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# *Modelling and Identification of the Musicians Blowing Part and the Flute Musical Instrument*

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**Abstract** — The implementation of digital musical instruments has been growing in the last few years. The musical domain is relying on the use of electrical musical systems that are still manually controlled by humans. Although the full control of such systems remains more theoretical especially when the melody is not well known and/or saved within this electrical musical system, this work tries to pass those boundaries by creating a fully autonomous control system for the flute instrument. As this paper is part of a bigger project, the modelling and identification part of the system formed by the musician lungs, mouth, and the exciter of the flute will be presented. The static and the dynamic model identification will be verified and will lead to a well-defined transfer function for the system. This TF will be used in future works for the control purpose.

**Keywords**- Static and Dynamic Identification; Transfer Function; Flute Instrument; Modelling; Acoustics.

## I. INTRODUCTION

Flute-like instruments share a common mechanism that consists of blowing across one open end of a resonator to produce an air jet that is directed towards a sharp edge or what is called the horn. Analysis of its operation involves various research fields including fluid dynamics, aero-acoustics, and physics. A contribution has been made in this study to extend its functionality to be played numerically using an artificial mouth that is controlled by a servo valve that mimics the human lips and pressure blown through them. An analysis of the servo controller and the artificial mouth are the focus of this study.

Experimental measurements are done where the obtained data is used to propose analytical models that accurately fit the observed measurements and can be used for simulations [1].

### A- Identification Methods

Measurements are carried out on a test case where the instrument is actually only represented by its resistive effect (an adjustable leak) and the artificial mouth is replaced by a rigid cavity. Two techniques may be used for parameter identification: step and frequency responses. Step responses have been preferred to frequency responses to avoid as much as possible the effect of friction on measurements, since the servo-valve is a part of the process to be identified [2].

Another method is the time-domain simulations that are carried out through a classical Runge-Kutta method of order 3, implemented in Simulink [3]. A high sampling frequency  $fs =$

$23 \times 44100$  Hz is used. This value is chosen both because the solution is not significantly different for higher sampling frequencies, and because it allows an easy resampling at a frequency suitable for audio production systems.

In parallel, equilibrium and periodic steady-state solutions of the model are computed using orthogonal collocation and numerical continuation. Starting from a given equilibrium or periodic solution, continuation methods, which rely on the implicit function theorem, compute the neighboring solution, which is the solution for a slightly different value of the parameter of interest (the so-called continuation parameter), using a prediction-correction method [4].

### B- Control of Musical Instruments

The latest technology in controlling a musical instrument numerically precisely wind instruments is based on the use of high processing computer systems and good quality actuators. Many researches have been made in this domain and many outcomes contributed in the modelling and control of such instruments, however none of them produced the aimed music quality that resembles the real outcome from a real musician with a high percentage accuracy [2] [5]. There is no full and well explained control method that really contributes in what we can say high precision and high quality numerically controlled flute. What we aim in this research is to hit the required quality in designing an accurate model of the artificial mouth and the blowing part attached to it.

### C- Existing Models

Many kinds of synthesis techniques have been developed since many years such as mathematical functions (Frequency Modulation, Additive) sampling, and source/filter models. None of the previous deals with the model complexities of a physical systems. When aspects of physical systems defy analysis, we can resort to simulation which is most the time selective and incomplete. Thus the key is to model the interesting aspects while keeping the simulation computation tractable. One of the widely used type of models is the Mass-Spring Model of a String [5]. Some of the characteristics of this model are: expensive to compute, the simulation is discrete time that utilizes the use of multipliers and adders, the number of modes corresponds to number of masses, stiffness, and other interesting properties.

Another type of the models is the waveguide model. It is introduced by Julius Smith, where the wave propagation is modeled by a delay element with two left-going and right-going waves. The physical variable (amplitude or flow) is the sum of the corresponding values in two delay lines. Moreover, a new model was also introduced and it is the lumped filters. They represent real systems (transmission lines, strings, air columns) and exhibit continuous, distributed losses. The Length (therefore period) can be frequency dependent and can model losses within waveguide. Last but not least, the flute physical model showed in fig.1 [5] [9].

Fig.1 shows the flute block diagram built from a Low Pass Filter (LPF), High Pass Filter (HPF) and a bore delay line.

