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Article

Pipe Organ Design Including the Passive Haptic Feedback Technology and Measurement Analysis of Key Displacement, Pressure Force and Sound Organ Pipe

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Abstract: In this work, an organ pipe instrument with a mechatronic control system including the Passive Haptic Feedback technology is implemented. The test bed consists of a motorized positioning stage mounted to a brace that is attached to a bridge on a platform. A simple pneumatic mechanism is designed and realized to achieve the same dynamics pressure for each measurement attempt on the keyboard. This system contain pipes, an air compressor, valves, and a piston connected to applied force pressure on the keyboard of the organ pipe. The pneumatic components, like valves and pressure regulators, mounted on the profile plate are connected to the main air supply line via flexible tubing or hoses to the air compressor and mechanical trucker. The pneumatic system has many types of valves that regulate the air speed, air flow, and power. The combination of valves and air compressor control the air flow and the mechanism of piston and pressure on the keyboard. The mechanical actuator presses the key to be tested, and a load cell detects the applied key force. A laser triangulation measurement system based on a Laser Displacement Sensor measures the displacement of the key during the key depression. The velocity of the key motion is controlled by the pneumatic actuator. A miniature-sized strain gauge load cell, which is mounted on a musical keyboard key, measures the contact force between the probe and the key. In addition, the quality of the audio signal generated by the organ instrument is estimated using the Hilbert transform.

Keywords: organ pipe; passive haptic feedback; displacement; key; Hilbert transform

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1. Introduction

Nowadays, the keyboard instrument is most strictly associated with the piano and digital keyboards, where the musical notes are defined by their initiation and release with the control of speed and time [1,2]. The piano's sound and noise play a crucial role as do the different key-pressing techniques as confirmed by several studies [3–5].The relationship between the pianists' finger movements and characteristics of the resulting sound in terms of the time and intensity of tones during the performance is proposed as a multiple force feedback keyboard or as virtual simulations to reproduce the feeling of a grand piano [6,7]. For the musician, playing an instrument is an activity that involves an acoustic sense and, in addition, is a multi-sensory activity, providing essential visual and haptic feedback information [8,9]. For this reason, different methodologies have been developed to measure and characterize the properties of grand piano and organ key mechanics that determine the haptic sensation of playing [10]. To evaluate the sound effectiveness and impact of a musical instrument, the characterization and objective measurement of the properties of the key mechanics are analyzed.In recent years, analysis of the complex perception–action mechanisms of the piano has been focused on the tactile feedback that follows the initial key press and the related early feedback during piano playing [11,12]. The sensory properties of the key action in organ playing concern both physical and perceptual characteristics [13,14]. The haptic interaction between the performer and the instrument is perceived by the organist during the performance [15]. This interaction involves several of the performer's senses including the tactile one and the kinesthetic one through the bodily movements and tension linked to internal body stimuli [16]. The haptic interaction between the key and finger is bidirectional in the instrument and allows a better correlation of action and generated sound in order to achieve the desired tonality [17,18]. The pianist controls the instrument through intention and the perceived feedback of the instrument according to a complex multi-modal system. The visual and force feedback, and the auditory and vibrotactile feedback perceived through the fingers and feet, respectively, in contact with the keys and pedals are considered the interaction between the musician and musical instrument. The influence of the vibration levels of the piano keys on a performer's personal judgment of the instrument quality, is studied in [19], observing the strong integration effects of auditory and tactile information. The vibrations of piano keys include broadband and tonal parts and are often perceived unconsciously close to the limits of human perception. In addition to the acoustic effects of different forms of touch, visual and tactile modalities may play an important role during the piano performance, influencing the production and perception of the musical expression of the piano [20]. An haptic interface with an embedded system based on a magneto-rheological fluid is presented in [21]. The type of "touch" in playing an acoustic piano can affect the final sound, considered a specific type of sensory perception. This sensation is primarily caused by the dynamic key response of piano mechanics. Digital keyboards typically simulate the touch sensations through feedback from passive mechanisms integrated in the keys. On the other hand, the interaction with instruments such as the piano and pipe organ provides tactile information to the performer [22]. A controllable linear actuator for key pressure is used to obtain objective measurements and to control the speed of the keys. The subjective consequences of the key action are necessary to study the role of haptic sensation in organ performance and thus can reveal the dynamic response of the key action associated with physical systems and objective properties [23]. In [24], the design and validation of an active haptic prototype by a custom-made linear actuator is proposed to enhance the touch of digital piano by reproducing the force feedback of an acoustic piano action [25]. The force or impulse acting on a key can be considered important variables for pianists to modulate the generated sound. The timbre of isolated piano tones can be audibly varied by the type of touch rather than the speed of the hammer. Various types of touch, such as 'percussive', characterized by a finger striking the key surface at a certain velocity, and 'non-percussive', which is based on the kinematic properties of the keys, are studied in [26]. Empirical evidence from perceptual experiments shows that the sound components relying on different touch patterns produce tones with discernible touch at the same hammer velocity [27]. The temporal actions response is tested for different grand pianos under different touch conditions and dynamic levels. Pressed and struck touch are chosen over the entire dynamic range to play five selected keys. In addition to the intensity of the tone, the precise timing of the sound emission is crucial to ensure the expressiveness of the musical performance. For a grand piano, the speed of the hammer that reaches the strings over a wide dynamic range from pianissimo to fortissimo is measured in [28]. Linear potentiometers and force-sensitive resistors are used to measure and detect the finger position and pressure exerted by a musician while playing an instrument [29]. The relationship between the key depression force on an upright piano and the level of loudness of a generated tone is examined in [30] using a force transducer built-in key. To investigate, characterize, and quantify the mechanical impedance characteristics that contribute to the feel of musical keyboard keys, special test rigs are developed, including mechanical design and computer control, in [31,32]. The key can be easily pressed with enough force to actuate a motion. Pneumatic actuators are preferred in such applications due to their similarity in compliance with natural muscle that provides the driving force. Force and displacement data play an essential role for validating keyboard design. A rapid measurement of force–displacement allows such components to be evaluated for intended functionality and high quality. This measurement also helps to understand the instability of structures caused by buckling, specifically in the case of key and switch input devices used in musical and computing instruments. The virtual mechanisms that reproduce haptic feedback are developed for active keyboards, where the key actuators are driven by the haptic interaction with the keyboard [33].

The authors propose a pipe organ instrument built on this framework.

