLAB script node which converts them to wave files (synthesis needs around 7 seconds to complete).

After choosing the appropriate parameters, one can click the synthesize button and the final report with all the required values needed for fabrication will be generated as shown in table 2.

Table 2. Flute design parameters

	Cents	Diameter	Distance from blow hole	Spacing	Frequency	Cut off	Note
Blow Hole	-599	10	410.10789	0	370.030523	0	
Finger hole 1	601	8	250.604341	32.70296	740.061046	1501.458	Gb5
Finger hole 2	386	8.5	217.901382	28.75101	653.631546	1659.045	E5
Finger hole 3	204	9	189.150368	36.28292	588.405587	1526.624	D5
Finger hole 4	0	7	152.867445	19.88815	523	1779.221	C5
Finger hole 5	-102	9.5	132.979298	46.26895	493.076312	1394.672	B4
Finger hole 6	-309	10	86.710353	38.67885	437.50847	1570.887	A4
Finger hole 7	-498	5.5	48.031505	48.03151	392.260196	989.227	G4
Inside Diameter	Key	Key fine tune	Lip Cover(%)	Units	Wall Thickness		
19	C5 - 523Hz	0	0	mm	1		

It is also important to note that the user can only choose the major key note of the desired flute output using the key button as shown in Figure 10.

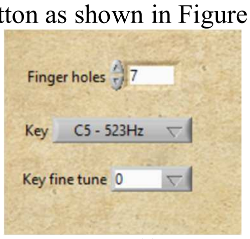

Figure 10 - Manual key tone entry

B- Graphical Synthesis

In this option, the user will get a graphical view of the flute with the holes. The hole width and location can be varied graphically and the new values will be automatically inserted in the predefined function thus producing new score files with modified outputs. Figure 11 shows the initial positions and sizes of the flute holes prior to modification.

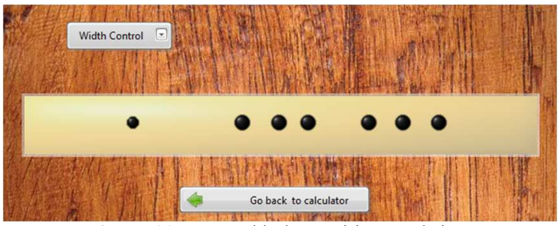

Figure 11 - Normal holes positions and sizes

Table 3 shows the generated report based on the position and widths of the holes in Figure 11.

Table 3. Normal position hole parameters

	Cents	Diameter	Distance from blowhole	Spacing	Frequency	Cut off	Note
Blow Hole	-498	10	383.715441	0	392.260196	0	
Finger hole 1	870.0838	17.142857	-1	56.24711	864.508873	1758.73	A5
Finger hole 2	386	8.5	191.706781	28.74597	653.631546	1659.19	E5
Finger hole 3	204	9	162.960808	36.30616	588.405587	1526.135	D5
Finger hole 4	0	7	126.654649	19.83884	523	1781.43	C5
Finger hole 5	-102	9.5	106.815809	46.51919	493.076312	1390.916	B4
Finger hole 6	-309	10	60.296622	60.29662	437.50847	1258.158	A4
Inside Diameter	Key	Key fine tune	Lip Cover(%)	Units	Wall Thickness		
19	C5 - 523Hz	0	0	mm	1		

Figure 12 shows a modified version of figure 11 in terms of the size and location of the holes. A larger hole size is represented and new values corresponding to those values are embedded into the functions, thus new score files regarding the musical output of this modification will be displayed in the output report.

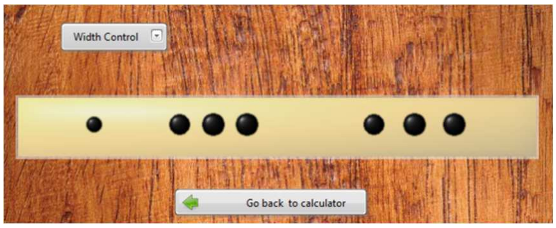

Figure 12 - Larger hole sizes and positions

Table 4 shows the generated report based on the position and widths of the holes in Figure 12.