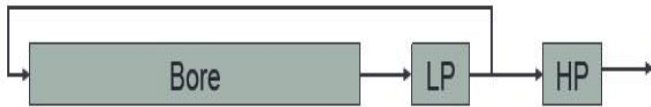


Fig. 1. Flute detailed physical model [5].

#### D- Purpose of This Work

The main purpose behind this work is to model and identify the artificial mouth and the pressure source driving it. Thus, this paper is divided into five sections. In section II, the system block diagram is presented. In section III, the model of the blowing part and the artificial mouth will be discussed. In section IV, the static and dynamic characteristics of the servo valve are presented along with input-output relationship between the artificial mouth and the exciter. Then, the result transfer function will be discussed. Section V concludes this paper and proposes some future works.

## II. SYSTEM BLOCK DIAGRAM

### A- Real Diagram (Lungs and respiratory system)

This section provides an overview of the respiratory parameters associated to flute playing by a musician. Although all components of the respiratory system are essential to its good functioning, we limit our description to the main respiratory concepts and mechanisms relevant to flute playing. The different parameters to be described include the pulmonary volumes, the main respiratory muscles and the pressure volume curve of the respiratory system [10] [11].

At first, we focus on the air movement into and out of the lungs required for flute playing. Pressure variations in the lungs and in the pulmonary airways create pressure gradients that regulate pulmonary ventilation. The muscles, by contracting, create forces which deform the structure of the respiratory system. The structure displacements modify the volumes of the cavities which, in turn, create pressure variations. Respiration depends on passive elasticity, surface tension and gravity which tend to take back the lung structure to its resting position and active forces (muscle activation).

Fig.2 shows the arrows in the lung drawings indicating the static forces exerted by the lung and the chest wall at different volumes [6].

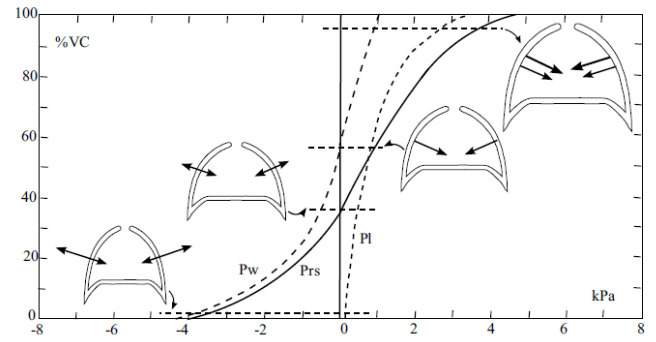


Fig. 2. Sketch of static volume-pressure curves of the lungs (PI), chest wall (Pw) and total respiratory system (Prs) during relaxation.

The model in fig.3 shows the breathing system at the Functional Residual Capacity (FRC) centered. At this point, the passive forces that represent elasticity, surface tension, gravity of the lungs, and the chest wall are equal and opposite. The gray block corresponds to the incompressible volume of the viscera, and the white block corresponds to the chest-wall cavity volume, above the diaphragm. The dotted lines represent the boundaries of FRC for both compartments. Arrows indicate the direction of the force applied by inspiratory and expiratory muscles [6].

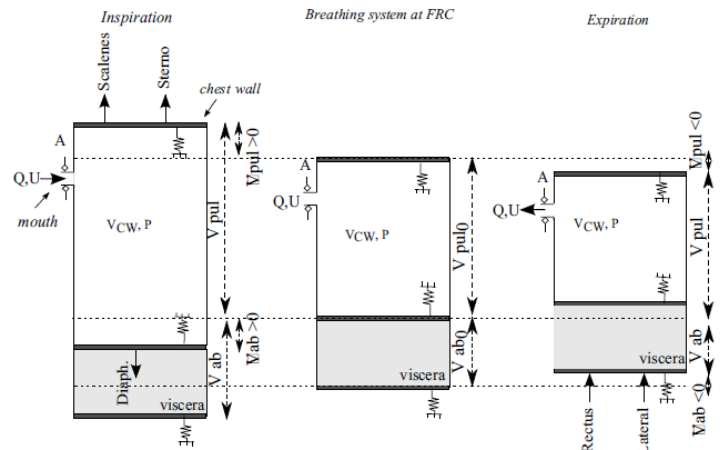


Fig. 3. Model of the flautist's thorax and mouth at different respiratory volumes.