Main Contributions

This study will contribute to the growing development and implementation of a pipe organ instrument with a mechatronic control system including the Passive Haptic Feedback technology. The prototype is developed in order to reflect the organist's and pianist's feelings to the keyboard's reactions for typical mechanical and electrical control systems. The test bed consists of a motorized positioning stage mounted to a brace which is attached to a bridge on a platform. The mechanical actuator depresses the key to be tested and a load cell measures the applied key force. A laser triangulation measurement system based on a Laser Displacement Sensor measures the displacement of the key during key depression. The velocity of the key motion is controlled by the pneumatic actuator. The pneumatic components, like valves and pressure regulators, mounted on the profile plate are connected to the main air supply line via flexible tubing or hoses to the air compressor and mechanical trucker. The pneumatic system has many types of valves that regulate the air speed, air flow, and power. Flow control or one-way flow control valves regulate the piston speed of pneumatic drives during advance and return strokes. The combination of valves and air compressor control the air flow and the mechanism of the piston and pressure on the keyboard. The pressure on the keyboard of the organ instrument is controlled by increasing the pressure of the pneumatic finger system. A strain gauge mounted on the musical keyboard key measures the contact force between the probe and the key. The sound achieved by pipes is recorded by using an electret microphone and microcontroller. More particularly, the main contributions are summarized as follows:

- The organ instrument was designed and realized to provide a mechanical and electrical control system as a mechatronic control system, and compare the perception of reactions.
- The prototype is developed in order to reflect the organist's and pianist's feelings to the keyboard's reactions for typical mechanical and electrical control systems using the pneumatic finger system. The pneumatic actuator is used to provide motion and linear force application to the organ keyboard.
- Measurements are made of the force and displacement of the key during the key pressing of the musical keyboard, and of the sound of the pipes for the analysis of the mechanical traction in organ pipes.
- The estimation of sound signals generated by the pipe organ is computed using the absolute value of the Hilbert transform and introducing amplitude ripple (AR), the low-to-high delay (LHD), and the high-to-low delay (HLD).

The paper is structured as follows: In Section 2, the organ pipe structure and experimental setup are described. In Sections 3 and 4, the measurements and the analysis of results are reported, respectively. Conclusions are presented in Section 5.

2. Organ Pipe Structure

In concert halls, pipe organs are large-scale instruments with thousands of pipes that can only produce a C-pitch sound with the timbre of a flute. Generally, 56 pipes are required for each timbre of sound, from the lowest note to the highest note. A pipe organ produces mechanical sounds by creating air in pipes. Organ pipes made of metal and wood vary in length and width to produce the full range of sounds, timbres, and notes of the musical scale. The number of pipes can reach several thousands, so the structure of pipes is huge. The wind chest is a wooden box that compresses and distributes air produced by the bellows throughout the pipes. The pipe that will emit sound is selected using the stops and the manuals. The stop is used to switch from one timbre to another, while the manuals select the tone (C, D, E, etc.) to be played. The mechanism driven by the manuals operates vertically through the wind chest, while the stops function horizontally, forming an arrangement that resembles an interconnected matrix, like a three-dimensional grid. The keyboard pattern is a system that transmits the movement of the keys pressed by the organist to the movement of valves that allow to compress air into the set of pipes on the wind chest. In Figure 1, the elements marked in red represent the valve-opening mechanism by pressing the keys on the organ instrument. Pressing the key, the dynamics are transferred to the tracker, which is connected to the sound valve. This movement causes the opening of the valve and the spring compression. Then, the audible chamber opens and induces a sudden flow air from a solid air container [34]. The mechanical transfer of the key movement to the movement of the air inlet valve into the pipe takes place in a purely mechanical manner known as keyboard traction (Figure 1). In an instrument with this type of handling, all the work of controlling the wind chest is performed by the player with their muscle strength. The mechanical traction can also be used to control the valves. A direct mechanical connection between the key and the valve is a suitable solution to play without the delays in the traction. A mechanical system also allows the organist to influence and regulate the sound of the organ by controlling finger pressure on the keys.

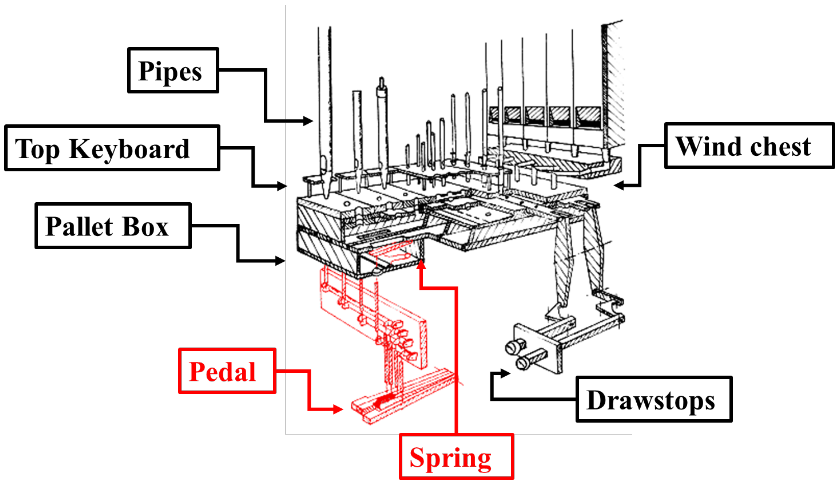


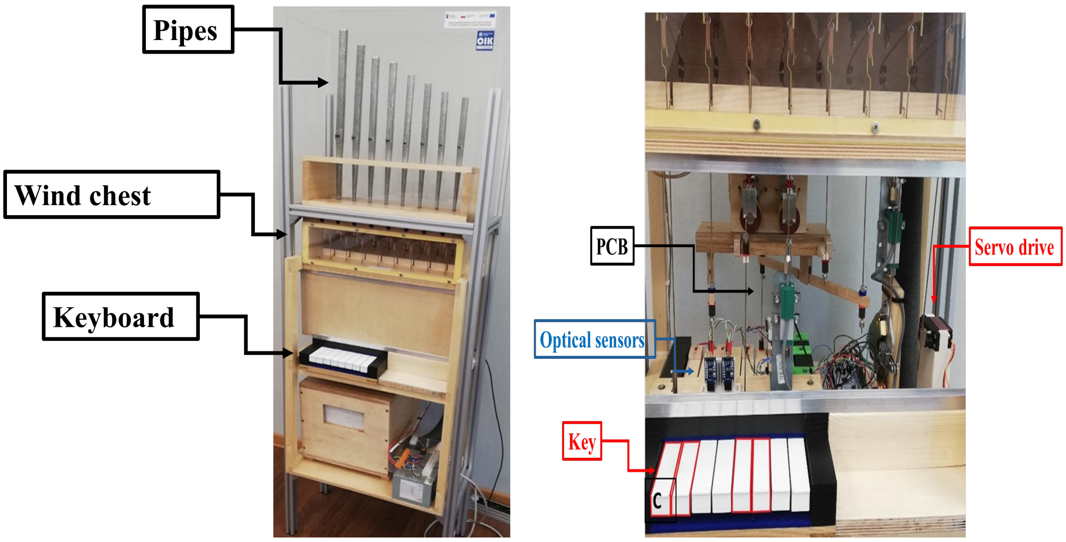
Figure 1. Mechanical organ instrument commonly used showing the mechanical traction with register cooperating with the tone and wind chest, pallet box, pedal, valve spring and the keyboard [34].

