Development of human-machine interface for ultrasonic fatigue testing machine

Orlando Miguel Gonçalves de Oliveira

Master Dissertation

Supervisor: Prof. Joaquim Gabriel

Co-Supervisor: Prof. Abílio de Jesus

Co-Supervisor at INEGI: PhD. Filipe Silva

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Master in Mechanical Engineering

October 2022

Abstract

Many engineering structural components experience fatigue due to very long loading histories (above 10^7 cycles). As such, ultrasonic fatigue testing is a method used to evaluate their behavior under these conditions. Ultrasonic fatigue testing machines consist of a piezoelectric transducer that transforms a power supply signal from an ultrasonic generator into a mechanical displacement at the transducer's mating surface. These vibrations are transmitted to a horn and booster, which amplify the displacement on the testing specimen.

This dissertation, developed at INEGI, has the goal of developing a human-machine interface for one of these testing machines. It started by analyzing the hardware parts already available at INEGI and choosing others to use in order to assemble a system capable of capturing the necessary data and managing the operation of the machine and its connections. A LabVIEW program was developed to display the data collected, control the operation of the machine, and calculate the stress in the specimen during the pre-load and the elapsing of the testing.

The work developed in this dissertation is a starting point in the development of an ultrasonic testing machine at INEGI. The assembly of the hardware and future changes to the LabVIEW code will be necessary to complete the automation.

Desenvolvimento de interface homem-máquina para máquina de testes de fadiga ultrassónica

Resumo

Muitos componentes estruturais de engenharia sofrem fadiga devido a histórias de carga muito longas (acima de 10^7 ciclos). Como tal, o teste de fadiga ultrassónica é um método usado para avaliar o seu comportamento nestas condições. As máquinas de teste de fadiga ultrassónica consistem num transdutor piezoelétrico que transforma um sinal de alimentação de um gerador ultrassónico num deslocamento mecânico na superfície de acoplamento do transdutor. Estas vibrações são transmitidas para um “horn” e um “booster”, que amplificam o deslocamento do provete de ensaio.

Esta dissertação, desenvolvida no INEGI, tem como objetivo desenvolver uma interface homem-máquina para uma destas máquinas de teste. Começou por analisar as peças de hardware já disponíveis no INEGI e escolher outras para utilizar de forma a montar um sistema capaz de capturar os dados necessários e gerir o funcionamento da máquina e as suas ligações. Foi desenvolvido um programa em LabVIEW para exibir os dados recolhidos, controlar o funcionamento da máquina e calcular a tensão na amostra durante a pré-carga e o decorrer dos testes.

O trabalho desenvolvido nesta dissertação é um ponto de partida para o desenvolvimento de uma máquina de testes ultrassónicos no INEGI. A montagem do hardware e futuras alterações ao código LabVIEW serão necessárias para completar a automação.

Acknowledgements

First, I express my acknowledgements to Professor Joaquim Gabriel and Professor Abílio de Jesus who, as supervisors of this project, contributed to its success through the sharing of opinions and transmission of important knowledge for the development of this dissertation.

To Engineer Filipe Silva, a thank you for the supervising and monitoring of the work at INEGI and for the availability and assistance during all phases of the dissertation. I also thank Professor Hélder Puga for his contributions about the ultrasonic generator. In general, I also thank all the collaborators of INEGI who helped me during the dissertation.

I would like to express my thanks to INEGI - Institute of Science and Innovation in Mechanical Engineering and Industrial Engineering, for the availability of facilities for the development of this dissertation, and to FCT - Foundation for Science and Technology - that supported this work through the project PTDC/EME-EME/7678/2020, "GCYCLEFAT - Long-Term Fatigue Behavior of Metal Engineering Alloys" and an Initial Researcher Fellowship, under Law No. 40/2004 of August 18 and FCT Scholarship Regulation No. 950/2019, of December 16, in force.

Finally, special thanks to my parents for their support throughout this course.

Cofinanciado por:

COMPETE 2020

PORTUGAL 2020

UNIÃO EUROPEIA
Fundo Europeu
de Desenvolvimento Regional

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

inegi driving science & innovation

List of contents

List of figures

List of tables

Acronyms

DAQ - Data acquisition

VHCF - Very High Cycle Fatigue

UFT - Ultrasonic Fatigue Testing

HCF - High Cycle Fatigue

HF - High Frequency

IP - Internet Protocol

RMS – Root Mean Square

1 Introduction

1.1 Project framework and motivation

For the testing of materials that undergo very long fatigue cycles during their operation, conventional fatigue testing methods aren't fast enough to test their resistance. As such, it is necessary to use other methods. One of these methods is ultrasonic fatigue testing, where a piezoelectric transducer, powered by an ultrasonic generator usually working at around 20 kHz, generates a mechanical displacement at the transducer's mating surface. These vibrations are transmitted to a horn and booster, which amplifies the displacement on the testing specimen.

In these machines, at an automation level, it is important to control the frequency of the generator and the transducer, to appropriately apply start and stop commands, have emergency stops (manual and automatic), calculate the stress during the testing and visualize the data that's acquired during the testing, most notably the deformation and temperature of the specimen.

The present master dissertation, developed at INEGI, in the UTAF unit, fits in the development of the automation of an ultrasonic fatigue testing machine developed in this institute.

1.2 The Giga-Cycle project at INEGI

INEGI (Institute of Science and Innovation in Mechanical Engineering and Industrial Engineering) is a Research and Technology Organization (RTO) dedicated to carrying out activities of research and innovation, the development of new technologies, and industry-oriented technologies. This institute, in operation since 1986, was created within the Department of Mechanical Engineering (DEMec) and Industrial Engineering and Management (DEGI) of the Faculty of Engineering of the University of Porto (FEUP) to contribute to the development of the Portuguese industry, ensuring the enrichment of the academic community.

This dissertation was developed at the Advanced Manufacturing Technologies Unit (UTAF) of INEGI, which is responsible for the use of innovative technology to improve products or processes related to manufacturing, under the Giga-Cycle Fatigue Behavior of Engineering Metallic Alloys (GCYCLEFAT) project by FCT, where the final goal is to develop and build an ultrasonic fatigue testing machine.

1.3 Objectives of the project

The aim of this dissertation is to develop a human-machine interface for an ultrasonic fatigue testing machine that allows to control an ultrasonic transducer and its power system, as well as several sensors. It will also be important to set up fatigue tests.

1.4 Project method

In a preliminary phase of the master dissertation, the work performed was based on researching the state of the art of technologies used in ultrasonic fatigue testing machines in order to better understand the work that needed to be done.

After this, the hardware already available at INEGI was analyzed, and other parts were selected in order to build a data acquisition and control system.

Finally, a LabVIEW program was developed that presents the data obtained, allows to input commands related to the operation of the machine, shows the stress during testing and other parameters and controls the correct functioning of the machine.

1.5 Structure of the dissertation

Based on the methodology applied in this project, the present dissertation is divided into four chapters after this introductory one.

In “State of the Art”, a summary of the available general fatigue testing technologies is made. After that, the ultrasonic fatigue testing technology is explained in more detail. Finally, a data acquisition system and control software for one of these machines is shown.

In “Components used”, the hardware components that were chosen to create the system capable of operating and controlling the testing machine are shown and the reasons behind their choice are explained.

In “LabVIEW program developed”, the software created is shown and its functioning described. Its code is explained, and its interface shown.

The overall conclusions of the work performed are presented in “Conclusions and future works”.

2 State of the art in fatigue testing machines

2.1 General fatigue testing machines

Fatigue testing consists in an application of cycling load acting on a fixed item until it is damaged. The test conditions are defined, the duration of test as well as several other indicators are registered. The meaning of damage could be defined in different ways i.e., full breakage or its symptoms. The damaged item is then inspected by analysing the type of damage, surface shapes, type of cracking and many other parameters. The registered indicators can be also analysed by checking some statistical relationships among them. Monitoring can aid destructive-type fatigue testing. There are also hybrid test routines where the specimen subjected to the test is monitored through an image processing system to perform the measurements e.g., the crack propagation process. [1]

Fatigue testing machines usually apply cyclic loads to test specimens. Therefore, fatigue testing is a dynamic testing mode, which can be used to simulate the behaviour of a material under real life loading conditions. They can incorporate tensile, compressive, bending or torsion loading. Some fatigue machines allow to generate a combination of these loading types. [1]

Construction and efficiency of fatigue machines are closely related to the development of technology in different areas. These include the development of mechanical structures, methods for measurement and calculation of fatigue life as well as the development of drivers and control systems. [1]

Continuous development of measurement methods, drivers and control systems, is especially visible on the example of fatigue testing. Methods of testing materials require not only extensive characterization of their mechanical properties, but also to accurately depict real operational loads occurring in constructional elements and machine parts. Hence, there is a need to build specialized machines for fatigue testing of materials using multiaxial loads of different waveforms in time, and to verify and improve formulated calculation models to predict the fatigue life of machine parts and structures. A fatigue machine can be classified, by purpose of the test, type of load, means of producing the load, operational characteristics, etc. [1]

The requirements placed on the drivers for working machinery, in particular fatigue machines drives are dependent on the technological needs of a given machine. In fatigue machines, the type of loading for a specimen is most often generated by: [1]

- servohydraulic actuators,
- servopneumatic actuators,
- electrodynamic actuators,
- electromagnetic actuators and vibrators,
- centrifugal and inertial vibrators,
- dead weight or constant spring.

The simplest way to refer the load with a constant amplitude is mounting the spring on one side of the specimen and set in motion by sliding the other part by means of the crank drive. [1]

If the plane motion is applied directly to the end of the specimen, without a spring, it must be maintained very high machine rigidity in relation to the specimen. Machines of this type use a crank lever system and cause large forces of inertia which introduces limitations to the frequency ranges and masses. Often oppositely distributed masses are used in order to reduce the inertia forces. [1]

The loads are also generated by the fixed weight or a spring constant. The forces caused by the spring are not always reliable, and errors caused by inertia deepen the overload. Fatigue machines based on pneumatic actuators are used less frequently than hydraulic machines. [1]

An example of a servohydraulic axial fatigue machine is presented in Figure 2.1. The presented testing machine for dynamic tests has the testing actuator mounted on the upper crosshead for maximum versatility. Optional tests also can be performed in addition to standard fatigue tests. Dynamic testing machines are available in various versions for test loads, in this case, from 25 to 2500 kN. [1]

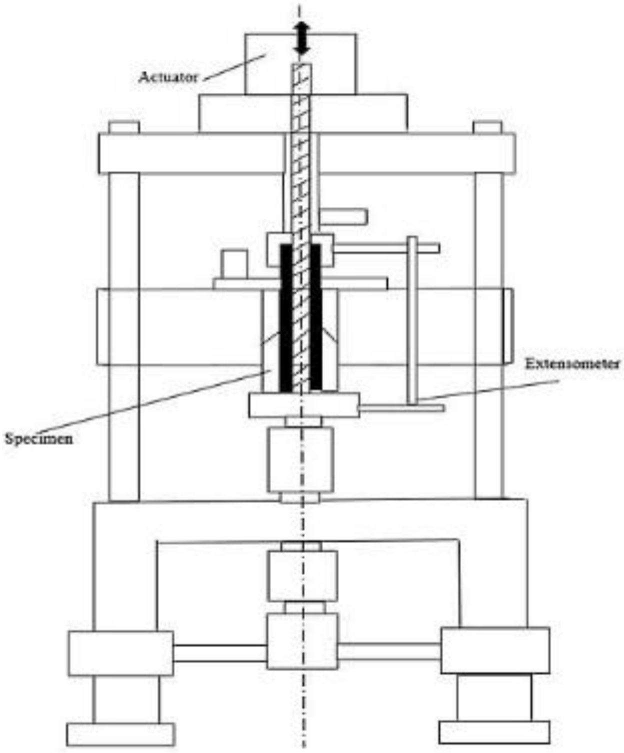


Figure 2.1 - General simplified view of an axial loading testing machine [1]

For tests up to 10^7 cycles, one commonly uses conventional servo-hydraulic machines. These machines typically work at frequencies from around 20 Hz for most technical materials, up to about 50 Hz. For the measurements, a specimen is loaded with a hydraulic cylinder which is driven by a servovalve-feedback control. Such a procedure generates oil pressure in every cycle; thus, the overall energy consumption is significant, and the large part of the power consumption which is transformed to heat must be dissipated by appropriate cooling. [2]

2.2 Ultrasonic testing machines

Fatigue studies throughout the last century have mainly focused on low cycle fatigue and high cycle fatigue (HCF) regimes up to 10^7 cycles because of cost and time constraints. These constraints are mainly attributed to the limitations of conventional test systems. However, many engineering structural components often experience very long loading histories (e.g., giga cycles). Therefore, several different design approaches have been explored to develop a new type of fatigue test systems in order to investigate fatigue and fracture performance of materials subjected to HCF in the range of 10^6 to 10^8 cycles and very high cycle fatigue (VHCF) in the range of 10^8 to 10^{10} cycles. [3]

In classical fatigue testing, the machines' low operating frequencies require unfeasible lengths of time for the completion of tests up to 10^9 cycles. For example, typical rotating bending machines operate at frequencies up to 30 Hz, servo-hydraulic machines work at frequencies up to 50 Hz and resonant fatigue machines work at up to 150 Hz. This means that to achieve 10^9 cycles, 'conventional' testing may require a machine to be operating between 2 months to more than 1 year, 24/7, i.e., without any interruptions. The recent development of ultrasonic fatigue testing (UFT) machines where frequencies can go as high as 20 kHz (or more) enabled tests to be extended to ranges larger than 10^9 in a fraction of the time, as little as 14 h (in theory), if no interruptions had to be made. Therefore, as demonstrated in Table 2.1, one can highlight a remarkable time and money-saving aspect which allows tests to take up to 400 times less time than with 'conventional' methods: from days to minutes, from months to hours, from years to days, from decades to weeks. Another attractive facet of this testing method is the great versatility offered for testing different types of fatigue such as tension, torsional, bending or flexural, fretting and even corrosion fatigue. The effects of diverse temperature environments, hot or cold, or loading patterns with different stress and biaxiality ratios can also be investigated to try and replicate real-life field conditions. [4]

Table 2.1 - Comparison between the duration different fatigue testing methods need to be completed, assuming tests can run uninterruptedly (approximate values, rounded to the nearest 0.5) [4]

Number of cycles	**Ultrasonic (20 kHz)**	**Resonance (150 Hz)**	**Rotating bending (30 Hz)**
10^7	8.5 min	1 day	4 days
10^8	1.5 h	1 week	1.5 months
10^9	0.5 days	2.5 months	1 year
10^{10}	1 week	2 years	1 decade

The advantages of UFT, associated with the improvements in piezoelectric devices, made these fatigue testing methods an attractive technique to establish S-N curves in VHCF regime. Presently, with the development of new sensors, new computational methods, and faster and more efficient control systems, VHCF gained increasing popularity as many of the challenges in the past could be addressed from incorporating technological innovation. [4]

The UFT machine does not require both ends of the specimen to be attached as the 'conventional' machine requires. UFT specimens are designed to have a particular mode shape vibrating at a given frequency: the operating frequency of the machine, usually 20 kHz. [4] The necessity to explore the durability of components with a minimum expected lifetime of 10^7 and above prompted researchers to use vibrating machines operating close to natural frequency of test samples. Test samples are designed to resonate at the operating frequency of the machine. By exciting the sample at a resonant frequency, it is possible to significantly reduce testing time while maintaining the quality of fatigue life results. Very high cycles experienced by certain automotive components and the ultrahigh cycles seen by aerospace parts created the need for an even faster testing method. VHCF characterization was facilitated by the development of 20-kHz piezoelectric transducers during the early part of the 1950s. The machine became the standard for all future ultrasonic fatigue testing systems. It consisted of a resonating stack displacing a test specimen. The variable amplitude of the transducer was able to produce a wide range of stresses at the sample level. Further increases in operating frequencies were achieved in the following years. Although an increase in resonating frequencies might lower required testing time, it also reduces the size of the stack and more importantly the specimen. Test specimens are designed based on the wavelength of their operating frequencies and the speed at which sound travels through the given material. Over time, 20 kHz has become the norm for ultrasonic fatigue testing mainly because of the wide selection of power supplies, transducers, and various safety considerations. [3]