Table 4. Large width hole parameters

	Cents	Diameter	Distance fror	Spacing	Frequency	Cut off	Note
Blow Hole	-599	10	409.336379	0	370.030523	0	
Finger hole 1	1333.4633	16	317.28527	14.562269	1129.827323	3328.765	Db6
Finger hole 2	1156.1674	15.785714	302.723001	22.108919	1019.849067	2681.687	C6
Finger hole 3	907.2761	15.6	280.614082	81.393266	883.282153	1388.613	A5
Finger hole 4	319.00253	15.166667	199.220816	28.719435	628.819687	2301.824	Eb5
Finger hole 5	157.9241	14.529412	170.50138	13.594913	572.952032	3267.457	D5
Finger hole 6	48.370693	15.294118	156.906467	121.659215	537.818677	1123.528	C5
Finger hole 7	-498	12.1	35.247252	35.247252	392.260196	1833.004	G4
Inside Diameter	Key	Key fine tune	Lip Cover(%)	Units	Wall Thickness		
19	C5 - 523Hz	0	0	mm	1		

After varying the locations and sizes of the holes, the user can go back to the main application to verify the new parameters that must be used to create the flute which will produce the same sound as the simulated in the application.

VI- CONCLUSION AND FUTURE WORKS

A full mathematical modelling, testing, and simulation were made to the flute musical instrument. A conversion tool is created capable of simulating and calculating all the flute's scientific and musical parameters such as: hole location and diameter, note frequency, cutoff frequency, using as input some flute specifications like inside diameter and wall thickness. Using MATLAB, we managed to synthesize an accurate flute sound corresponding to all the frequencies that we have calculated previously. Implementing everything in LabVIEW, the VI is capable of creating score files corresponding to each note then calling a MATLAB script note to synthesize wave files using the score files created. Now the VI is capable of playing the wave files created when mouse goes over the frequency box. The final step was creating a 2D interactive flute design showing a prototype of the outcome of the selected input and capable of changing the hole width and position along with a report indicating all the required values that a flute designer needs to design a pre simulated flute wind musical instrument.

As for the future work, lots of ideas could be implemented in order to enhance this application as configuring other parameters like the flute material type and studying in more details the exciter air turbulence. Also it is of a great importance to analyze the visco thermal losses of the exciter in order refine the output parameters of the flute. A very important step remains by implementing the synthesized flute the exact values obtained from this LabVIEW application.

References

[1] D. Ferrand and C. Vergez, "Blowing machine for wind musical instrument : toward a real-time control of the blowing pressure," in *16th Mediterranean Conference on Control and Automation*, Ajaccio, 2008.

[2] J. Solis and A. Takanishi, "Toward understanding the nature of musical performance and interaction with wind instrument-playing humanoids," in *19th International Symposium in Robot and Human Interactive Communication*, Viareggio, 2010.

[3] G. Le Vey, "Optimal control theory and design of wind instruments : oscillation regime optimization," in *16th Mediterranean Conference on Control and Automation*, Ajaccio, 2008.

[4] J. Launay, N. Allanic, P. Mousseau, R. Deterre and C. Plot, "Effect of viscous dissipation in the prediction of thermal behavior of an elastomer cylindrical flow," *Journal of Materials Processing Technology,* vol. 252, pp. 680-687, 2018.

[5] P. Andersen, V. Henríquez and N. Aage, "Shape optimization of micro-acoustic devices including viscous and thermal losses," *Journal of Sound and Vibration,* vol. 447, no. 12, pp. 120-136, 2019.

[6] R. Mignot, T. Helie and D. Matignon, "Digital Waveguide Modeling for Wind Instruments: Building a State–Space Representation Based on the Webster–Lokshin Model," *IEEE Transactions on Audio, Speech, and Language Processing,* vol. 18, no. 4, pp. 843 - 854, 2010.