2.1. Designed Organ Instrument

A pipe organ instrument with a mechatronic control system has been implemented, including the Passive Haptic Feedback technology. The mechanical parts transmit the control signal by means of the cable and lever systems, while the electric part has an electromagnetic switch actuator. The control system that connects the keys of musical instrument with the actuators (e.g., pipes) is referred to as the traction system. The traction system consists of all structures and mechanisms involved in the transfer of motion and dynamic forces between the available and executive elements. Mechanical traction is commonly used to control the pipe organ. The force is transmitted by means of mechanical elements. The dynamics is provided by the muscle strength of the organist that is playing. This type of control is the optimal solution from the musical perspective. Organists, playing the instrument, have the freedom of creation and benefit from the dynamics of the sound produced by the organ pipe. The low latency between the key and the wind chest allows to play without any of the delays that occur with other types of control.

2.2. Pipe Organ Design

In Figure 2a, the organ keyboard has an octave with eight keys with various control systems (handling). The keys C, D, G, and A, marked in red in Figure 2b, have mechanical traction, E has electric traction, and F and H have high mechatronic traction Passive Haptic Feedback in various configurations of the design.The dynamics analysis and mechanical traction of the pipe organ dynamics require the measurement of the force applied on the key of the musical keyboard, the key displacement, and the sound of the pipes. A pneumatic mechanism enables the pressure for a given repeatable and adjustable key and its speed of movement. The sound achieved by pipes is recorded using an electret microphone. The pressure applied on the keys, also called the contact force, is detected by printed force sensor FSR (Force-Sensing Resistor). The key displacement is measured using the laser triangulation technique. All data are transferred to two computers operating via a connection to two-channel oscilloscopes.



(a) (b)

Figure 2. (**a**) A prototype of an organ instrument; (**b**) keyboard of organ instrument realized.

2.3. Measuring Devices

The measurements were made using the following:

- Pneumatic mechanism of pressing the button;
- DFRobot Analog Sound Sensor V2.2 module with sound sensor (electret microphone);
- FlexiForce Pressure Sensor (FSR)–SparkFun SEN-08712;
- LK-G152 Keyence LK-G5001 controller and LK-G152 Laser Displacement Sensor;
- Universal Multifunction Digilent Analog Discovery 2 measuring instrument and Digilent Analog Discovery BNC adapter.

Figure 3 displays the measurements made, such as sound, displacement of the key, and pressure (force), using the experimental setup assembled for the organ instrument.

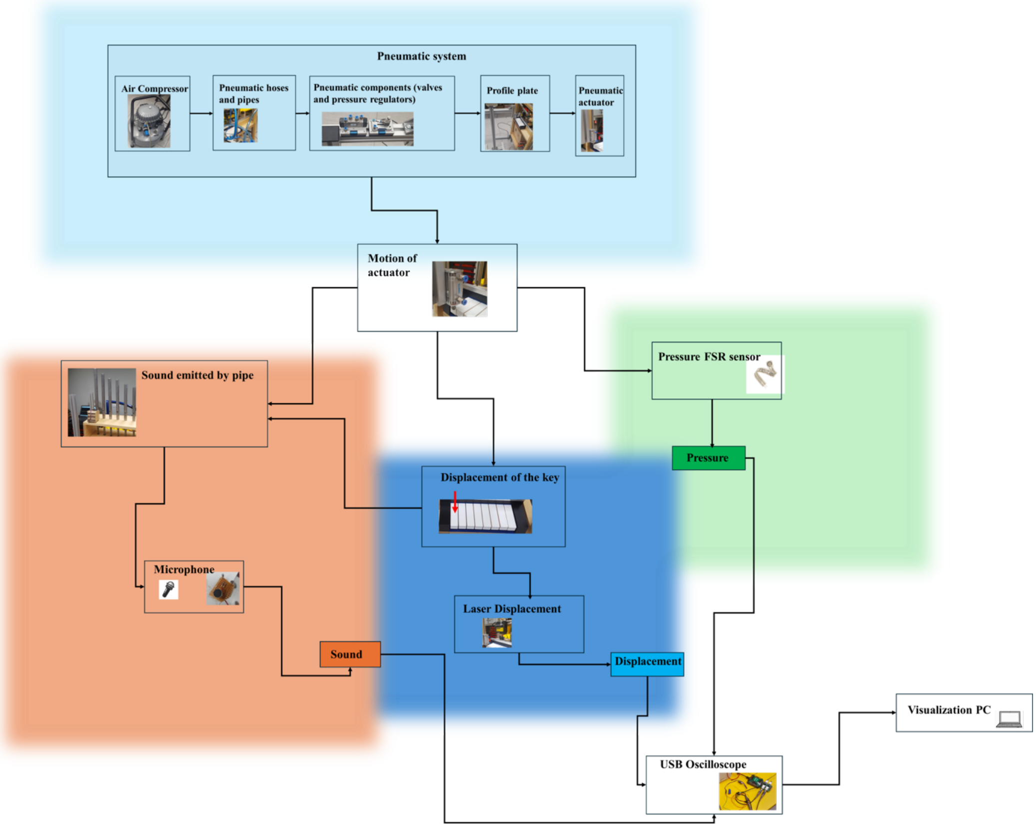


Figure 3. Diagram of the conducted measurements in the organ pipe.

2.4. Key Pressing: Pneumatic Mechanism

A simple pneumatic mechanism was designed and realized to achieve the same dynamics pressure for each measurement attempt on the keyboard. This system contains pipes, an air compressor, valves, and a piston connected to applied force pressure on the keyboard of an organ pipe. The piston is controlled by a two-position 4/2 way valve, indirectly controlled by an applied pneumatic input signal. The shut-off valves with a spring are used as auxiliary valves and actuated by a physical button. The entire system is connected to the air preparation unit. All actuators and control elements are connected with compressed air lines (pipelines). All elements of the pneumatic system are placed in a support of aluminum H-profiles obtained by the extrusion process, which guarantees maximum strength in a wide range of corner elements with even, regular sides. The pneumatic actuator is used to provide motion and linear force application to the organ keyboard.