Long loading cycles of HCF and VHCF regimes, typically 10^7 cycles or greater, are the key design criteria in many engineering applications such as aerospace, automotive, transportation, and offshore industries. Since HCF and VHCF failures affect safety, reliability, readiness, and support cost for many machine systems made from metal alloys, the fundamental understanding of fatigue resistance and potential prevention strategies for these HCF regimes are essential. Various fatigue damage modeling approaches in time and frequency domain have been recently proposed to provide fatigue life assessment of structures in HCF regimes. [3]

The development of ultrasonic fatigue testing system allows to advance experimental research capabilities in fatigue and fracture in HCF and VHCF regimes. The developed test system shown in Figure 2.2 is comprised of an acoustic horn, sample, transducer, power supply, displacement sensor and control system, and data acquisition (DAQ) system. This ultrasonic fatigue testing machine is developed and built with the integration of these elements and components. [3]

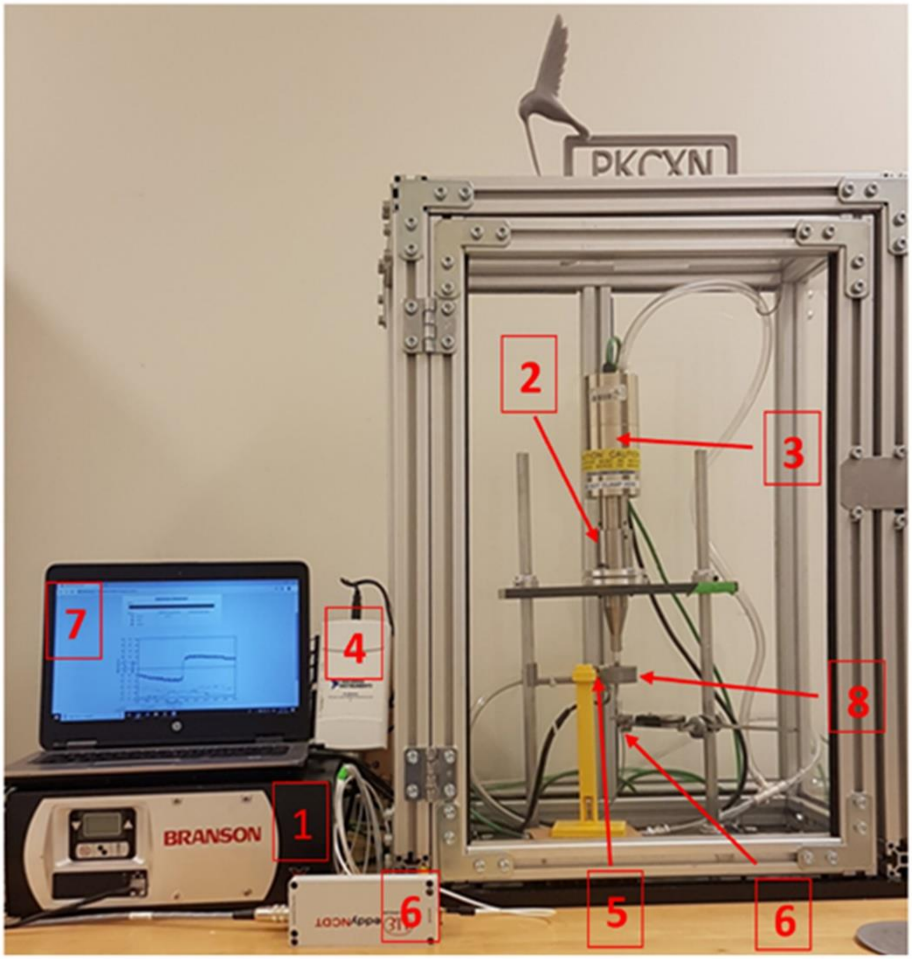


Figure 2.2 - Integrated ultrasonic fatigue testing system (1-Power supply; 2-Acoustic horn and sample; 3-Transducer; 4-Data acquisition system; 5-Temperature sensor; 6-Displacement sensor; 7-Computer; 8-Cooling system.) [3]

The piezoelectric transducer transforms the power supply signal into a mechanical displacement of 2 to 20 μm at the transducer mating surface. A mylar disk helps transmit these vibrations to the booster, which further amplifies the displacement. The longitudinal ultrasonic waves traveling through the entire stack create the region of maximum stress at the center of the sample. The sample is subjected to zero mean stress (ie, $R = -1$). Figure 2.3 shows the stress-displacement distribution over the entire length of the acoustic stack. [3]

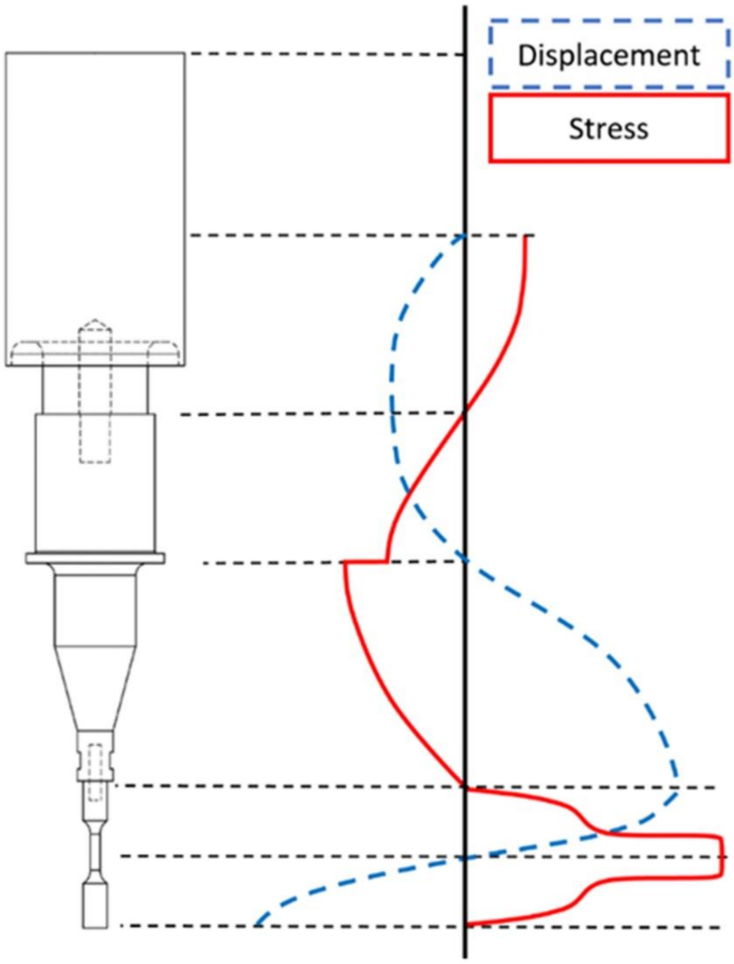


Figure 2.3 - Displacement and stress distribution across a resonating acoustic stack [3]

Testing time is a crucial factor in VHCF tests. Thus, testing with high frequencies is highly desirable. Using ultrasonic fatigue testing, testing times can be reduced by a factor of 20–100 as compared to conventional techniques. Operating in the resonance region of the specimen is indispensable for reaching the necessary and defined vibration amplitudes. Thus, all vibrating parts, including transmission pieces, amplification pieces and specimen must be appropriately designed. [2]

As depicted in Figure 2.4, ultrasonic fatigue systems are generally composed by the following parts:

- A generator with power outputs of between 5 and 500 W (e.g., a series of 500 W units), a piezoelectric transducer, and an ultrasonic horn (i.e., a mechanical amplifier), providing longitudinal sinusoidal vibrations with about 20 kHz (frequencies up to 40 kHz are also possible, but have some shortcomings). [2]
- Measuring units and closed-loop control units to regulate the (constant or variable) vibration amplitude, the pulse-pause-sequence, the number of cycles, and the frequency and allow for on-line classification of the amplitudes and displays for several of these values. The predefined amplitude value can be reached very quickly (in about 100 cycles); overshooting is avoided through a feed-back control and the use of an induction displacement gage, which allows accurate adjustment of the control signal. Online data recording allows verification of the accuracy. [2]
- A frame and devices for superposing static loads, low-frequency cyclic compression or tension loads (mode I, leading to R ratios $\neq -1$), or shear loads (mode II or III). For fully

reversed tension–compression loading (i.e., R = −1), the specimen must be fixed at only one end. [2]

- Possible additions such as a cooling device, cryostats, environmental chambers (for liquids, gases, as corrosion chambers or furnaces), or crack growth detection devices, such as, e.g. cameras, microscopes, strain gages, DC potential drop measurement devices. [2]

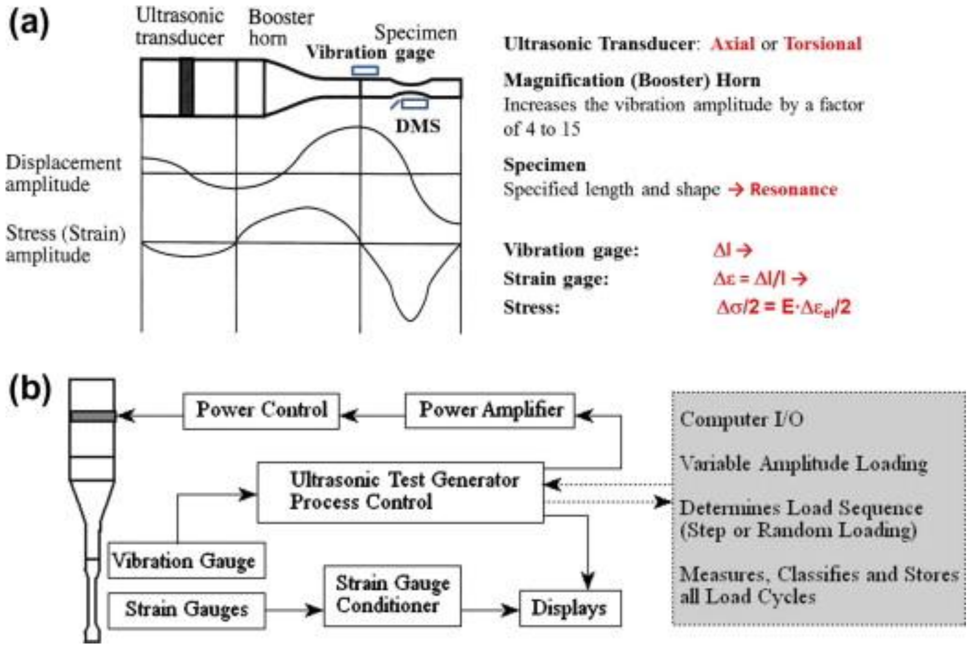


Figure 2.4 - Principles of ultrasonic fatigue ((a) Resonance vibration and strain/stress amplitude variation along load axis. (b) Control units) [2]

When loading with high frequencies, special attention must be given to controlling the resulting damping heat. A possible procedure to avoid the specimens' heating is to load with periodic interruptions (pulsed loading). Thereby, pulse-lengths are typically between 25–100 ms (500–2000 cycles) and pauses can vary between 25 and 1000 ms and depend on the damping of the specimens' material. Additionally, liquids and compressed air can be used for cooling; in the case of liquids, however, possible corrosion effects must be considered. [2]

Ultrasound fatigue testing systems available nowadays are highly accurate: amplitudes can be measured up to ±1% by using an inductive coil assembly and a control unit; on-line data recording verifies the data. The accuracy is constant over a large range of ultrasonic power (from 5 to 500 W), which becomes important when wanting to measure cyclic hardening or softening, as this requires power variations during the testing procedure. The frequencies are also recorded and can be controlled to ±0.005% (1 Hz). Figure 2.4b illustrates the electronic control system of ultrasonic fatigue equipment. Accurate controlling of the frequencies is required firstly to maintain the resonance and secondly as crack detection method, since the growth of a crack can cause changes in the resonance frequency. [2]

Commercially available ultrasonic fatigue machines such as Shimadzu USF-2000A [5] and 3R MEG20 [6], shown in Figure 2.5, implement fatigue testing at 20 kHz and perform testing at 10^9 and 10^{10} cycles. They possess built-in generators that operate at 20kHz and can also control stress amplitude from a PC-operated controller.

Figure 2.5 - Commercially available UFT machines (left - Shimadzu USF200; right – 3R MEG20) [5] [6]

In [7], an ultrasonic fatigue testing machine was developed in order to perform fatigue tests. The ultrasonic part of the machine is a “classical” setup composed of a piezoelectric converter powered by an ultrasonic generator and cooled by compressed air. A horn is used to mechanically amplify the ultrasonic wave generated by the piezoelectric converter. This machine, shown in Figure 2.6, is connected to a mechanical system in order to apply a quasi-static load to hold the crack open during imaging. The horn vibration node is set on top of the static loading system, which is composed of a worm wheel driven by a stepper motor able to produce 1 kN load with ±1 N accuracy. The machine can control the displacement and the force imposed to the specimen is monitored by a load sensor. In the experiments reported in this article, the static load used to open the internal cracks during imaging was 80% of the maximum stress applied under cyclic loading at 20 kHz. The specimen stays at the same place for imaging under static load and cycling: a crucial issue for analyzing the series of 3D images which do not need to be realigned.