[7] H.-C. Zeng, C.-R. Luo, H.-J. Chen, S.-L. Zhai, C.-L. Ding and X.-P. Zhao, "Flute-model acoustic metamaterials with simultaneously negative bulk modulus and mass density," *Solid State Communications,* vol. 173, pp. 14-18, 2013.

[8] V. Girka, I. Pavlenko and S. Puzirkov, "Study of surface flute modes propagation in a cylindrical metal waveguides with noncircular cross-section and plasma filling," in *International Conference on Mathematical Methods in Electromagnetic Theory*, Kharkov, Ukraine, 2000.

[9] M. Shepard, How the Flute Work: An Intro to flute acoustics, 2001.

[10] Y. Nishioka, K. Suzumori, T. Kanda and S. Wakimoto, "A new control method utilizing multiplex air vibration for multi-DOF pneumatic mechatronics systems," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Taipei, Taiwan, 2010.

[11] A. Kergomard and J. Chaigne, Acoustique des instruments de musique, Belin (Echelles): 2ème édition revue et augmentée, 2013.

[12] Rochester, Physics of Music PHY103 Lab Manual "Constructing a PVC Flute, Astrophysicists at University of Rochester, 2011.

[13] F. Blanc, "Production de son par couplage écoulement/résonateur : étude des paramètres de facture des flûtes par expérimentations et simulations numériques d'écoulements," Université Paris VI, Paris, 2009.

[14] E. Ducasse, "Modélisation et simulation dans le domaine temporel d'instruments à vent à anche simple en situation de jeu : méthodes et modèles," Université du Maine, Maine, 2001.

[15] S. Terrien., "Instrument de la famille des flûtes : analyse des transitions entre régimes," Université Aix-Marseille, Marseille, 2014.

[16] H. Haddar, T. Hélie and D. Matignon, "A Webster-Lokshin model for waves with viscothermal losses and impedance boundary conditions: strong solutions," in *International congress in Mathematical and numerical aspects of wave propagation*, Jyväskylä, Finland, 2003.

[17] R. Mignot, "Réalisation en guides d'ondes numériques stables d'un modèle acoustique réaliste pour la simulation en temps réel d'instruments à vent," Télécom ParisTech, Paris, 2009.

[18] H. Boutin, S. Le Conte, J. L. Le Carrou and B. Fabre, "Modèle de propagation acoustique dans un tuyau cylindrique à paroi poreuse," in *Congrès Français d'Acoustique*, Le Havre, 2018.

[19] G. Abou Haidar , R. Abi Zeid Daou and X. Moreau, "Modelling and Identification of the Musicians Blowing Part and the Flute Musical Instrument," in *Fourth International Conference on Advances in Computational Tools for Engineering Applications*, Zouk, Lebanon, 2019.

[20] G. Abou Haidar, X. Moreau and R. Abi Zeid Daou, "System Approach for the Frequency Analysis of a Fractional Order Acoustic Tube: Application for the Resonator of the Flute Instrument," in *Fractional Order Systems: Mathematics, Design, and Applications for Engineers*, Amsterdam, Elsevier, 2021.

[21] C. V. B. F. D. A. B. Soizic Terrien, "Calculation of the steady-state oscillations of a flute model using the orthogonal collocation method," in *hal-00903310v1*, France, 2013.

[22] P. Gilbert, Physics in the arts, Academic Press, 2012.

[23] A. Chaigne and J. Kergomard, Acoustique des instruments de musique, Paris: Belin, 2008.

[24] W. Offermans, For the Contemporary Flutist", "Etude 4: Bamboo Tone', 1992.

[25] Y. Bao, Irish Flute Design Optimization, 2013.

[26] D. M. a. D. D'andréa-Novel, "Spectral and time-domain consequences of an integro-differential perturbation of the wave PDE," in *in 3rd WAVES conference*, Mandelieu, France, 1995.

[27] J. W. Coltman, Effect of Material on Flute Tone Quality, 1970.

[28] C. Forster, "Musical Mathematics: On the Art and Science of Acoustic Instruments," 2010.