Pneumatic Cylinder

The pneumatic system, pneumatic cylinders, and actuators operate when compressed air is forced into the cylinder to move a piston located within it. The "work" is performed by a mechanism attached to the piston, which converts the energy generated into practical use. Pneumatic actuators are based on some form of pressurized and compressed air entering a chamber, where the gas builds up pressure. When it has built up enough pressure in contrast to the outside atmospheric pressure, it results in the controlled kinetic movement of a device such as a piston or gear. This resulting movement can be directed in either a straight line or circular motion. The key components of a pneumatic actuator include end-caps, a piston, a rod, a scraping seal, a barrel, a guide, and sealing gaskets. All pneumatic force depends on air pressure and the piston area. Usually, the air pressure is set at 50 psi. A proportional pressure regulator VPPM - Festo VPPM-6L-L- 1-G18-0L10H-V1P-S1C1 is used to control the pressure and provide a quick response in the pneumatic system (Figure 4). The output pressure, proportional to an electrical command signal, is unaffected by changes in pressure. An inlet solenoid valve shifts proportional to the flow and maintains the system presence. The variable opening effect controls pressure at low-flow conditions and avoids the digital steps of traditional on/off solenoids. The Planet Air compressor L-S50-25, a fully automated and equipped pneumatic device, converts power into potential energy stored in pressurized air which is in an anti-corrosive stainless steel boiler. In Table 1, the technical data of such an air compressor are reported.

Table 1. Technical data of air compressor.

Technical Data	Planet Air Compressor L-S50-25
Voltage	230 V
Frequency	50 Hz
Motor	0.46 kW
Displacement	50 L/Min
FAD/efficiency	32 L/Min
Pressure	16 bar
Maximum current drain	2.9 A
Tank size	24 L
Noise level	45 dB
Pressure	max. 16 bar
Dimensions (H × W × D)	400 × 400 × 510 mm
Weight	28,000 kg

In order to connect the main air compressor to the pneumatic instruments, the pneumatic hoses and pipes are used to distribute the compressed air to the various system components (Figure 4).

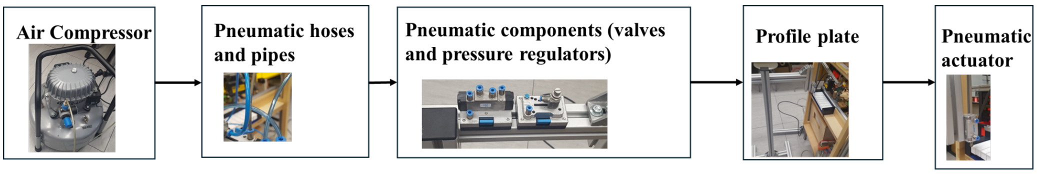


Figure 4. Pneumatic system and pneumatic components.

Pneumatic components like valves, cylinders, or pressure regulators are connected to the main air supply line via flexible tubing or hoses (Figure 4). The pneumatic system has many types of valves that regulate the air speed, air flow, and power. Flow control or one-way flow control valves regulate the piston speed of pneumatic drives during advance and return strokes. This is realized through the suitable restriction of the flow rate of the compressed air in the exhaust air or supply air direction. The adjustable one-way flow control valve is screwed into the function plate, incorporating a straight push-in fitting. The unit is slotted into the profile plate via a quick release detent system with a blue lever. The one-way flow control valve consists of a combination of a flow control valve and a non-return valve. The non-return valve blocks the flow of air in one direction, whereby the air flows via the flow control valve. The throttle cross section is adjustable by means of a knurled screw. The setting can be fixed by means of a knurled nut. Two arrows indicate the direction of flow control on the housing. In the opposite direction, the air flow is unrestricted via the non-return valve. The 3/2-way valve with a push button actuator, normally closed, is assembled in a polymer housing. The unit is mounted on the profile plate via a quick release detent system with a blue lever. The valve is actuated by pressing the push button. Releasing the push button returns the valve to the normal position via a return spring. The one-way flow control valve consists of a combination of a flow control valve and a non-return valve arranged parallel to the flow control valve. The flow control cross section can be adjusted with a knurled screw (Figure 5).

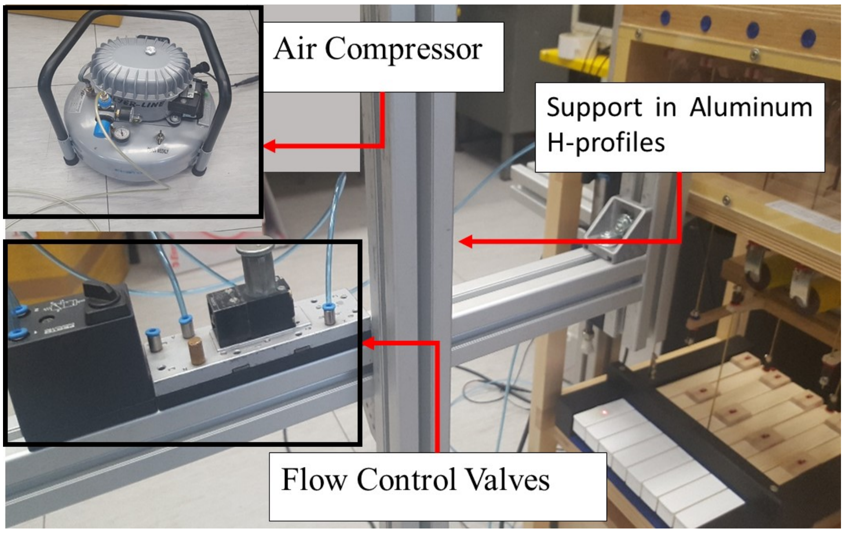


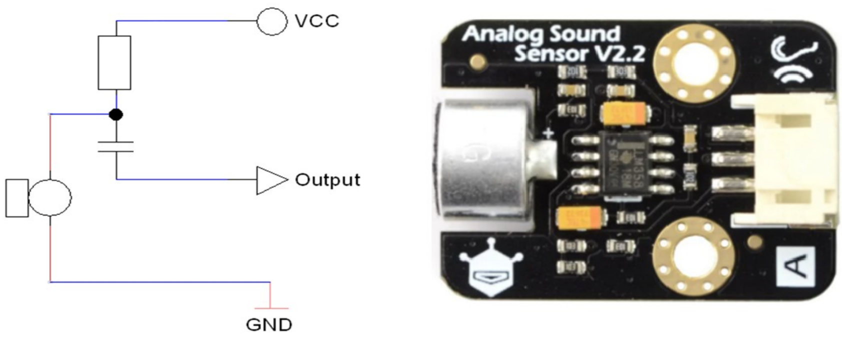
Figure 5. Pneumatic system: air compressor, pressure regulators, and valves on support.