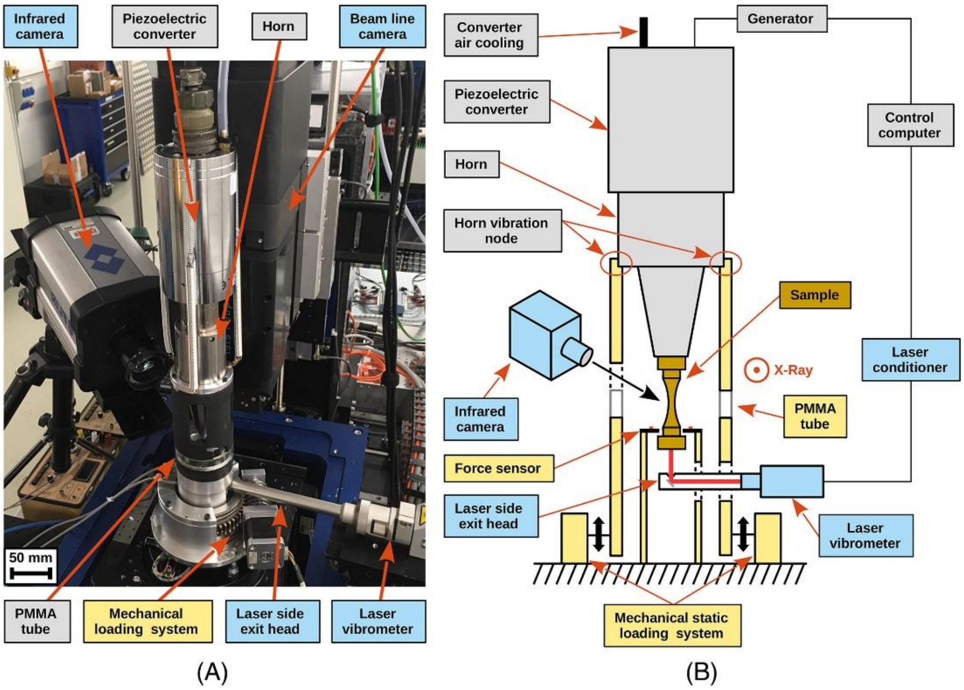


Figure 2.6 – Picture(a) and scheme(b) of an ultrasonic testing machine [7]

The advantages of UFT, associated with the improvements in piezoelectric devices, made these fatigue testing methods an attractive technique to establish S-N curves in VHCF. Presently, with the development of new sensors, new computational methods, and faster and more efficient control systems, VHCF gained increasing popularity as many of the challenges in the past could be addressed from incorporating technological innovation. [4]

The UFT machine does not require both ends of the specimen to be attached as the 'conventional' machine requires. UFT specimens are designed to have a particular mode shape vibrating at a given frequency: the operating frequency of the machine, usually 20 kHz. [4]

The resonant system is composed by a piezoelectric actuator, a booster, a horn, and the specimen sequentially assembled in series by screw connections. These four elements form the resonant system of the testing machine as shown in Figure 2.7. The mechanical vibration generated by the piezoelectric actuator is meant to reproduce a pure sine wave with a frequency of 20 ± 0.5 kHz. This wave is transmitted from element to element down to the bottom of the specimen with displacement and stresses. The principle of operation of the vibration system is based on free vibration resulting in a minimum of force contact between the elements. The booster and horn (typically, a conical sonotrode) are also used to amplify the amplitude of the vibrations transmitted to the test specimen. [4]

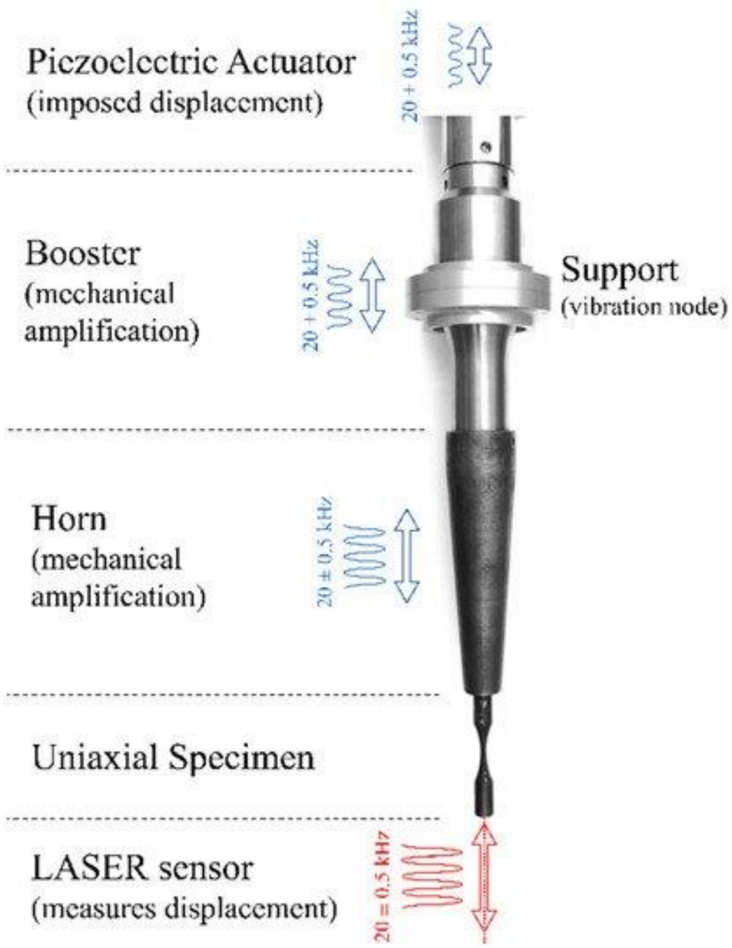


Figure 2.7 - UFT machine resonant system components of one of the machines at Instituto Superior Técnico, University of Lisbon [4]

Besides the resonant system just described, UFT machines should also include:

- A measurement system which can be made of various instrumentation devices from strain gauges, laser doppler vibrometers, thermocouples, infrared cameras, and other data-gathering transducers. Here, different configurations can be found due to resource limitations (usually budget related) or the differences in the objectives of the experiments being conducted; [4]
- A control or safeguarding system which monitors and maintains suitable conditions for the experiment through the implementation of a feedback control loop system, for example. This system is usually responsible for avoiding the overheating of the test specimen, which is one of the greatest problems in UFT. [4]

2.3 Data acquisition systems in UFT machines

When designing an ultrasonic fatigue testing machine, the data acquisition system must be able to monitor and control parameters like temperature, stress level, frequency, and power output.

In [8], an in-house custom-made package was developed under LabVIEW® from National Instruments (NI) for online monitoring and control of the VHCF machine. Communication between the peripherals and the software is done using a multifunction data acquisition (DAQ) device from NI (NI USB-6216). The NI USB-6216 is a multiplexed 16-bit DAQ with a maximum analog input sampling frequency of 400kS/s. It can measure up to 16 analog signals at a time and has 32 digital TTL inputs and outputs. This interface allows setting up the initial testing frequency and initial power delivered to the piezoelectric actuator, based on a pre-determined value for the axial stress. It also indicates and logs the specimen's temperature, displacement, frequency, power delivered to the piezoelectric exciter and number of cycles until fracture. Furthermore, it includes an algorithm to estimate and monitor the damping ratio evolution during the whole test. When the fatigue test is finished, a summary with the monitoring history is shown on the computer screen and stored into a spreadsheet file.

This package includes three main displays:

- Primary Setup menu (Figure 2.8) – The measurement channels and acquisition settings are set up in this menu, namely the sampling frequency and the time duration of an acquisition block. These settings are related to the nature of the continuous acquisition process in LabVIEW. One run is composed by a finite number of time signal blocks. Each block is then "averaged" to extract amplitude and frequency. Long blocks may produce inaccurate results due to the rapid change in both temperature and frequency, whereas short blocks may produce instability due to the need of faster processing capabilities. The Primary Setup also offers the possibility of setting the displacement value at the tip of the specimen. During measurement, a closed-loop feedback system adjusts the exciter's power so that the average displacement per block is constant; [8]

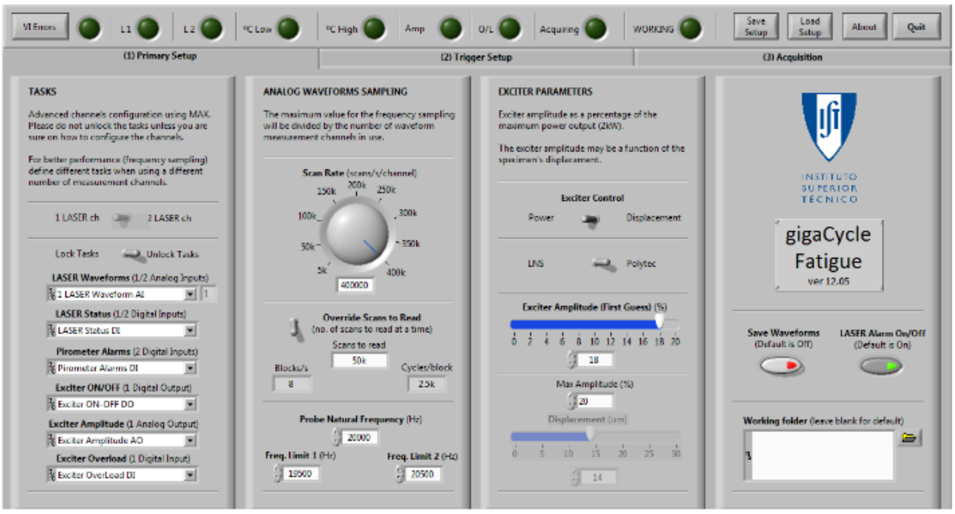


Figure 2.8 - LabVIEW software's primary setup [8]

- Trigger Setup menu (Figure 2.9) – The trigger setup offers the possibility to test the performance of the configuration set on the primary setup. This interface is also used to determine delays in the exciter that are very hard to predict otherwise. Once the primary settings are set and the triggers have been determined, there is no need to run the trigger setup again; [8]

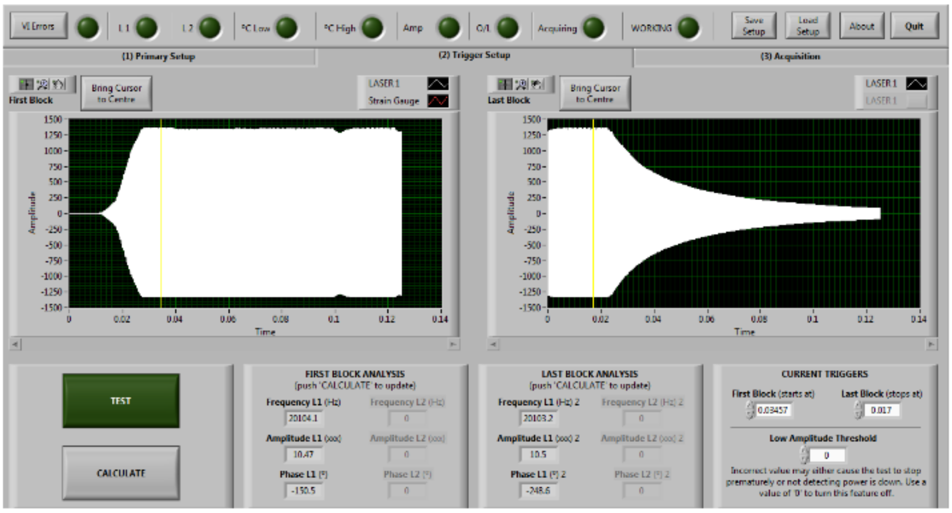


Figure 2.9 - LabVIEW software’s trigger setup [8]

- Acquisition display (Figure 2.10) – The acquisition display shows the current time signal block and the history for a single run. It plots the frequency evolution per block, the average displacement per block and the logarithmic decrement in the last block. The last block is a transient response time signal of the resonant system at free vibration, giving information on the damping factor. [8]

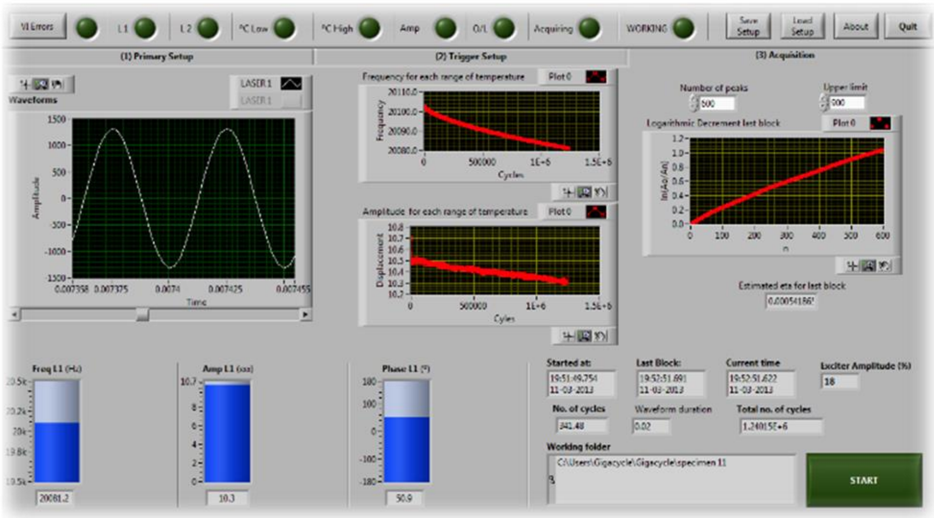


Figure 2.10 - LabVIEW’s software’s acquisition display [8]

When performing an ultrasonic fatigue test without any type of feedback control, the piezoelectric system delivers a constant power output continuously. Temperatures may increase to very high levels and, in some materials, values greater than 300 ºC have been registered. The increase in temperature has a strong effect on the frequency, the displacement amplitude and, thus, on the stress amplitudes being generated. In order to keep displacement and stress as steady as possible, two control algorithms based on the measured test parameters were implemented. These algorithms are integrated in the LabVIEW package and are based on temperature control and amplitude control. Both controls can operate together or independently. [8]

In basic test setup the power provided to the piezoelectric actuator is set and there is no feedback-loop control. The fatigue test starts and runs continuously, without interruption, at 20 kHz. The signals from the laser and pyrometer are acquired and stored in order to monitor the specimen. The displacement amplitude per measurement period of time (block) is the average of the values measured at steady state. Because the test runs continuously, the temperature will eventually rise to a value outside an acceptable range. [8]

In temperature control the fatigue test runs as long as temperature is kept within a preset interval ΔT. Temperature is continuously monitored while the test is in progress, while at the same time amplitude, frequency and power are measured and stored. When temperature reaches the upper limit, the test is interrupted. The specimen cools down until temperature reaches the lower preset value and is restarted. This process is illustrated in the "saw tooth" plot in Figure 2.11. Temperature control contributes to the stability of the vibration amplitude during test but it does not eliminate it completely. [8]

With amplitude control activated, the displacement is monitored at the free end of the specimen during each period of time (block). The piezoelectric actuator's power is continuously readjusted between blocks to keep the vibration amplitude at a constant pre-established value. [8]

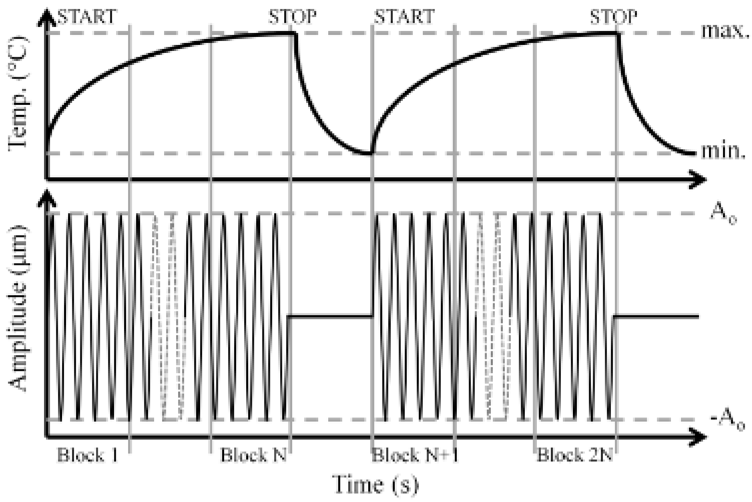


Figure 2.11 - Illustration of record signal with amplitude/temperature control [8]

3 Measuring system

In this chapter, the characteristics of the physical components used to capture the data necessary to carry out the monitoring and control system interface will be described, and it will be explained how they will be integrated to form the physical control and measuring system.

3.1 Physical system of the ultrasonic fatigue testing machine

The system used is composed by an ultrasonic 20 kHz generator controlled by a PC to generate the electrical signal that excites the piezoelectric transducer, which will transform this signal into a mechanical movement that will excite the specimen to test (after this mechanical movement passes the horn and booster present in the machine until reaching the specimen).

A load cell will be used to measure the force present in the specimen during the pre-loading of the specimen. During the testing, a pyrometer will be used to measure the temperature of the specimen. If the temperature exceeds a given value, the procedure is stopped. There will be an inductive probe that measures the displacement at the end of the specimen and strain gauges to measure its strain. During the testing, air cools the specimen.

A pressure switch will be used to measure the air pressure. If it goes below a set value, the testing procedure stops, and a solenoid valve is actuated that cuts off the air supply to the system. This will also happen if the testing procedure fails. When the testing procedure ends, the air supply is cut, so that compressed air isn’t wasted when the test ends without surveillance (e.g., the test ends during nighttime). Pneumatic unions will be used to manage the pneumatic circuit and a pressure regulator will be used for the pneumatic supply of the transducer.