### B- Components Used

Since what we are aiming to model is the blowing part and the artificial mouth of the flute, then we will be proposing two main parts to be modelled and identified. The main components used in implementing the aimed design are the 6 bars air compressor, pressure sensor, servo valve, flow sensor, artificial mouth, and the mouth piece of the flute instrument. Fig.4 shows the block diagram of the model.

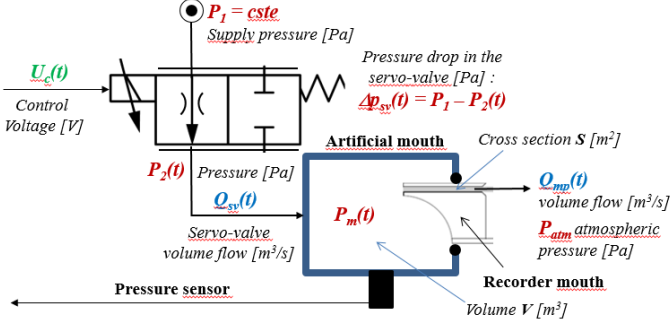


Fig. 4. Blowing part and artificial mouth blocks

A complete physical workbench was developed to model and test the diagram in fig.4.

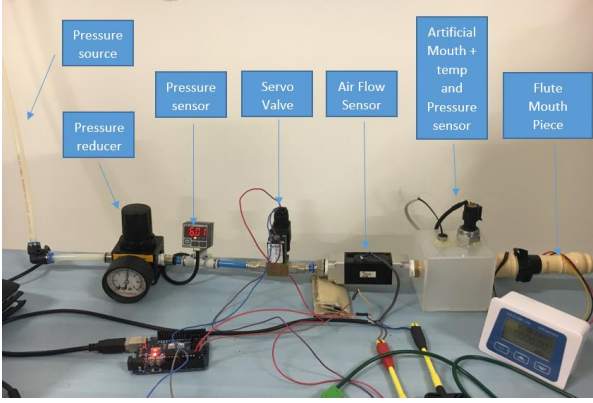


Fig. 5. Physical workbench of the overall system modelling

### III. COMPONENTS MODELLING

#### A- Servo Modelling

Three different pressures can be observed in fig.5: The constant supply pressure  $P_1$  of the servo-valve coming from the air compressor, the pressure  $P_2(t)$  at the output of the servo-valve and the pressure  $P_m(t)$  measured inside the artificial mouth. All these pressures are being compared to the atmospheric pressure  $P_{am}$ .

The pressure drop in the components and the interconnections are defined as follow:

- pressure drop in the servo-valve:

$$\Delta p_{sv}(t) = P_1 - P_2(t); \quad (1)$$

- pressure drop in the servo-valve-artificial mouth connection pipe:

$$\Delta p_{pipe}(t) = P_2(t) - P_m(t); \quad (2)$$

- pressure drop in the wind instrument mouth piece:

$$\Delta p_{mp}(t) = P_m(t) - P_{am}. \quad (3)$$

In this study, the servo-valve and the artificial mouth are connected directly without any pipe, so one can consider that  $\Delta p_{pipe}(t) = 0$  and so  $P_2(t) = P_m(t)$ .

Furthermore, these different pressures are linked by the relation:

$$\Delta p_{sv}(t) + \Delta p_{mp}(t) = P_1 - P_{am} = \text{constant}, \quad (4)$$

showing that if  $\Delta p_{mp}(t)$  increases, then  $\Delta p_{sv}(t)$  decreases, and reciprocally.

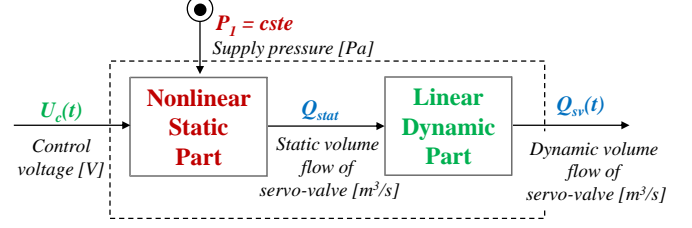


Fig. 6. Block diagram of the servo-valve decomposed into a nonlinear static part and a linear dynamic part

#### A.1 Nonlinear model of the actuator

The actuator is a servo-valve (Bürkert 2832) [8]. It provides a volume flow  $Q_{sv}(t)$  that is function to the inlet electrical current and the supply pressure  $P_1$ . The servo-valve is controlled by a voltage to current power amplifier (maximum output current of 400mA for a 10V input voltage). Various analysis and experiments carried out in [7] [8] reveal that the servo-valve can be decomposed in two parts: a nonlinear static part and a linear dynamic part as in fig. 6.