A non-return butterfly valve enables to control the mechanism of piston velocity during the extension. The pressing of physical buttons on the two-position valves causes the extension and retraction of the piston.

2.5. Sound Emitted by the Pipes: Microphone

Electret Microphone

An electret microphone with a preamplifier and filters is used. An electret microphone is used to record and convert sound into an electrical signal. The front plate, known as the diaphragm, is made of electret, a very light material with a fixed surface charge. It is an electrical insulator (dielectric) with a quasi-permanent electric charge or dipole polarization. The circuit system is supplied by Vcc voltage. To read the microphone signal, a probe is connected to the output (Figure 6a).



(**a**) (**b**)

Figure 6. (**a**) Schematic diagram of an electret microphone pre-amplifier; (**b**) DFRobot Moduł Analog Sound Sensor V2.2.

The capacitor is added to filter noise and spurious signal data. An Analog Sound Sensor V2.2 module from DFRobot Gravity is adopted with a sound sensor equipped with an analog output with the advantages of high compatibility with Arduino or Raspberry PI microcontrollers. The specifications of Analog Sound Sensor V2.2 include the supply voltage from 3.3 V to 5.0, the analog output signal, and the two mounting holes with a diameter of 3 mm at a distance of 5 cm. The kit includes a cable with a tip compatible with the gold pin standard, pitch 2.54 mm (Figure 6b).

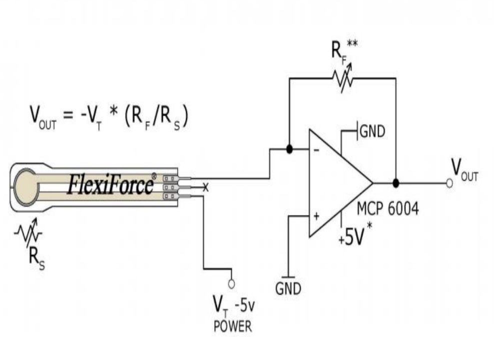
2.6. Pressure Applied on Key: Pressure Sensor

2.6.1. Force Sensitive Resistor (FSR)

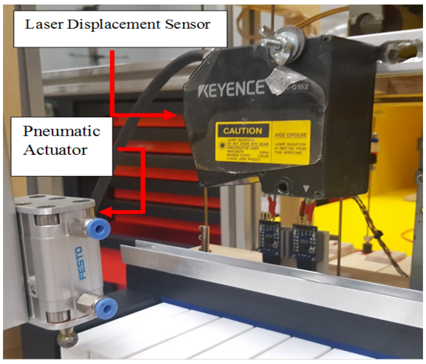
The FlexiForce Pressure Sensor - SparkFun SEN-08712 allows the detection and testing of pressure and force. It has two integrated layers separated by a dielectric spacer. The resistance of FSR changes in the function of pressure force or stress variation applied to the sensor, as the distance between the conductive particles inside the composite changes, varying the overall material conductivity. The voltage read from the FSR, and then the received signal in the calculation program, can be scaled. The sensor resistance changes only when the pressure is applied to the round area at the end of the sensor. The sensor itself is thin and flexible, but the resistance does not change while being flexed. The sensor is connected to the signal amplification system and an oscilloscope to read the output voltage.

2.6.2. Laser Displacement Sensor

The Keyence LK-G152 Laser Displacement Sensor (Figure 7a) and Keyence LK G5001 Laser Displacement Controller were used to measure the displacement of the key. The controller is connected to the laser head which sends a laser beam to the tested object (Figure 7b). By changing the distance to the measurement object at which the beam is directed, the voltage changes at the voltage output of the controller. The LK- G152 is a 1D Laser Triangulation Displacement Sensor for high-precision distance measurement on the surface. With the KEYENCE custom LI-CCD, superior Ernostar lens, and ABLE algorithm, the sensor is able to automatically ensure stable and accurate measurement. The traditional oscilloscopes are used to process the signals received from the sensors. In this case, a USB oscilloscope Digilent Analog Discovery 2 was used to measure, visualize, generate, record, and control mixed-signal. The analog and digital inputs and outputs can be connected to a circuit using simple wire probes; alternatively, the Analog Discovery BNC Adapter and BNC probes can be used to connect and utilize the inputs and outputs. Analog Discover 2 is connected directly to the computer's USB plug.



(**a**)



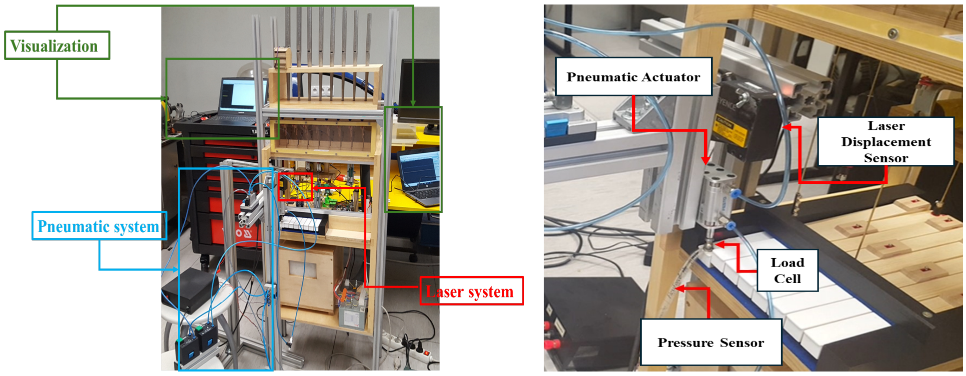
(**b**)

Figure 7. (**a**) Schematic diagram of the pressure sensor connected to the amplification circuit; (**b**) Laser Displacement Sensor and pneumatic actuator in organ pipe.

3. Measurements

3.1. Measuring Instrument

The measuring instrument was connected using a USB connector to a PC with WaveForms software developed by the manufacturer Digilent. The Force-Sensing Resistor (FSR), made of plastic with the connection tab crimped on a delicate material, was connected to the amplifier circuit, and located at tested keys of the organ instrument. From the amplifier circuit, the signal voltage changing (displacement) was read. The LK-G152 Laser Displacement Sensor was mounted on aluminum profiles as in a pneumatic system. The laser sensor was positioned so that the laser beam was focused on the tested button. A cable for reading the displacement signal was used out of the connected LK-G5001 controller (Figure 8b). The DFRobot Analog Sound Sensor V2.2 module with a sound sensor was placed in front of the tested pipe, and it was connected to a power supply providing a constant voltage of 5 V. Then, the signal wire was led out.