Two buttons will be used for turning the solenoid valve on and off and as a machine emergency stop respectively. A 24 V DC power supply will power some of these components.

A data acquisition system will be used to measure the required physical quantities and an Arduino Uno board will do the logical relations needed for the control of the machine.

A scheme of the projected system, with the physical units that need to be measured is shown in Figure 3.1.

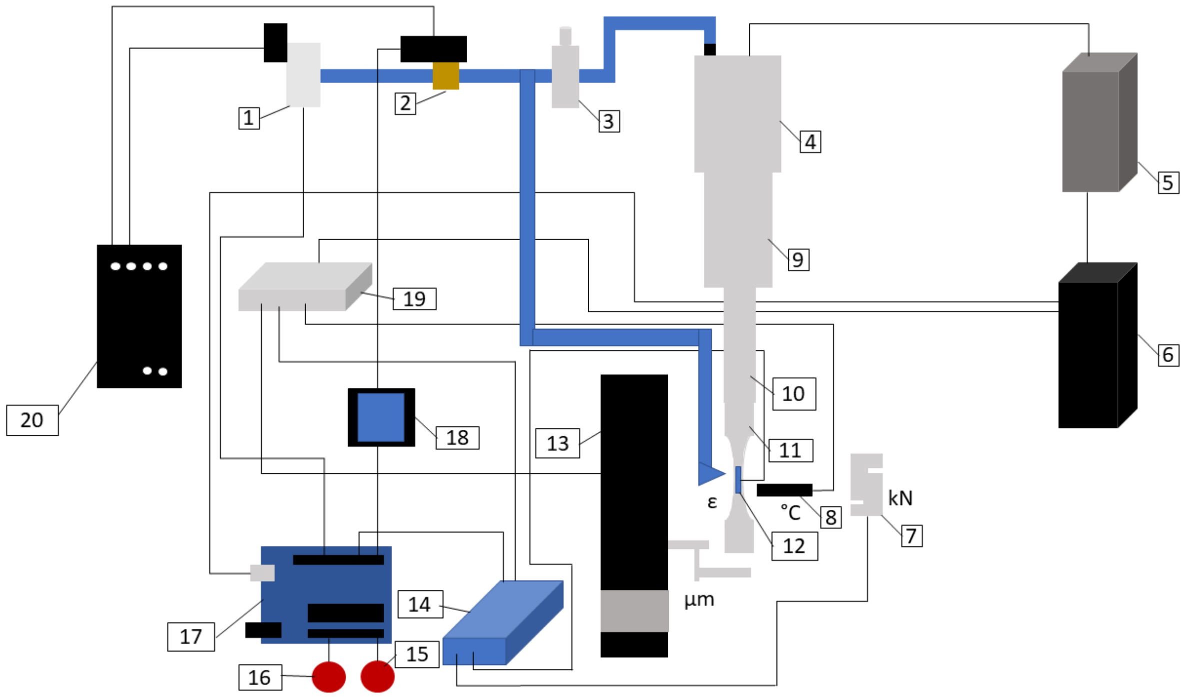


Figure 3.1 - Physical assembly of the components used in the project (1 – pressure switch; 2 – solenoid valve; 3 – pressure regulator; 4 – transducer; 5 – generator; 6 – computer; 7 – load cell; 8 – pyrometer; 9 – booster; 10 – horn; 11 – testing specimen; 12 – strain gauge; 13 – proximity sensor; 14 – amplifier; 15 – emergency button; 16 – bistable button; 17 – Arduino Uno; 18 – relay; 19 – DAQ; 20 – power supply)

3.2 Ultrasonic generator

The generator used to power the piezoelectric transducer is the MPI2000 Ultrasonic Sonorod Generator developed by Mastersonic, shown in Figure 3.2. It has 2 kW power, generates frequencies around 20 kHz and connects to a piezoelectric transducer through an HF output connector to generate the mechanical excitation on the specimen (after it passes through a horn and a booster). The MPI2000 also has an RS-485 output which connects to a PC by a RS-485/USB converter. It also possesses a 25-pin DSUB interface socket to read or input signals referring to the generator's operation. This socket is of optional use, and it is not necessary to use it for the generator to work. The ultrasonic generator gets its power supply (210-250VAC/50-80Hz) via a connection cable with power socket.

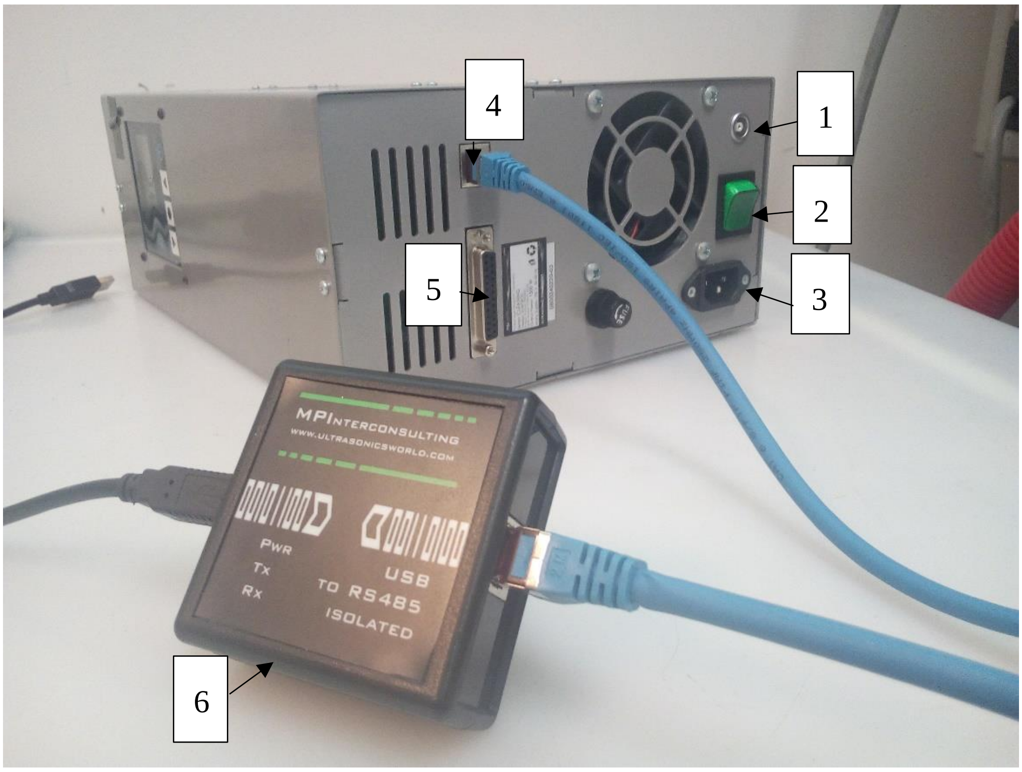


Figure 3.2 – Mastersonic MPI2000 Ultrasonic Sonorod Generator (1 – HF output connector; 2 – ON/OFF button; 3 – power connector; 4 – RS-485 connector; 5 – DSUB socket; 6 – RS-485/USB converter)

The generator has a front panel, shown in Figure 3.3, that allows to start the generator once it has been turned on and to select/change its parameters. Error messages are also shown here. The bicolor LED is blue if the generator is switched on and works properly and red in the event of an error.

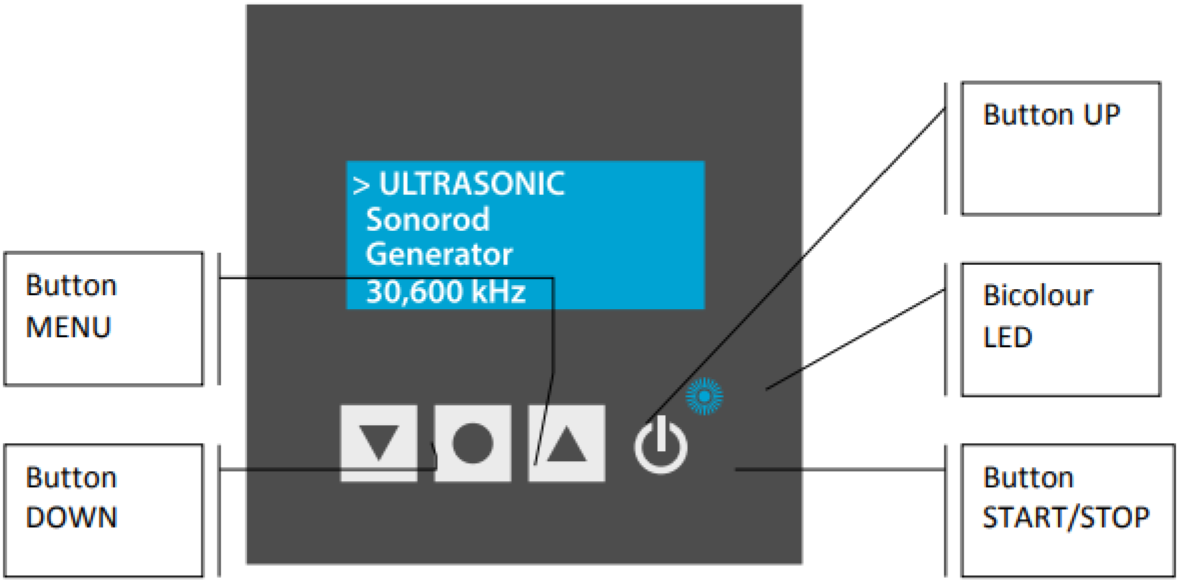


Figure 3.3 - Front panel of the generator

The generator is operated through a software program developed by the manufacturer in LabVIEW. It has 8 tabs to set different parameters of the generator.

The first one is the COMM tab, shown in Figure 3.4. For the generator to communicate with the software, the port where the RS-485/USB converter connects to the PC needs to be set. Then, by using the “Scanning for Generators” button, the Modbus address of the generator will be found. After this, a new baud rate and Modbus address of the generator can be set. It is necessary to confirm these 2 parameters in the “Network settings window”.

Figure 3.4 - COMM tab of the generator software

The second tab is the CONTROL tab, shown in Figure 3.5. From here, the general settings of the generator can be applied. In this tab the start frequency, the output power of the generator, the frequency span around the starting frequency where the generator will seek the working frequency of the transducer, the maximum current allowed over the transducer and the time the generator will be turned on (in continuous operation) can be set. If the time parameter is set to 0, there is no time limit for the operation of the generator, and it has to be turned off manually. In this tab, other parameters of the generator such as the version of the software, the change in the starting frequency caused by the generator’s frequency regulator, the transducer’s working frequency, the value of the analog power set point of the 25-pin connector, the output root mean square (RMS) current and voltage that pass through the transducer, the PWM ratio over the gates of the power transistors in the generator, the actual output power and working phase are shown. On top of that, error messages are also shown.

By pressing the RESCAN button, the settings and parameters of the generator will be uploaded into the software. By pressing the WRITE button, the parameters set in the software will be written in the generator’s memory. It is also possible to write and read these parameters from a text file using two buttons on the bottom of this tab.

The values used for the initial settings of these parameters are 21.5 kHz for the start frequency, 2 kW for the power set point, 2 kHz for the frequency span and 1 A for the maximum current. Since the generator won’t be used in continuous operation mode, the time parameter won’t influence its operation in this project. After this, the values for the maximum current can be changed between 0.8-1.2 A if it is necessary to have more or less power in the transducer.

Figure 3.5 - CONTROL tab of the generator software

The third tab is the SCAN tab, shown in Figure 3.6. Here, the operating parameters of the transducer can be taken. In this tab, an active operating area of transducers is shown. By pressing the SCAN button, a scanning procedure on low power is started that indicates the phase characteristic (red line) and the consumed output current (white line). After this, the frequency start can be selected by dragging the yellow cursor to the area where the red line starts to grow 400 Hz, which corresponds to a value close to the working frequency of the transducer. The value of the selected frequency is shown in a box on the left side of this tab and on the right side of the CONTROL tab. Here, the “frequency” and the “cursor frequency from scan tab” boxes should have the same value. This tab also has a slider to set the scanning phase at startup. A recommended setting for this is around 1000 units. After starting the generator, it scans and finds the load by reaching the Scanning Phase at Startup value. This means the load is found and after that the regulating of the set power and set current is possible.

After using the SCAN tab, the values of the start frequency and the frequency span in the CONTROL tab should be changed depending on the values of this tab’s graphic. It is expected that the start frequency of the transducer is somewhere around 20 kHz, and a recommended span frequency value is 0.5 kHz.

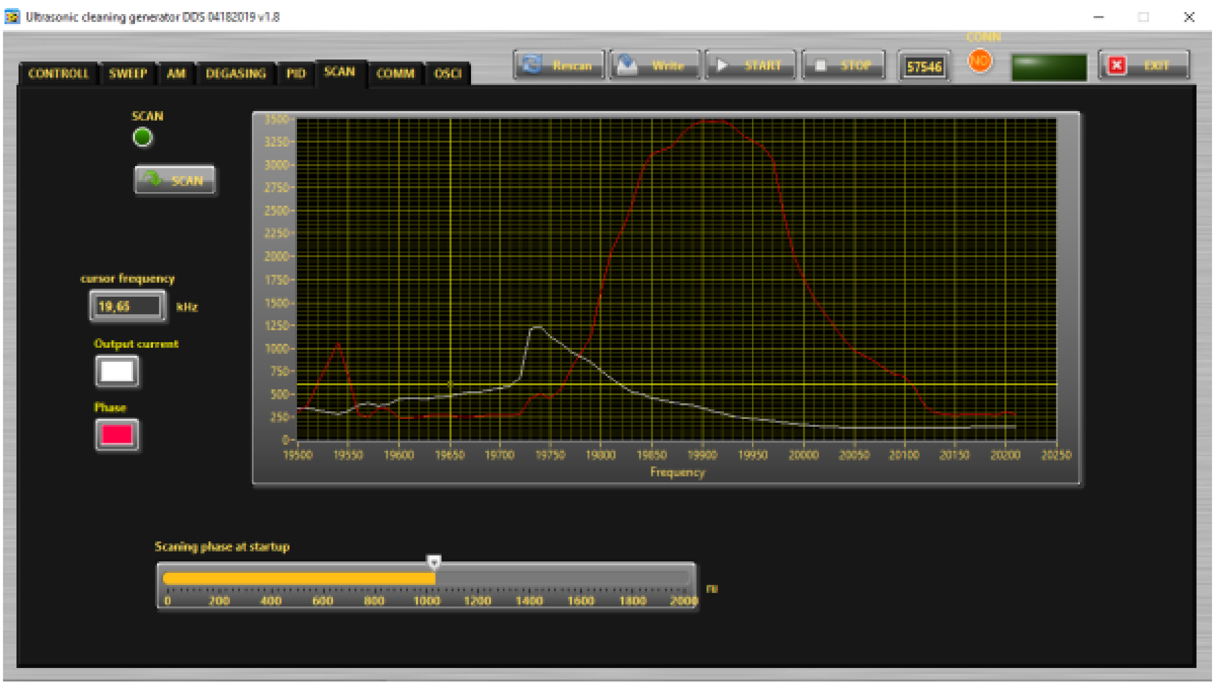


Figure 3.6 - SCAN tab of the generator software

The other tabs and their functionalities are:

- PID tab – in this tab, shown in Figure 3.7, some more parameters related to the phase of the generator can be set. They are:
    - Phase Protection Set Point – If everything is normal and the transducer functions properly, the operating phase will be 2000-2500 units. If the transducer is working on air (no load) the phase will increase to 3000 units and higher. This is a limit used as a protection against "No load operation" to save the transducer. 3000-3500 units is a recommended value for this setting.
    - Filter Depth – During the operating process, some small fluctuations of the phase signal are possible. With Filter Depth, it can be set how fast the phase protection reacts. Recommended values for this setting are 5 or 6.
    - Regulator voltage – This is the Ki of the output voltage regulator (amplitude). Recommended values for this setting are 5 V when there is no load and 10 V (eventually up to 15 V) when the transducer is connected to a load.
    - MIN Power – This is the minimum allowed power of operation of the transducer. This is a protection from low load or no load operation. It can also be a "low level liquid in the tank" protection. A recommended value for this setting is 0.2 kW.
    - Output Voltage – the maximum output voltage (in VRMS). The recommended value for this setting is 200-400 V.
    - DC Power Scale Factor – this scale relates to the power set point in the CONTROL tab. It should be adjusted depending on how much power the transducer needs. The recommended value for this setting is 1.