The static volume flow  $Q_{stat}$  in output of the nonlinear part depends of the control voltage  $U_c$  and the supply pressure  $P_1$  and can be described by a nonlinear function,

$$Q_{stat} = \text{NL1}(U_c, P_1), \quad (4)$$

such that,

$$\forall P_1 > P_{1l}, \begin{cases} \text{if } U_c < U_l(P_1), \text{ then } Q_{stat} = 0 \\ \text{if } U_c > U_h(P_1), \text{ then } Q_{stat} = Q_{\max} = a P_1 + b \\ \text{if } U_c \in [U_l(P_1); U_h(P_1)], \text{ then } K_{sv}(P_1) = \frac{\Delta Q}{\Delta U} \end{cases} \quad (5)$$

#### A.2 Linear Model of the Actuator

The linear dynamic part between  $Q_{stat}$  and  $Q_{sv}(t)$  is modeled by a second order differential equation [1] [2] as presented in equation (6):

$$\ddot{Q}_{sv}(t) + 2\zeta \omega_0 \dot{Q}_{sv}(t) + \omega_0^2 Q_{sv}(t) = \omega_0^2 Q_{stat}, \quad (6)$$

where  $\zeta$  and  $\omega_0$  will be determined in the identification part.

#### B- Artificial Mouth

The artificial mouth is the central part that connects the volume flow  $Q_{sv}(t)$  from the servo-valve to the pressure  $P_m(t)$  at the input of the mouth piece of the wind musical instrument. During the transient response, dynamics induced by the filling of the mouth cavity has to be taken into account. Assuming air is a perfect gas, the state equation is given by:

$$P_m(t) = \frac{r T}{V} M(t), \quad (7)$$

where  $r$  represents the thermodynamic constant of air equal to  $287 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ,  $T$  is the temperature of air at ambient conditions (equal to  $293.5 \text{ K}$ ) and  $M(t)$  is the mass of the air inside volume  $V$  (representing the artificial mouth). The mass  $M(t)$  of air inside

the cavity depends on the difference between the volume flow  $Q_{sv}(t)$  at the input of the mouth and the volume flow  $Q_{mp}(t)$  at the output (blown into the instrument). Since only small variations are considered, the air density  $\rho$  can be considered constant. In this case, the mass  $M(t)$  is given by:

$$M(t) = \rho \int_0^t (Q_{sv}(\tau) - Q_{mp}(\tau)) d\tau + M(0), \quad (8)$$

where the expression of  $Q_{mp}(t)$  is given by Bernoulli law:

$$Q_{mp}(t) = \alpha \sqrt{\Delta P_{mp}(t)}, \quad (9)$$

with  $\alpha = S \sqrt{\frac{2}{\rho}}$ ,  $S$  being the cross-section.

Figure 7 presents the block diagram of the nonlinear model of the artificial mouth obtained from equations (7), (8), and (9) where  $Q_c(t) = Q_{sv}(t) - Q_{mp}(t)$  is the volume flow of compressibility.

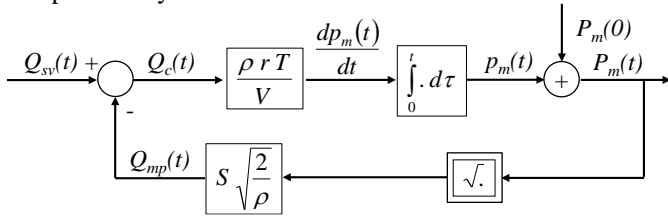


Fig. 7. Block diagram of the nonlinear model of the artificial mouth

Figure 8 presents an example of time responses obtained with the simulator. The analysis of the nonlinear model using the simulator allowed us to conclude that the amplitude of 0.1V of the harmonic signal  $U_c(t)$  represents an upper bound of the small variations  $u_c(t)$  around the operating point considered.