(**a**) (**b**)

Figure 8. (**a**) Experimental setup of organ instrument and measurement apparatus; (**b**) laser displacement system, pneumatic actuator, flexible pressure sensor on musical keyboard.

For each measurement, the audio and pressure/displacement signals obtained by the sensors were achieved at the same time and connected to different computers. The probes were led out from the appropriate channels on the BNC adapter and connected to the sensor signal cables. The flexible sensor was located for each key of the keyboard to measure the pressure force, and the measurement of the displacement was obtained by laser. In order to provide the results of the dynamics of the mechanical traction, the measurements were made to exhibit the behavior of the instrument in relation to the pressing force of the key and the speed of key press. The pressure was controlled by increasing the pressure of the pneumatic finger system, while the key pressure speed was set via the throttle check valve. The exact times of the speed of key pressing were read by a measuring device as the fall speed of the displacement signal slopes.

3.2. Campaign of Measurements

A couple of keys on the musical keyboard are actuated manually in classical music (Figure 1). In the implemented organ instrument, the keys are actuated using a pneumatic actuator (Figures 5 and 8a,b). The pressure measurements are obtained as readable data using the piezoresistive force sensor FlexiForce Sensor located on the key of the musical keyboard and connected to the oscilloscope as shown in Figure 8b. Pressing hard, the sensor's resistance is lower such that the resistance changes from infinite to ∼300 k. The pressure on the key, where the piezoresistive force sensor is located, is carried out by a pneumatic linear actuator (Figure 9).

A pneumatic linear actuator is powered by compressed gas and designed to convert compressed air into a linear motion. The amount of force that a pneumatic linear actuator is able to produce is related to the size of the piston and the pressure of the compressed gas. This means that by increasing the inlet air compression or the width of the piston, the effective actuator force will increase. Pressure can often be adjusted while in use, allowing the proper amount of linear force to be created. In our case, the valve system is used to control the air pressure. The key motion was determined by applying the force to the keys of the keyboard with a given key reaction speed by the actuator system in order to simulate the same reaction of an organist. In a data acquisition system, the force and velocity of the key reaction are measured in a mechanical control system. The sound produced by the mechanical actuator in the organ pipe is acquired and amplified by a microphone and collected by an oscilloscope (Figure 10).

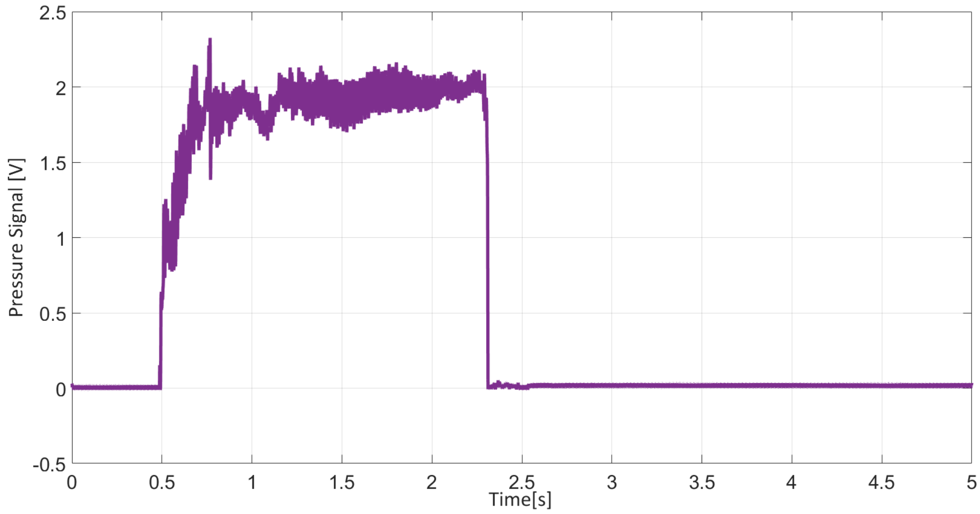


Figure 9. Pressure signal achieved during the test measurement.

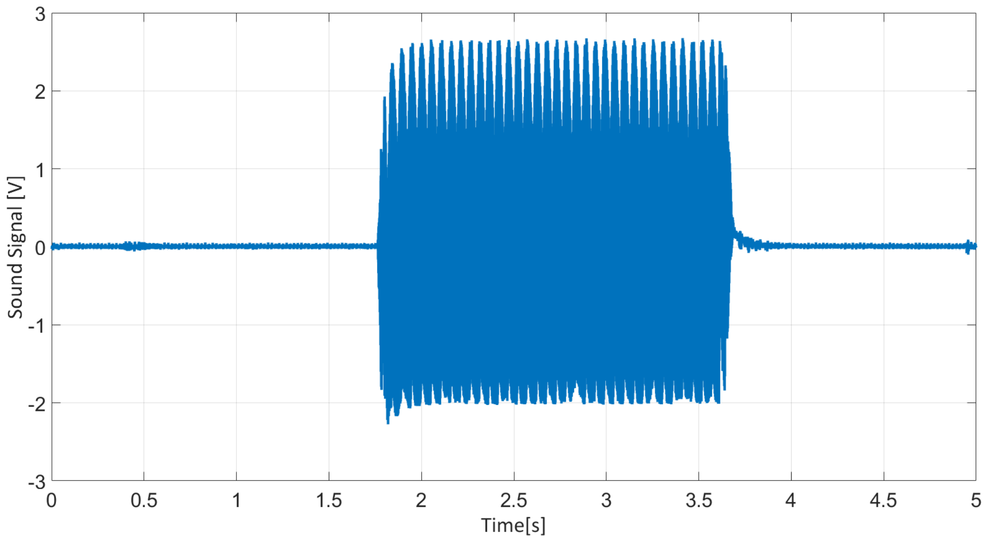


Figure 10. Sound signal achieved during the test measurement.

The sampling frequency is 300 kHz for a good description of the harmonics of sound waves generated by the pipes. Generally, humans can detect sounds in a frequency range from about 20 Hz to 20 kHz. So, it is preferred to extend the sampling frequency at 300 kHz. The sound signal in Figure 10 emitted by the pipes exhibits a noise phenomenon that can be due to mechanical noises and air leakage. Unfortunately, there was no possibility to physically isolate the noise from the recording; however, the signal was amplified and filtered. The miniature-sized strain gauge load cell (FlexiForce Pressure Sensor-SparkFun), which is mounted on a musical keyboard key, measures the contact force between the probe and the key. The load capacity of the cell is 1 kgf (9.81 N). When the force is applied, the relative change in resistance is measured by the sensor. The load cell signal is converted into a numeric value expressed in voltage. The load cell measurement read in the oscilloscope is expressed in volts and can be converted to force in kg_f (9.81 N) or in g_f. When the force is applied, the sensor measures the relative change in resistance. The load cell signal is converted into a numerical value expressed in voltage V[mV]. The load cell measurement read in the oscilloscope is expressed in volts read by the oscilloscope, taking into account that 14 mV is equivalent to 1 g force g_f, and the force can also be expressed in newtons (1 g = 0.0098 N). The force is obtained as stress on the key of the organ pipe (the key is stressed by the force of a finger in general) and by making the movement at a certain speed. The force expressed in g_f in function of time is reported in Figure 11.