The phase graphic on the right side of this tab should be similar to a squared wave when the generator is operating.

Figure 3.7 - PID tab of the generator software

- AM (Amplitude Modulation) Tab – in this tab, shown in Figure 3.8, the amplitude of the signal sent by the generator can be modified.
  - Amplitude modulation frequency MAX – the maximum value of the frequency of the amplitude modulation. The biggest value is about 50 Hz.
  - Modulation Depth – the depth of the amplitude modulation.
  - Amplitude modulation frequency MIN – the maximum value of the frequency of the amplitude modulation.
  - Sweep speed – the speed of changing from Amplitude modulation frequency MIN to Amplitude modulation frequency MAX.

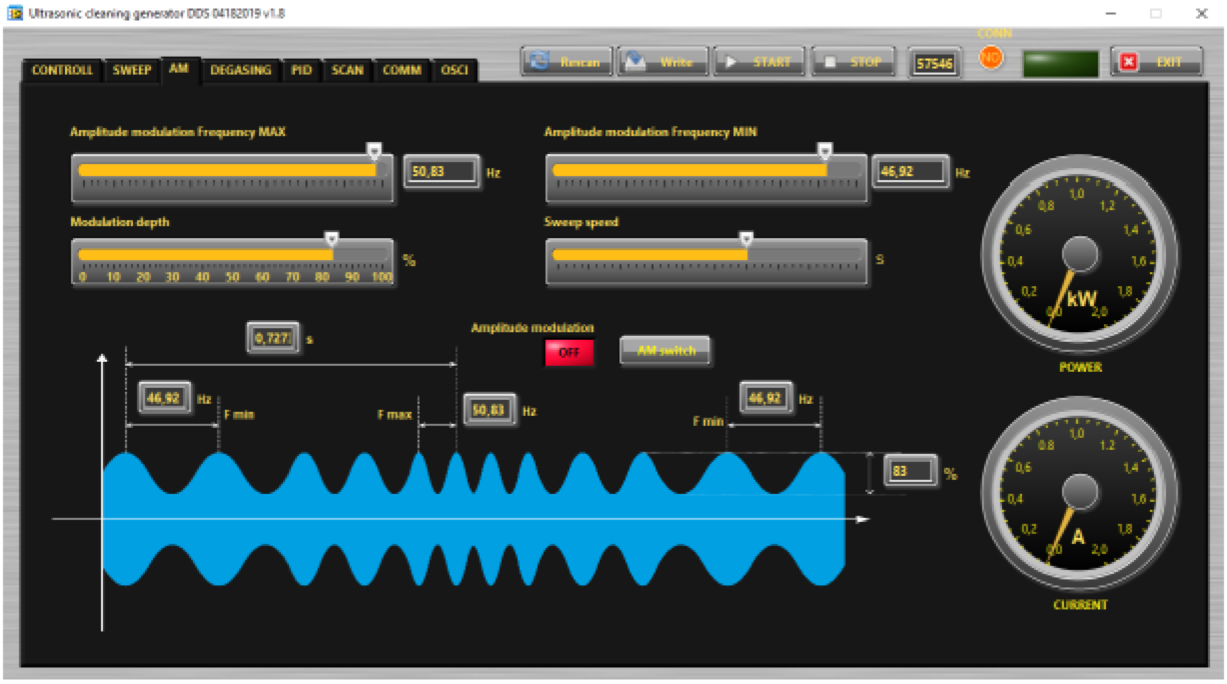


Figure 3.8 - AM tab of the generator software

- SWEEP tab – in this tab, shown in Figure 3.9, some parameters related to the signal generated can be set.
  - Sweeping depth– This is the deviation of the sweeping frequency around the central operation frequency in Hz.
  - Sweeping frequency – The desired sweeping frequency in Hz can be set here.
  - Smoothing – This changes the shape of the sweeping frequency from rectangular to similar to sinusoidal.
  - Sweeping Type – in three possible modes: OFF – no sweeping; AMMM – semi-random sweeping; Periodic – periodic sweeping.

Figure 3.9 - SWEEP tab of the generator software

- DEGASING tab – in this tab, shown in Figure 3.10, the generator can be set to operate intermittently, which will be the used mode in this project.
  - Time ON – Sets the operation time of the generator in degassing regime.
  - Time OFF – Set the non-operation time of the generator in degassing regime.
  - Degassing time – This is the total time the generator operates in this mode.

Figure 3.10 - DEGASING tab of the generator software

- OSCI tab – in this tab, shown in Figure 3.11 the frequency, output current, phase, amplitude, power and PWM can be measured and displayed in a graphical format.
  - Startup – This is the speed of shifting down the operating frequency until reaching Scanning Phase at Startup value. The recommended value is 25-30.
  - Regulator Current – This sets the Ki (amplitude) of the current/power regulator. The recommended value is 250.

Figure 3.11 - OSCI tab of the generator software

3.3 Piezoelectric ultrasonic transducer

A piezoelectric ultrasonic transducer is a device that works on the principle of the converse piezoelectric effect, which converts a mechanical excitation into an electrical signal or vice versa. In this effect, when a voltage is applied to a piezoelectric material, it undergoes physical deformations proportional to applied charge.

The piezoelectric transducer shown in Figure 3.12 will be used to convert the electrical signal that is output by the generator into a mechanical excitation that will connect into the horn and booster, and in turn, into the specimen being tested. It operates at around 20 kHz and connects mechanically with the specimen to transmit the vibration and to the generator through an HF cable to receive the electrical excitation. It includes a 6 mm diameter pneumatic connection so that compressed air can cool the transducer when it operates. It operates at a maximum current of 2 A and a maximum voltage of 1000 V.

Figure 3.12 - Piezoelectric ultrasonic transducer used

3.4 Pyrometers

Depending on its temperature, each object emits a certain amount of infrared radiation. A change in the temperature of the object is accompanied by a change in the intensity of the radiation. For the measurement of "thermal radiation" infrared thermometry uses a wavelength ranging between 1 µm and 20 µm. The intensity of the emitted radiation depends on the material and its emissivity which is known for most materials.

Infrared thermometers are optoelectronic sensors. They calculate the surface temperature based on the emitted infrared radiation from an object. The most important feature of infrared thermometers is that they enable to measure the temperature of objects contactless. Consequently, these devices help to measure the temperature of inaccessible or moving objects without difficulties. Infrared thermometers basically consist of the following components:

- lens
- spectral filter
- detector
- electronics (amplifier/ linearization/ signal processing)

The specifications of the lens determine the optical path of the infrared thermometer, which is characterized by the ratio Distance to Spot size. The detector in cooperation with the processing electronics transforms the emitted infrared radiation into electrical signals.

To measure the temperature of the specimen throughout the testing, the CS LT Infrared Thermometer by Optris is used. It can be set to output a voltage of 0-10 V or 0-5 V and be used as an analog device (type-k thermocouple or direct mV output) or connect directly to PC by a USB connection. Its temperature range is -50 to 1030 °C, its spectral range is 8-14 µm, its optical ratio is 15:1, its accuracy is ±1.5 °C or ±1.5 % of reading (whichever is greater), its repeatability is ±0.75 °C or ±0.75 % of reading (whichever is greater), its temperature coefficient is ±0.05 K/ K or ±0.05 %/ K (whichever is greater) and its temperature resolution is 50 mK. Its response time is 14 ms and its warm-up time is 10 minutes.

It was set to output a voltage ranging from 0-5 V, corresponding to a temperature from 0-500 ºC. It is connected to a power supply according to the circuit presented in Figure 3.13, with a resistance of 10 kΩ.

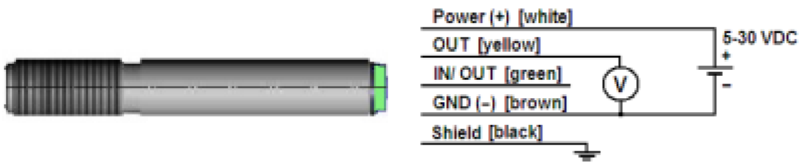


Figure 3.13 – Optris CS LT Infrared Thermometer electric connection to power supply

3.5 Proximity sensor

To measure the vibration displacement of the specimen, an inductive proximity sensor was used to measure the distance between the bottom tip of the specimen and itself. The sensor sends an output signal between 0-10 V that can be measured through a DAQ. However, the distance corresponding to the output voltage depends on the material that is being tested. As such, it is necessary to manually measure the distance that a certain voltage represents at least twice by using a micrometer present on the sensor, so that a distance-voltage curve can be generated and the relation between them measured.

The sensor is shown in Figure 3.14, with focus on its micrometer.

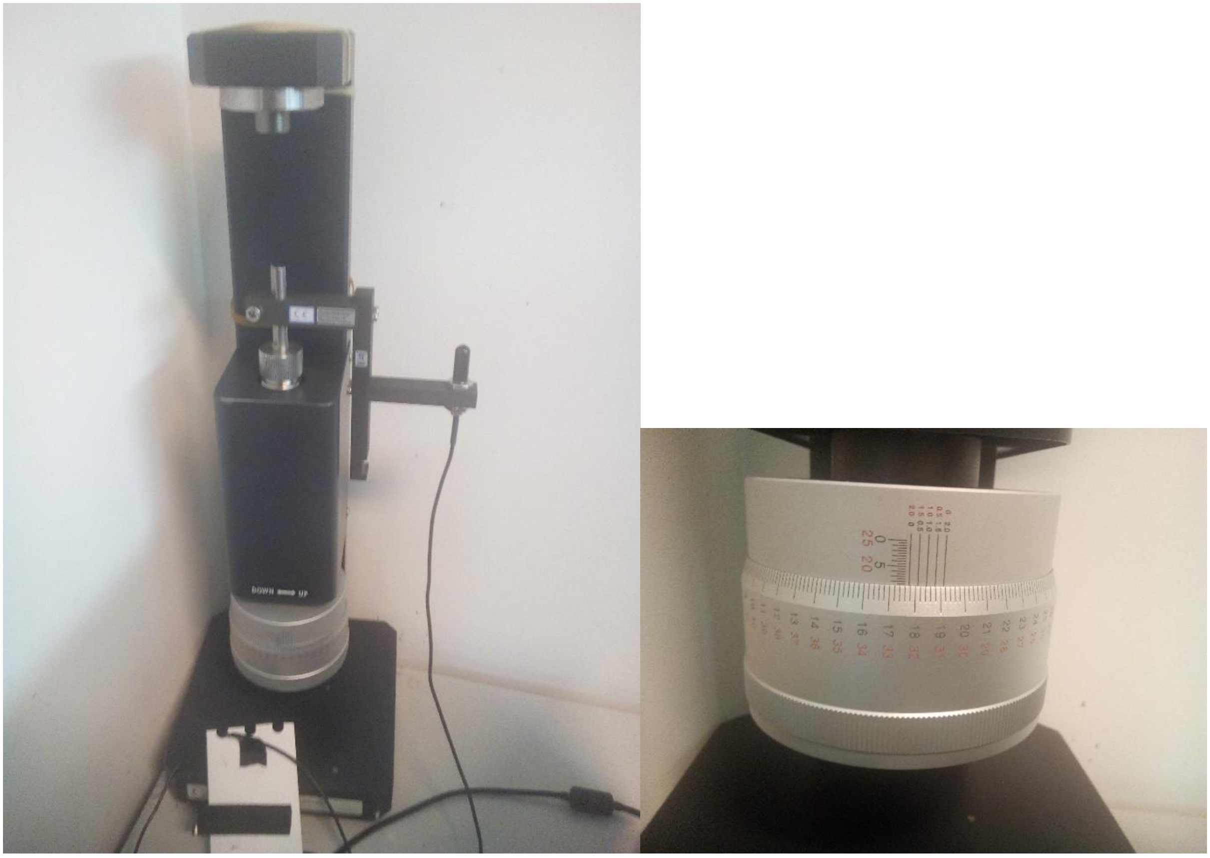


Figure 3.14 - Inductive proximity sensor used

3.6 Strain gauges

To measure the changes in length of the specimen being tested, 2 strain gauges are used in each test with a sensitivity of 10 mV/V and powered by a 5V supply. They are connected to the amplifier that converts the output to 0-5 V.

Following the amplifier’s instructions, a 6-wire half bridge is mounted. However, without the internal resistor and implementing the circuit outside it becomes a quarter bridge circuit with an external dummy strain gauge. There is a quarter bridge circuit with an external dummy strain gauge, where one strain gauge actively measures strain, and the other one is mounted to complete the circuit. This is shown on Figure 3.15; the dummy strain gauge allows to compensate the temperature effect, if necessary.

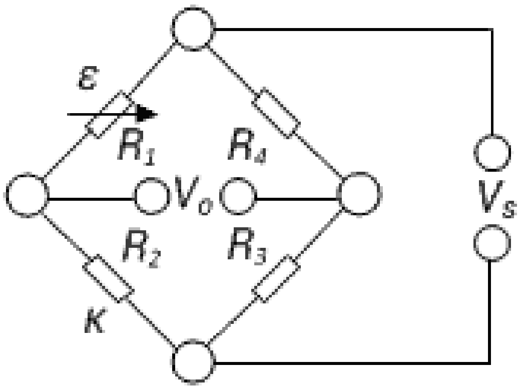


Figure 3.15 - Strain gauge (R_1) in a quarter bridge circuit with an external dummy strain gauge (R_2)

For acquisition of the voltage difference, an Elsys Strain Gauge Amplifier MK2, shown in Figure 3.16, was used alongside the Kistler DAQ system described in Section 1.13. The amplifier's defined gain (G_{amp}) is 10 and the strain gauges used in this project have gauge factors of either 1.90 or 1.93. The different values are due to differences in manufacturing lots.

Figure 3.16 - Elsys Strain Gauge Amplifier MK2

The gauge factor is given by Equation 3.1:

$$G_f = \frac{\Delta R_1/R_1}{\Delta L/L} = \frac{\Delta R_1/R_1}{\varepsilon} \tag{3.1}$$

Where:

G_f, is the gauge factor

R_1, is the resistance of the strain gauge

L, is the specimen length

ε, is the specimen strain

ΔR_1, is the variation of the resistance of the strain gauge

The output voltage is dependent on the supply voltage and since the resistors have the same resistance, Equation 3.2 shows that:

$$V_0 = \left(\frac{-\Delta R_1/R_1}{R_1 + \Delta R_1/R_1 + R_2 + R_3 + R_4}\right) * V_s \approx \left(\frac{-\Delta R_1/R_1}{4}\right) * V_s \tag{3.2}$$

Where:

V_0, is the output voltage

R_1 to R_4 are the resistances of the circuit

V_s, is the supply voltage

So, implementing the gauge factor and the gauge amplifier factor on Equation 3.2, the strain comes in Equations 3.3 and 3.4.

$$V_0 = -\frac{G_f \varepsilon}{4} G_{amp} V_s \tag{3.3}$$

$$\varepsilon = -\frac{4V_0/V_s}{G_f G_{amp}} \tag{3.4}$$

Where:

G_{amp} is the gauge amplifier factor

The stress is then obtained by multiplying the measured strain by the Young Modulus of the material.