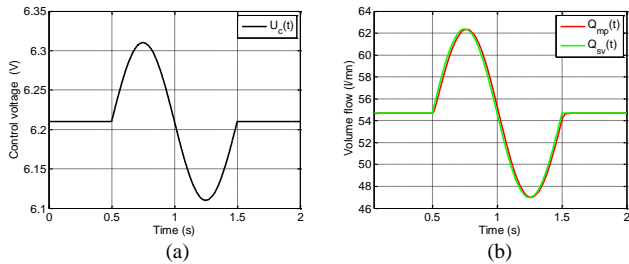


Fig. 8. Time responses of the nonlinear model: control voltage  $U_c(t)$  (a), volume flow  $Q_{sv}(t)$  and  $Q_{mp}(t)$  (b).

### B.1 Linearized model of the Artificial Mouth

In order to linearize the model of the artificial mouth, the initial condition  $P_m(0)$  is considered as an equilibrium pressure:  $P_m(0) = P_m^e$ . Thus the pressure  $P_m(t)$  inside the artificial mouth is expressed as follows:

$$P_m(t) = P_m^e + p_m(t), \quad (10)$$

where  $p_m(t)$  is a small variation around  $P_m^e$ .

As for the volume flow  $Q_{mp}(t)$  inside the mouth piece, its expression becomes:

$$Q_{mp}(t) = Q_{mp}^e + q_{mp}(t), \quad (11)$$

$$\text{where } Q_{mp}^e = \alpha \sqrt{P_m^e} \text{ and } q_{mp}(t) = \frac{1}{R_{mp}} p_m(t), \quad (12)$$

$$\text{with } \frac{1}{R_{mp}} = \left. \frac{\partial Q_{mp}}{\partial P_m} \right|_{P_m=P_m^e} = \frac{\alpha}{2\sqrt{P_m^e}}. \quad (13)$$

Figure 9 presents the block diagram of the linearized model around the static equilibrium pressure  $P_m^e$  where  $C_{am}$  is the pneumatic capacity associated with the volume  $V$  of the artificial mouth and  $R_{mp}$  is it's resistance.

$$C_{am}(s) = \frac{V}{\rho r T}. \quad (14)$$

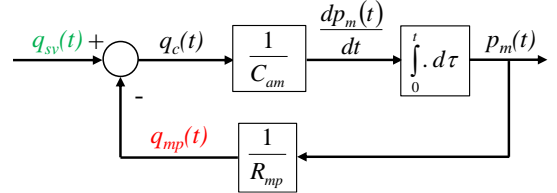


Fig. 9. Block diagram of the linearized model of the artificial mouth

From the block diagram of figure 7, the transfer function  $H_1(s)$  of the artificial mouth is deduced:

$$H_1(s) = \frac{\bar{P}_m(s)}{\bar{Q}_{sv}(s)} = \frac{R_{mp}}{1 + R_{mp} C_{am} s} = \frac{H_0}{1 + s/\omega_1}, \quad (15)$$

$$\text{where } H_0 = R_{mp}, \tau = R_{mp} C_{am} \text{ and } \omega_1 = 1/\tau. \quad (16)$$

From relations (10) to (13), the linearization of the artificial mouth leads to a transfer function that will be part in the overall resulting transfer function to be discussed in section iv.

### C- Exciter Characteristics

The exciter is the most complex part in the flute modeling process due to its nonlinear behavior as shown in figures 10 [4] and 11. The air jet exits the formation channel and crosses an open space before hitting a sharp edge called the labium. On its way it is perturbed by the air particles oscillating at the open end of the resonator, called the mouth of the flute [1].