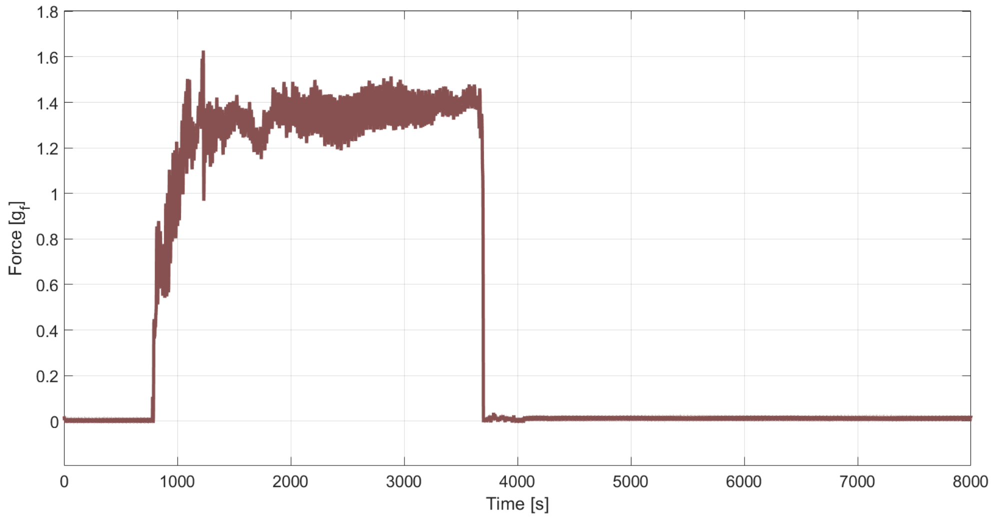


Figure 11. The force applied on key recorded by oscilloscope.

The key displacement for C key is expressed in mm with maximum value of 11 mm (Figure 12).

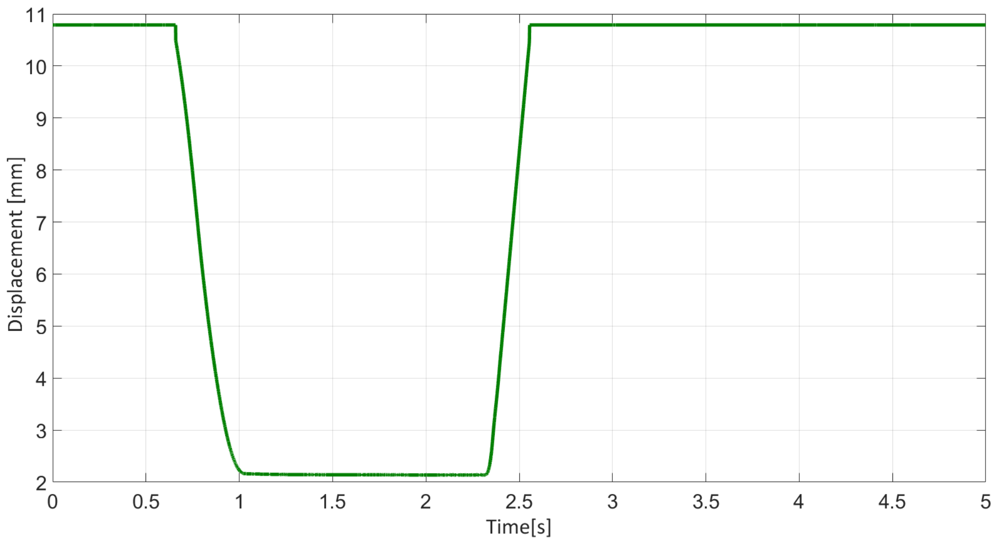


Figure 12. Displacement signal achieved during the test measurement.

4. Data Processing

In this session, the performance of the system is carried out in terms of velocity response by analyzing the signal acquired by the sensors. Theoretically, the notes generated by the organ pipe can be considered AM-modulated signals, where the carrier is the frequency generated, and the modulating signal is pressure $P(t)$. Under this hypothesis, the audio signal generated by the organ $s(t)$ can be written as

$$s(t) = P(t) * cos(2 * \pi * ft) \tag{1}$$

This approximation is possible because the fundamentals of the notes generated by the organs are several dB over the harmonics. However, due to the non-ideality of the components composing the pipe organ, the actual signal modulating the carrier is a noisy and delayed version of $P(t)$. It is defined as $\overset{*}{P}(t)$ as this noisy and delayed signal that actually modulates the carrier. The more $\overset{*}{P}(t)$ is similar to $P(t)$, the more the signal generated by the organ will be similar to the desired one. For this reason, the analysis of

$\overset{*}{P}(t)$ allows to estimate the performance of the system. $\overset{*}{P}(t)$ is the envelope of the generated signal, and by definition can be estimated by the magnitude of the analytic signal $z(t)$ of $s(t)$, where:

$$z(t) = s(t) + jHT(s(t)) \quad (2)$$

where $HT(s(t))$ is the Hilbert transform of $s(t)$. What has just been stated makes it possible to estimate PP directly from the audio signal generated by the pipe organ computing the absolute value of the Hilbert transform of this signal.

In Figure 13, the pressure signal P(t), the audio signal s(t), and finally $\overset{*}{P}(t)$ are shown.