3.7 Load cell

To measure the mechanical stress applied on the specimen, the RSCC tension load cell from HBM, shown in Figure 3.17 is used. It’s supplied by a 5 V power supply and its nominal sensitivity is 2 mV/V. The load cell measures forces from 0-5 kN. It is connected to the Elsys amplifier that converts the output to 0-5 V.

Figure 3.17 – HBM RSCC tension load cell

Similarly to the strain gauge, the load cell uses a Wheatstone bridge to output the voltage (V_0), with the difference being that in this case, it is a full bridge circuit. As such, the force equation is shown in Equations 3.5 and 3.6:

$$V_0 = \left(\frac{R_1}{R_1 + R_2} - \frac{R_3}{R_3 + R_4}\right) * G_{amp} * V_s \tag{3.5}$$

$$F = \frac{V_0}{V_s * G_{amp}} * 5000 \tag{3.6}$$

3.8 Pressure switch

To verify if the air pressure is above a minimum value in the pneumatic circuit, therefore detecting failures/lack of pressure in the pneumatic network, a pressure switch is required. The pressure switch chosen was a PEV-1/4-B from Festo, shown in Figure 3.18. This model was chosen because it has a normally open contact and a normally closed contact that are triggered when the air pressure inside the pneumatic circuit reaches a certain adjustable value (1-12 bar). It connects to a ¼ inch diameter pneumatic tube. It has a maximum switching output voltage of 125 V DC and a minimum load current of 1 mA at 24 V.

Figure 3.18 – Festo PEV-1/4-B pressure switch

3.9 Pneumatic solenoid valve

To close the pneumatic circuit and avoid the waste of compressed air when the test is forced to stop or finishes, a solenoid valve is used. The model used is the VZWD-L-M22C-M-G14-40-V-1P4-8 from Festo, shown in Figure 3.19. This valve is in-line, 2/2-way normally closed, returns to the original position by mechanical spring, connects to a ¼ inch diameter valve, it has a nominal width of 4 mm, operates at 24 V DC, can operate up to a pressure of 8 bar and a standard nominal flow rate of 310 L/min. It consumes 6.8 W of power, has a switching time on of 25 ms and switching time off of 10 ms.

This valve is used to let the air pass through it when it is actuated by the pressure switch and to close the pneumatic circuit when it isn't.

Figure 3.19 – Festo VZWD-L-M22C-M-G14-40-V-1P4-8 solenoid valve

3.10 Pressure regulator

A pressure regulator is used to regulate the pressure of the air that goes into the piezoelectric transducer. The model used is the MS4-LR-1/4-D6-AS-Z from Festo, shown in Figure 3.20. It connects to a ¼ inch diameter valve and can operate from 0.8 to 14 bar. It can regulate pressure from 0.3 to 7 bar using a rotating button with retention. It has a standard nominal flow rate of 1800 L/min.

Figure 3.20 – Festo MS4-LR-1/4-D6-AS-Z Pressure regulator

3.11 Buttons

To manually switch the solenoid valve and to emergency stop the testing, two 24 V DC buttons were used. The button that switches the solenoid valve is bistable and the emergency button is rotating. These buttons are shown in Figure 3.21a and 3.21b, respectively.

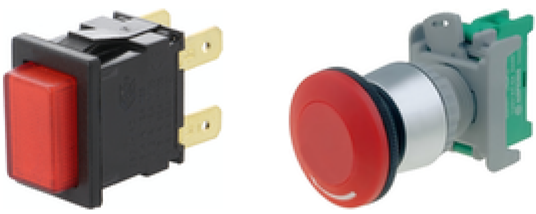


Figure 3.21 - Buttons used (a – bistable button; b – emergency button)

3.12 Power supply

The minimum required current of the power supply is calculated on Table 3.1.

Table 3.1 - Required current of the power supply

Component	Current
Pressure switch	1 mA
Solenoid valve	6.8W / 24V = 0.283A
Total	0.284 A

To supply the necessary power to the components that operate on a 24 V DC voltage, a 24 V DC 2.5 A (60 W nominal power) power supply from Schneider (model ABLM1A24025), shown in Figure 3.22, was used to convert the 230 V AC single-phase supply. A power supply with relatively high current was chosen to leave room for an eventual addition of more components to the project that need to be supplied by it.

Figure 3.22 - Schneider ABLM1A24025 power supply

3.13 Arduino

To acquire the inputs from the pressure switch and the buttons, to set the position of the solenoid valve, to establish the logical relations between these components and to record the voltage from the load cell, an Arduino Uno board, shown in Figure 3.23b, was used. It has 13 digital I/O pins, 6 analog pins and other pins for power, ground and other functions shown in the diagram present in Figure 3.23a.

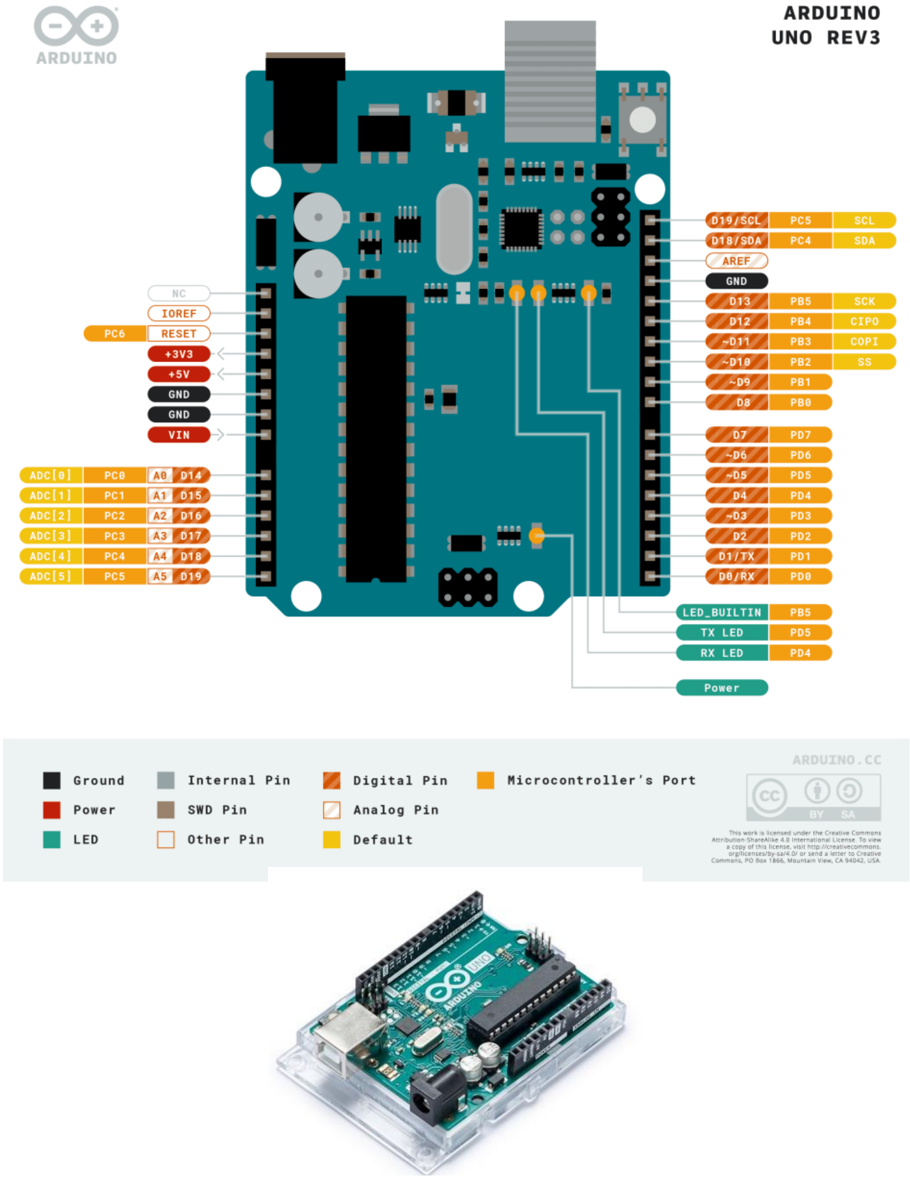


Figure 3.23 - Arduino Uno (a - pin assignment; b - real view)

The pressure switch and the button were connected as digital inputs, the relay shown in Figure 3.24 will control the solenoid valve, and the load cell is connected to an analog input. The Arduino Uno board is powered by a USB connection to the PC used to execute the LabVIEW program developed in this project (described in Chapter 4) to monitor the testing procedure.

Figure 3.24 - 5 to 24 V DC relay used

The relay, the buttons, the pressure switch and the load cell were connected to the Arduino Uno board according to the scheme presented in Figure 3.25.

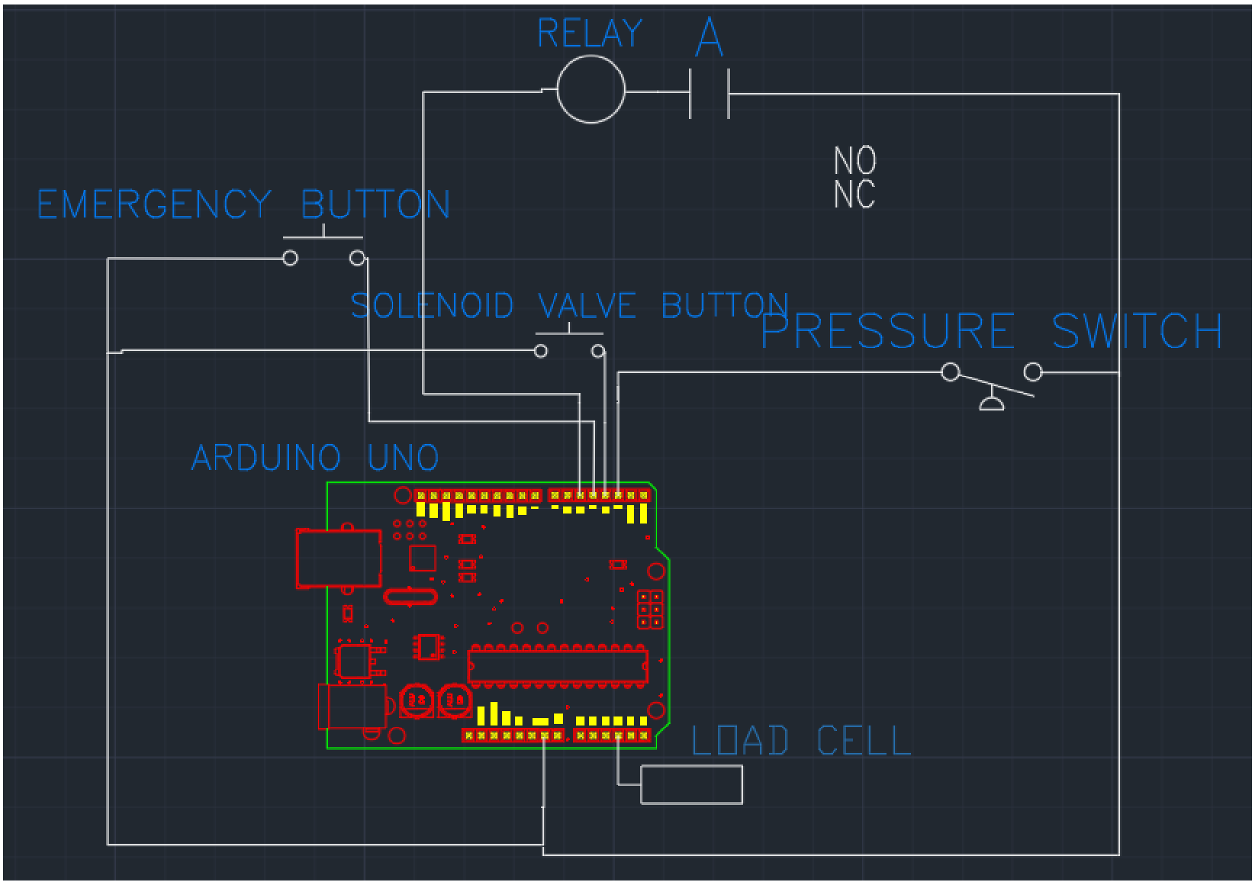


Figure 3.25 – Electrical connections of the components to the Arduino Uno

The pneumatic connections used in this system are shown in Figure 3.26.

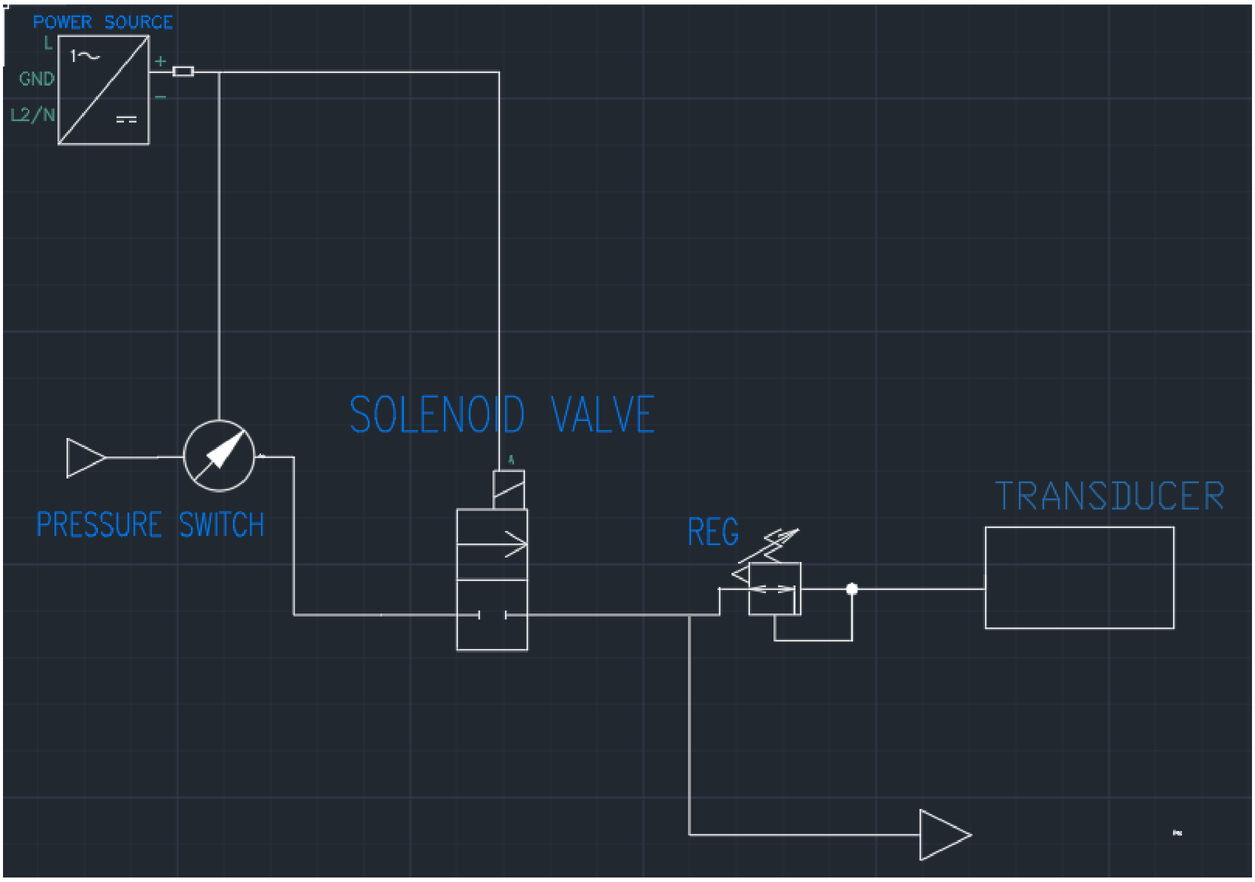


Figure 3.26 - Pneumatic scheme of the components used in the project

3.14 Data acquisition (DAQ) system

To record the outputs from the pyrometers, the proximity sensor, and the strain gauges, a DAQ system from Kistler (LabAmp 5165 A4), shown in Figure 3.27, was used. It has 4 inputs, 4 outputs (they will not be used in this project) and a 200 kHz sampling rate.