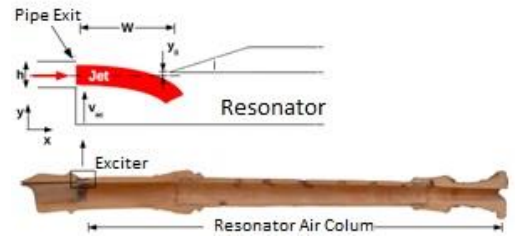


Fig. 10. The mouth piece and exciter link in a flute (see [4])

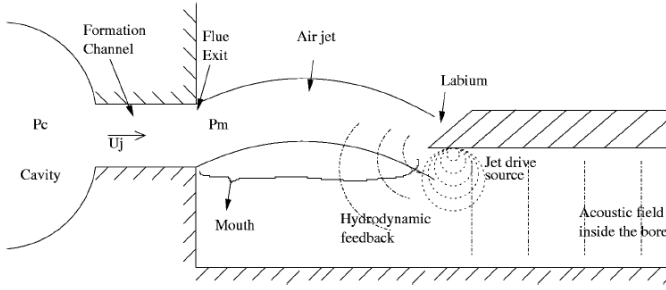


Fig. 11. Organ Pipe Geometry

As shown in the fig.1, as the air pressure coming from the pressure cavity or the mouth feeds the exciter and hits the labium, the turbulences will occur due to the nonlinear behavior that results from this interaction between the air flow and the labium.

#### IV. SYSTEM IDENTIFICATION

##### A- Servo Valve

The servo valve is acting as the actuator that controls the amount of air flow needed to the artificial mouth. It is studied from both static and dynamic perspectives in order to have the proper data needed in modelling and verifying the blowing part.

##### A.1 Static Results

Several measurements were done on the physical workbench to study the flow behavior at the output of the of the servo valve with respect to its input voltage. As shown in fig.12, the flow is directly affected by the variation in the input voltage with a change in the input pressure from one bar up to six bars. The servo-valve is controlled by a voltage to current linear power amplifier (maximum output current of 400mA for a 10V input voltage) [8].

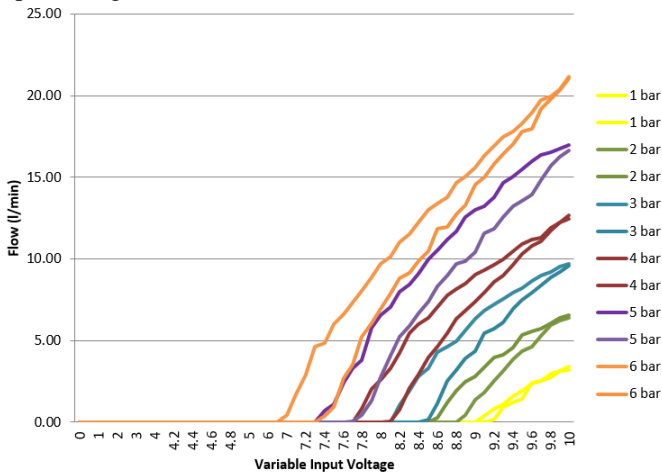


Fig. 12. Variable input voltage versus flow output with respect to different input pressure

For a maximum constant pressure of 6 bars, the variation between the input variable voltage (from 0 to 5V) and the output voltage of the servo valve is shown in fig.13. At an input voltage

of about 3.6V the output is 1.105V and this is the point at which the valve starts conducting and allowing the flow of pressure.

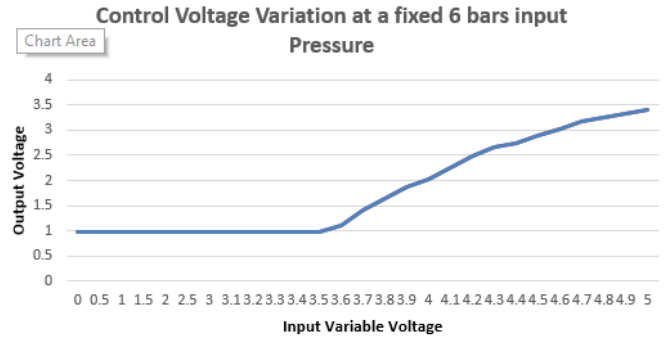


Fig. 13. Variable input voltage versus output voltage under a constant input pressure of 6 bars.

The hysteresis effect is also shown in fig.12. where the servo valve is assumed to operate in its linear range. This model should be considered as the linear part of the complete model. Due to friction indeed, some gain as well phase delay must be added to the model. These additional gain and phase may be estimated using first harmonic approach.