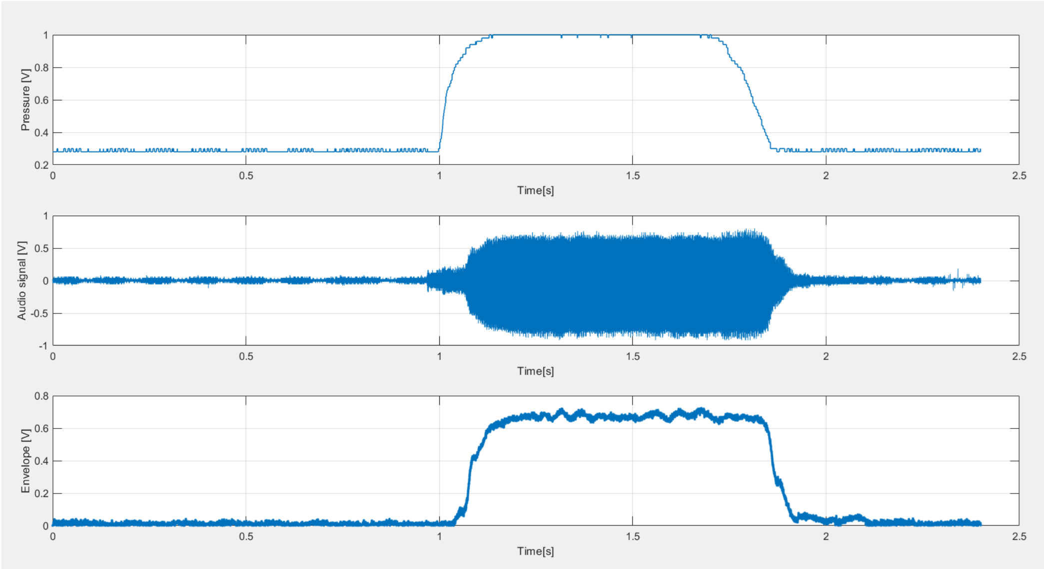


Figure 13. The first graph shows the pressure P(t), the second, the audio signal generated by the pipe organ, and finally the last one, $\overset{*}{P}(t)$ estimated by the computation of the absolute value of the Hilbert transform.

The trend of the curves shown in the graphs confirms what was previously stated: $\overset{*}{P}(t)$ is a noisy and delayed version of P(t). In particular, $\overset{*}{P}(t)$ presents a certain delay compared to P(t) and the amplitude ripple.

In order to evaluate the quality of PP, some quantities are introduced, which are the amplitude ripple (AR), the low-to-high delay (LHD), and the high-to-low delay (HLD). The AR is defined as the ripple amount of the envelope, while LHD and HLD are defined, respectively, as the time difference between the pressure's and the envelope's signals given that they reach 50% of their sustaining value starting from 0, and the time difference between these signals given that they reach 0 starting from their sustaining level. Analyzing in MATLAB, the signals generated by the pipe organ are estimated to have a mean value of LHD equal to 0.026 s, a mean value of HLD of 0.083 s, and a ripple of 16% (Figure 14).

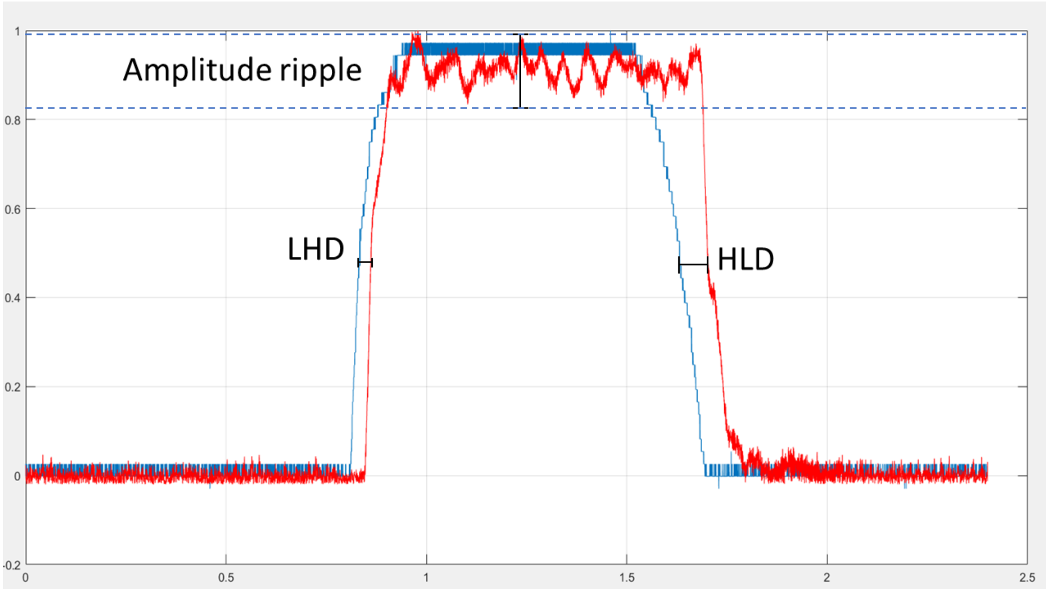


Figure 14. Amplitude ripple (AR), the low-to-high delay (LHD), and the high-to-low delay (HLD) of $\overset{*}{P}(t)$ and P(t).

5. Conclusions

A miniaturized organ pipe with a mechanical control system including the Passive Haptic Feedback technology has been developed in order to reflect the organist's and pianist's feelings to the keyboard's reactions for typical mechanical and electrical control systems. For the investigation and the characterization of the organ pipe, a mechanical actuator was provided to test the force applied on the keys, measured by a pressure sensor mounted on the musical keyboard key, and a Laser Displacement Sensor was used to measure the displacement of the key. The velocity of the key motion was controlled by the pneumatic actuator.

The pneumatic components, like valves and pressure regulators, mounted on the aluminum profile plate are connected to the main air supply line via flexible tubing or hoses to the air compressor and mechanical piston. The pneumatic system has many types of valves that regulate the air speed, air flow, and power. Flow control or one-way flow control valves regulate the piston speed of pneumatic drives during advance and return strokes. The combination of valves and the air compressor control the air flow and the mechanism of the piston and pressure on the keyboard. The pneumatic actuator is used to provide motion and linear force application to the organ keyboard. In particular, the pressure on the keyboard of the organ instrument is controlled by increasing the pressure of the pneumatic finger system. An analysis of the force–displacement characteristic and sound effect of the tested miniaturized pipe organ was carried out. In addition, the performance of the system in terms of the response velocity and the quality of the sound signal in terms of the amplitude ripple, the low-to-high delay, and the high-to-low delay were estimated using the Hilbert transform of the signal. The acoustic and pressure signals were performed with the delay at the beginning due to the inertia of the pneumatic actuator arm and the distribution of the direction of acoustic energy. Opening or stopping the pipe affects the generated sound but also the sound pressure level and direction of propagation of the acoustic energy. However, the proposed control based on a pneumatic finger system is the optimal solution, from the musical perspective, to analyze the behavior of the realized instrument in relation to the pressing force of the key, the speed of the key press, and the sound emitted by the pipes. Developing electrical–mechanical techniques and integrating data from multiple sensors can provide a more comprehensive understanding of air flow in organ pipes and improve the control systems for better construction and performance.

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