Figure 3.27 - Kistler LabAmp 5165 A4 DAQ

Kistler provides a software program for the operation of the DAQ in LabVIEW. The operation of this program will be described in Chapter 4.

3.15 Assembly of the components

The load cell and the strain gauge connect to the amplifier. The magnetic sensor, the pyrometers and the output from the amplifier that represents the strain gauge signal connect to the DAQ device. The output from the amplifier that represents the load cell signal, the pressure switch, the bistable button, and the emergency button connect to the Arduino. An output pin from the Arduino connects to a relay that connects to the solenoid valve. The DAQ device and the Arduino connect to the PC by a USB connection. The PC sends and receives signals from the ultrasonic generator through a USB/RS485 converter. The ultrasonic generator then sends an electric signal to the piezoelectric transducer by the use of an HF cable.

The components mentioned are assembled in a way that is summarized below and represented by the diagram shown in Figure 3.28.

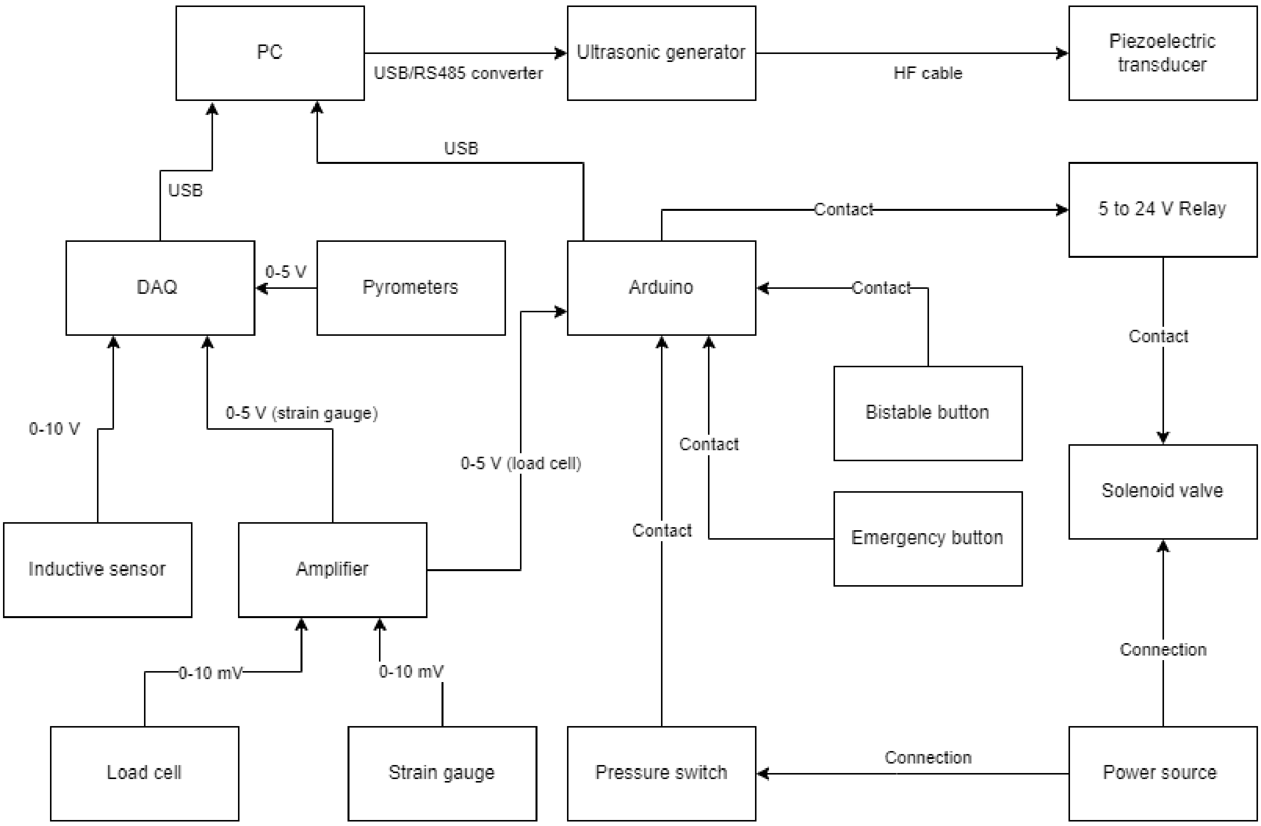


Figure 3.28 - Representation of the assembled components during the project

A list of the components used in this project is shown in Table 3.2.

Table 3.2 - List of the components used in the project

Part number	**Part name**	Part description	Quantity
1	Mastersonic MPI2000 Ultrasonic Sonorod Generator	Electric signal generator	1
2	Piezoelectric ultrasonic transducer	Conversion of the electric signal into a mechanical signal	1
3	Optris CS infrared thermometer	Temperature measurement	1
4	Inductive proximity sensor	Displacement measurement	1
5	Strain gauges	Strain measurement	1
6	HBM RSCC tension load cell	Force measurement	1
7	Festo PEV-1/4-B pressure switch	Pneumatic circuit pressure monitoring	1
8	Festo VZWD-L-M22C-M-G14-40-V-1P4-8 solenoid valve	Control of the air passage of the pneumatic circuit	1
9	Festo QS-10-6 pneumatic reducer	Reduction of the pneumatic wire from 10 mm to 6 mm	1
10	Festo QST-10 pneumatic T-union	Division of the pneumatic circuit in 2	1
11	Festo MS4-LR-1/4-D6-AS-Z pressure regulator	Regulation of the pressure of the air that enters the transducer	1
12	Bi-stable button	Control of the solenoid valve’s operation	1
13	Emergency button	Machine emergency stop	1
14	Schneider ABLM1A24025 power supply	Supply of electricity for the 24 V DC components	1
15	Arduino Uno board	Microcontroller	1
16	5 to 24 V DC relay for Arduino	Conversion of an Arduino output for the entrance of the solenoid valve	1
17	Kistler LabAmp 5165 A4 DAQ system	Acquisition of the necessary measurement voltages	1

4 LabVIEW program developed

In this chapter, the LabVIEW program developed for the ultrasonic testing machine will be explained and the coding and graphical interface developed will be shown.

4.1 Code developed

In LabVIEW, the code is written using blocks. In this section, the code that was developed to create this project will be explained and its interactions will be described.

4.1.1 Communication with DAQ

The first part of the program refers to the communication with the Kistler DAQ. Kistler provides an open-source application to operate the DAQ through LabVIEW. In the given code, the first part has a case selector with 10 cases, as shown in Figure 4.1. These 10 cases refer to the connection and disconnection of the DAQ, its start and stop operations, checking its status, gettting channel settings, setting and getting its parameters, closing of panels, events and exiting the program. For each, it has an associated code block that makes the program take the action corresponding to the case.

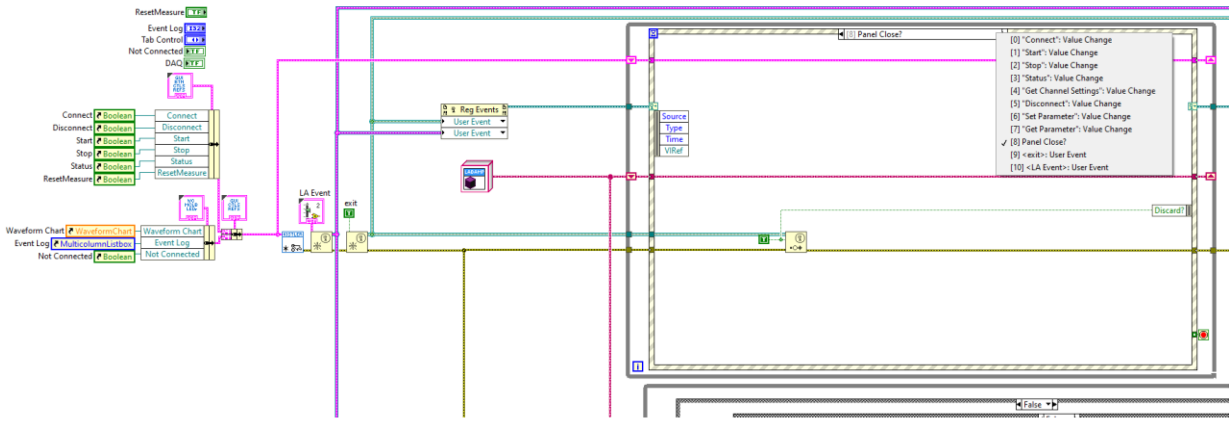


Figure 4.1 - First part of the Kistler DAQ code

The second part of the program is the data received by the inputs in the physical system, shown in Figure 4.2. The original program only displayed the data captured in a waveform chart. To better visualize that data, another block was added that converts the data into a .csv file.

After this, there were also other additions to the program. The data received is converted into a matrix, and after receiving information on which channel the signal from the pyrometer is connected to and taking into account only the latest received input, the program converts it into a single voltage reading. It is then converted from Volts into degrees Celsius according to the pyrometer's conversion factor and it is compared to an input maximum value. If that maximum value is surpassed, a display on the interface lights up and a global variable associated to it is turned on. This variable is used in a case selector inside the part of the program related to the Arduino.

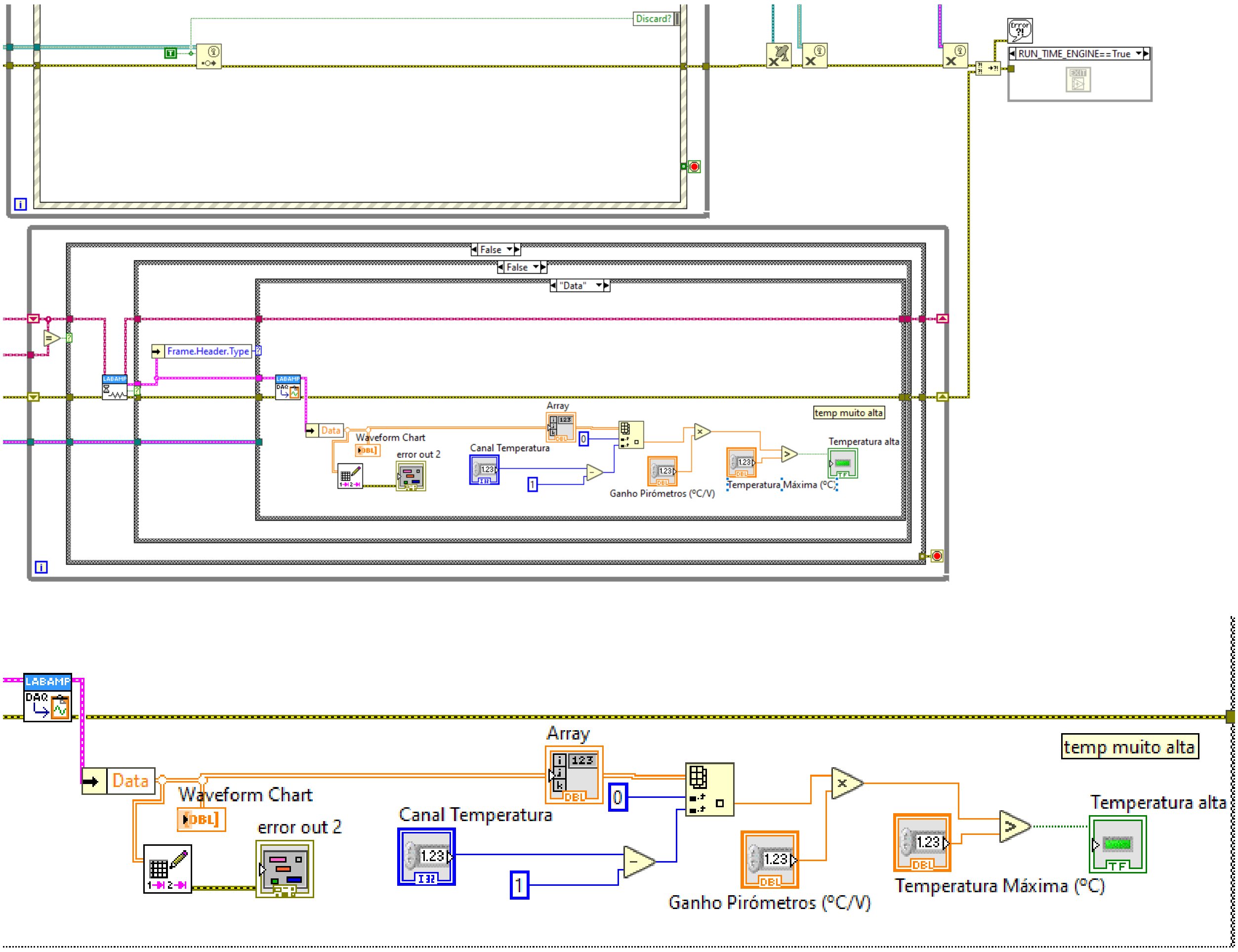


Figure 4.2 - Second part of the Kistler DAQ code (a - overall view; b - code altered during the development of the project)

4.1.2 Communication with Arduino

The next part of the program refers to the communication with the Arduino Uno. For this, the LabVIEW addon LINX was used.

First, it is necessary to go to the LINX Firmware Wizard window in LabVIEW (in the Tools tab) that is associated with this addon. In this window, the microcontroller device family (Arduino), the model (Uno), and the firmware upload method (Serial/USB) are selected. After that, the COM port of the PC associated to the USB cable that connects it to the Arduino needs to be selected. Finally, the firmware version (LINX – Serial/USB) and the upload type (Pre-Built Firmware) are chosen. After these steps, the installation is complete.

In the series of code blocks related to the Arduino board, the first block is associated with the initialization of the board itself. The variables that have to be input into it are the type of communication (Serial) and the COM port of the PC that is connected to the USB cable.

After the program is initialized, the first commands are to read the digital inputs from the bistable button and the pressure switch, associated to the digital pins 2 and 3 of the Arduino Uno board.

After this, there is a case selector block that executes 1 out of 2 series of blocks depending on the inputs mentioned above. When either of them is at a high value, the program executes the series of blocks corresponding to the “True” case. In this case, the digital output associated to pin 5 of the Arduino board is set to output a high value, which actuates the solenoid valve and lets the air pass through the pneumatic circuit. If neither of them is turned on, the program executes the series of blocks corresponding to the “False” case. In this case, the digital output associated to pin 5 of the Arduino board is set to output a low value, which deactivates the solenoid valve and doesn’t allow the air to pass through the pneumatic circuit. Besides this, there is also a block in the “False” case that sets a stop command to the generator as true. This command will be explained further in the subsection about the communication with the generator.