##### A.2 Dynamic Results

The moving armature itself is modeled as a mass/spring second-order system. The Laplace transfer function of the actuator is then:

$$A(s) = \frac{w_r^2}{s^2 + 2\zeta w_r s + w_r^2}, \quad (17)$$

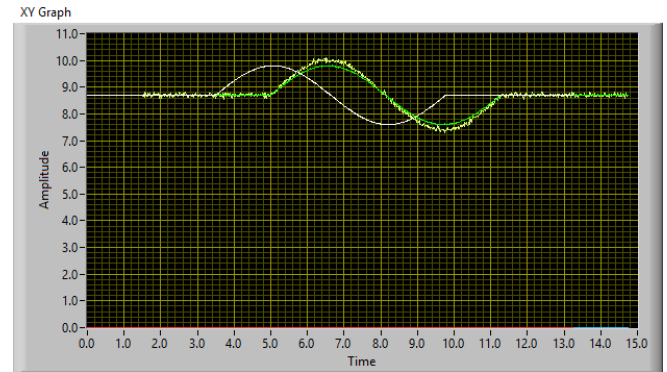


Fig. 14. Dynamic characteristics of the servo valve

We used LabVIEW to plot both the input signal driving the servo valve and the output signal representing the flow of the flow sensor as in fig.14. A sine wave signal with an amplitude 0.1 and frequency 1Hz was generated numerically and was assigned to the analog output pin of my RIO NI module. Then this signal was fed to an operational amplifier with a gain of four to create the desired offset. The output signal was a little bit noisy and shifted by  $\pi/4$ . This allows us to verify the maximum gain at which the valve operates and that was at frequency equal to 240Hz. The white signal is the input wave with an offset of 8.7V and amplitude of 0.9V and the two green

and yellow signals are two outputs shifted by  $\pi/4$  with amplitudes a little bit larger than the input signal. This output also allowed us to calculate the damping factor from the following equation:

$$w_n = w_d \sqrt{1 - \xi^2} , \quad (18)$$

where  $w_n$  = undamped natural frequency, and  $w_d$  = damped natural frequency.

Thus  $\xi = 0.3$  and  $\omega_0 = 2\pi \cdot 240$  rad/s.

### B- Resulting Transfer Function

After calculating the damping factor and the cutoff frequency, we can now derive the transfer function of the servo valve and that of the artificial mouth from the previous calculations. The resulting transfer function that represents the output to input relation of the servo valve is:

$$H_{sv}(s) = \frac{Q_{sv}(s)}{U_c(s)} = \frac{K_{sv}}{1 + 2\zeta \frac{s}{\omega_0} + \left(\frac{s}{\omega_0}\right)^2} . \quad (19)$$

The transfer function that represents the output to input relation of the artificial mouth is:

$$G(s) = \frac{P_m(s)}{Q_{sv}(s)} = \frac{R_{bec}}{1 + R_{bec} C_{pneu} s} = \frac{G_0}{1 + \frac{s}{\omega_1}} . \quad (20)$$

The overall transfer function of the system is:

$$G(s) = \frac{P_m(s)}{U_c(s)} = \frac{G_0}{\left(1 + \frac{s}{\omega_1}\right) \left(1 + 2\zeta \frac{s}{\omega_0} + \left(\frac{s}{\omega_0}\right)^2\right)} , \quad (21)$$

where  $G_0 = K_{sv} * H_0$ .

The overall transfer function models the first part of the flute musical instrument which is the blowing part and the artificial mouth, setting the floor for the controller part that will be the next step in this research. The results from the identification part were tested on the workbench and compared to the simulated results that were very satisfactory. Thus the static and dynamic measurements and calculations were accurate to fit a model of this partaking into consideration all the affecting parameters.

## V. CONCLUSION AND FUTURE WORKS

A full study, modelling, and identification was made to the blowing and artificial mouth of the flute wind musical

instrument. The full relation between the pressure input from the lungs of the musician up to the mouth then to the exciter of the instrument were verified and modelled.

The next step will be realizing the experimental model and its characteristics by comparing both numerical simulation and experimentation results. Moreover, a fractional order controller will be designed, tested, and compared to a traditional PID integer order controller seeking more precision and accuracy in the desired output. The final objective will be to model the whole flute system with its three main parts and recalibrate the simulator and the test bench controls and actuators so that it delivers the aimed target of resembling the accuracy in playing the flute musical instrument numerically.

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