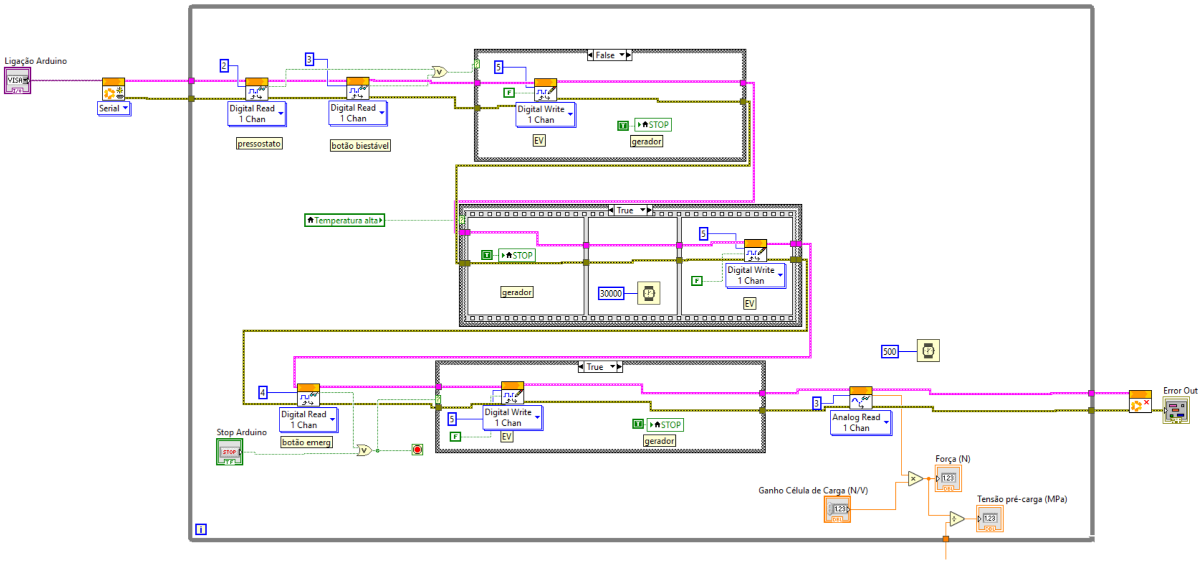
Next, there is another case selector, that depends on the status of the high temperature alert mentioned in the previous subsection. If the alert is turned on, a command is sent to the generator to stop and, after a 200 ms wait, the relay that connects to the solenoid valve is turned off through a digital output of the Arduino. If the alert is not triggered, there are no commands executed.

Then, there is a third case selector that executes a series of blocks depending on the digital input of the emergency button associated to digital pin 4 of the Arduino and a STOP button that was implemented on the program. If either of them is turned on, the program sends a command to the generator to stop and the relay that connects to the solenoid valve is turned off through a digital output of the Arduino. On top of that, these inputs will also cause the program to stop.

Finally, the program has a block that captures the input of the load cell associated with analog pin 3 of the Arduino board. After that, based on the scale factor of the load cell, the voltage of this input is converted to a force value in Newtons. This force is then converted to stress by dividing it by the section area of the test specimen.

All these blocks after the initialization block are contained in a loop that executes every 500 ms. After the loop, there is a block that closes the Arduino program.

This part of the code is shown in Figure 4.3.



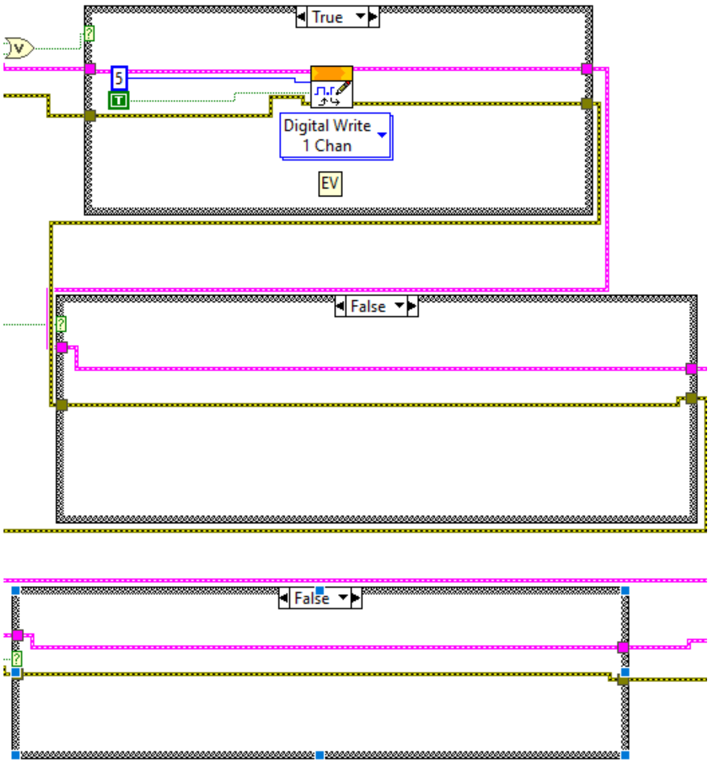


Figure 4.3 - Arduino Uno code (a - overall view; b - alternate cases)

4.1.3 Stress calculation during the testing

The third part of the program refers to the calculation of the mechanical stress on the specimen during the testing.

This calculation is done by using a *Formula Node* block, shown in Figure 4.4. The inputs used are the Young Module and the density of the material, the total length of the specimen, the length of the L2 section of the specimen (the section with the biggest radius), the R1 and R2 diameters of the specimen (at the thinnest and widest regions of it, respectively) and the specimen's displacement, which changes with time. The outputs given by the block are the L1 length of the specimen (the section with the smallest radius) and the mechanical stress of the specimen at its center. The equations used in this block are the ones shown from Equation 4.1 to 4.7:

$$c = \sqrt{\frac{E}{\rho}} \tag{4.1}$$

$$\omega = \pi * \frac{c}{l} \tag{4.2}$$

$$k = \frac{\omega}{c} \tag{4.3}$$

$$\alpha = \frac{1}{L_2} * \cosh^{-1}\left(\frac{R_2}{R_1}\right) \tag{4.4}$$

$$\beta = \sqrt{\alpha^2 - k^2} \tag{4.5}$$

$$L_1 = \frac{1}{k} * \tan^{-1}\left(\frac{1}{k} * (\beta * \coth(\beta * L_2) - \alpha * \tanh(\alpha * L_2))\right) \tag{4.6}$$

$$\sigma = \beta * E * A_0 * \cos(k * L_1) * \coth(\alpha * L_2) \tag{4.7}$$

Where:

E, is the Young Module of the material

P, is the density of the material

c, is the velocity of the wave propagation

ω, is the angular frequency

l, is the total length of the specimen

k, is the wavenumber

α, is a variable to adjust the hyperbolic cosine for the specimen

L_2, is the length of the section with the biggest radius of the specimen

R_1, is the diameter of the specimen at its thinnest region

R_2, is the diameter of the specimen at its widest region

β, is a variable to facilitate the integration of the displacement second order differential equation

L_1, is the length of the section with the smallest radius of the specimen

σ, is the stress of the specimen during the testing

A_0, is the specimen's displacement

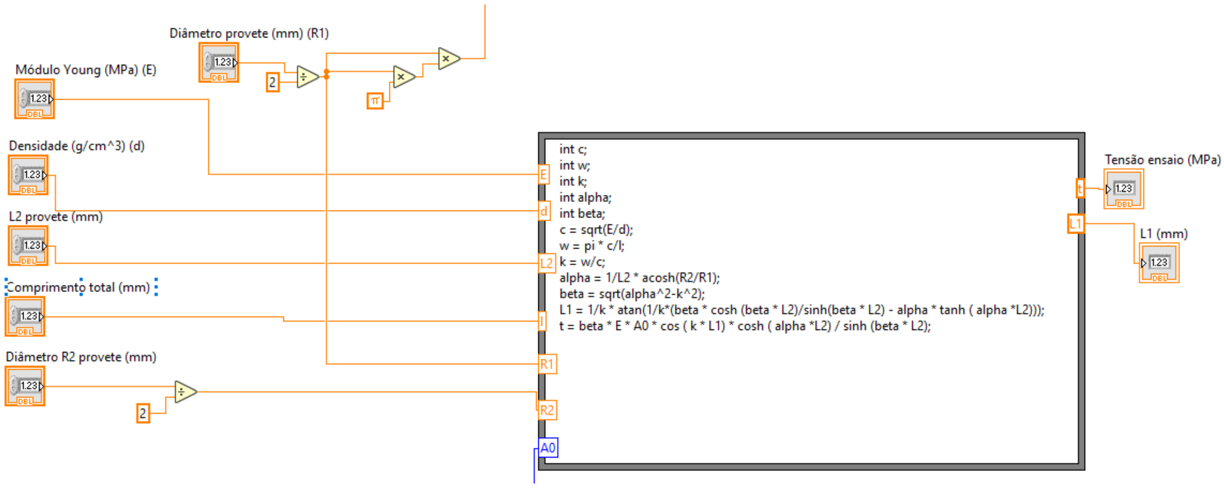


Figure 4.4 - Stress calculation code

4.1.4 Communication with generator

The last part of the program is responsible for the communication with the generator. Ideally, the LabVIEW program to operate the generator would be used, but since Mastersonic did not make the code for it available for editing, incorporating that into this program was not possible.

Instead, the communication was done using the Modbus communication protocol. To use this, an add-on related to the Modbus protocol was installed (LabVIEW Modbus Library). The Modbus parameters associated with the generator are shown in Table 4.1. It should be noted that the parameters present in this table are not as many as the software for the generator presents. This brings some limitations to what is possible to do in the LabVIEW program.

Table 4.1 - Generator Modbus protocol addresses

MODBUS RS485 RTU - no parity, 8 bit, 2 stop bit											
register	**parameter**		**dim**	**bit 0**	**bit 1**	**bit 2**	**bit 3**	**bit 4**	**bit 5**	**bit 6**	**bit 7**
0000	BEAT counter	read	cnt								
0001	Start frequency	read/write	10Hz/bit								
0002	Ouput power set point	read/write	1W/bit								
0003	Span set pont	read/write	ru								
0004	Capacitot	read/write	1nF/bit								
0005	Regulator Ki	read/write	ru								
0006	Regulator Ku	read/write	ru								
0007	Imax	read/write	1mA/bit								
0008	Modbus adress	read/write	-								
0009	Command word	write	bit field	RESET	START	STOP	SCAN	WRITE	DEGASING	Spare	Spare
0010	Status	read	bit field	ON	Overcurrent	Overvoltage	Overload	Overheat	NO load	Frequency error	Spare
0011	Analog set point	read	1W/bit								
0012	Output current	read	1mA/bit								
0013	Output voltage	read	1V/bit								
0014	PWM	read	0.1%/bit								
0015	power	read	1W/bit								
0016	Span	read	ru								
0017	Frequency actual	read	10Hz/bit								
0018	Frequency shift	read	10Hz/bit								
0019	Time ON	read/write	1s/bit								
0020	Degasing time	read/write	1s/bit								
0021	Time OFF	read/write	1s/bit								
0022	Time	read/write	1s/bit								
0023	Baud rate	read/write	ms								
0024	MIN power	read/write	1W/bit								

In the code, the first block refers to the initialization of the Modbus communication. In this block, the required inputs are the COM port that connects the PC to the generator, the baud rate of communication (115200 baud), the unit ID of the generator (1), the serial type (RTU), the parity (none) and the flow control (none).

The “read holding registers” block will be used to read parameters from the generator.

The first of these blocks is used to read a bit field related to generator alerts. There is a constant with the value of 1 that indicates to the block that there is 1 address to be read. The output is an array of decimal numbers, and its most recent element is converted into an array of booleans, which are then displayed in the user interface. The 7 alerts displayed are:

- The generator is turned on;
- There is an excess of current on the transducer;
- There is an excess of voltage on the transducer;
- There is an excessive load on the transducer;
- There is an excessive temperature on the transducer;
- There is no load on the transducer;
- There is an error in the tuning of the transducer’s frequency.

This bit field is associated to address 0010 of the generator.

The next block reads the output voltage and current of the generator. There is a constant with the value of 2 that indicates to the block that there are 2 addresses to be read. There is also another block to separate the elements of the array so that they can be displayed in the interface of the program. The addresses of these parameters are 0012 and 0013. The output voltage of the generator will be used as a basis for the calculation of the displacement of the specimen. This value will be multiplied by the scaling factor of the transducer that will be deduced after initial measurements with the proximity sensor. After that, the resulting displacement value will be displayed in the interface and used as an input in the *Formula Node* block shown in the previous sub-section.

The last block reads the real frequency that the generator is operating at and the difference between that value and the value set previously. It functions similarly to the previous block, with the difference that the 2 outputs are multiplied by 10 to be displayed in Hz. The addresses of these parameters are 0017 and 0018.

After the reading blocks, there is a waiting period of 200 ms until the part of the program related to the writing of parameters executes.

This first part of the communication code is shown in Figure 4.6.

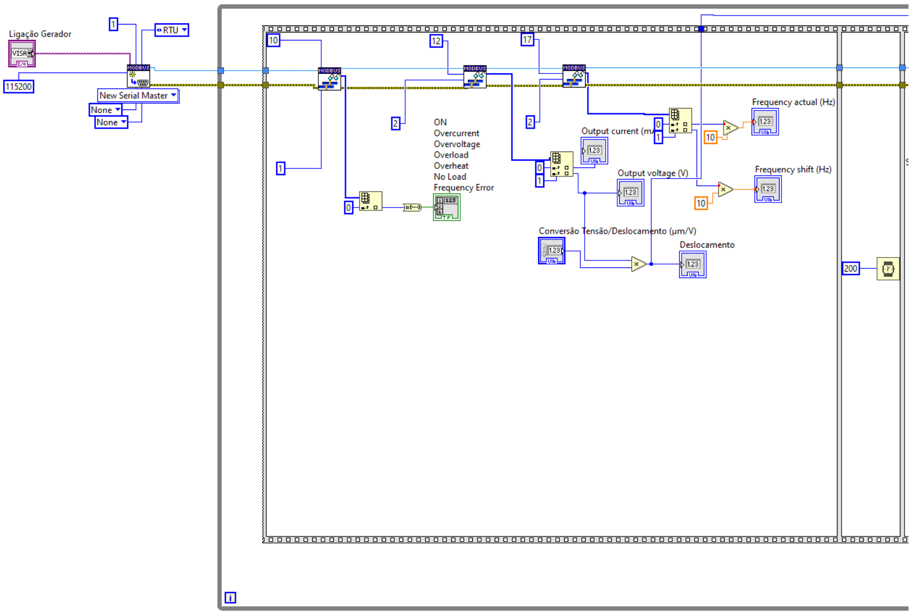


Figure 4.5 - First part of the Modbus generator code

After this, the program sends to the generator certain commands based on the inputs in the interface of the program using “write holding registers” blocks. The first ones are the start frequency of the generator, the frequency span around the start frequency where the generator can search for the transducer’s frequency and the regulator K_i (or amplitude) of the generator, which use sliding bars to input the desired value. The value of the start frequency has to be divided by 10 before it enters the holding register (since 10 Hz correspond to 1 bit according to the information in Figure 4.5).

These 3 first commands are associated to Modbus addresses (or registers) 0001, 0003 and 0005 of the generator.

The next “write holding registers” block is a bit field used to input commands to the generator. To that effect, 6 boolean variables were created: RESET, START, STOP, SCAN, WRITE, DEGASING, with its effects being the ones explained in section 2. These boolean variables are treated as an array of booleans, which is then converted to decimal before being input into the block. This bit field is associated with address 0009 of the generator.

The last “write holding registers” block is related to the degassing parameters of the generator. The inputs are the “Time On”, “Degassing time” and “Time Off” commands, which will be set using sliding bars. Their effects are described in section 2. Their addresses in the generator are 0019, 0020 and 0021.

After the writing blocks, there is a waiting period of 200 ms until the part of the program related to the reading of parameters executes again.

These writing and reading blocks are inserted into a loop. In this loop, there is also a button to stop its execution. After the loop is exited, there is a block that closes the Modbus communication with the generator.

The second half of the communication code is shown in Figure 4.7.

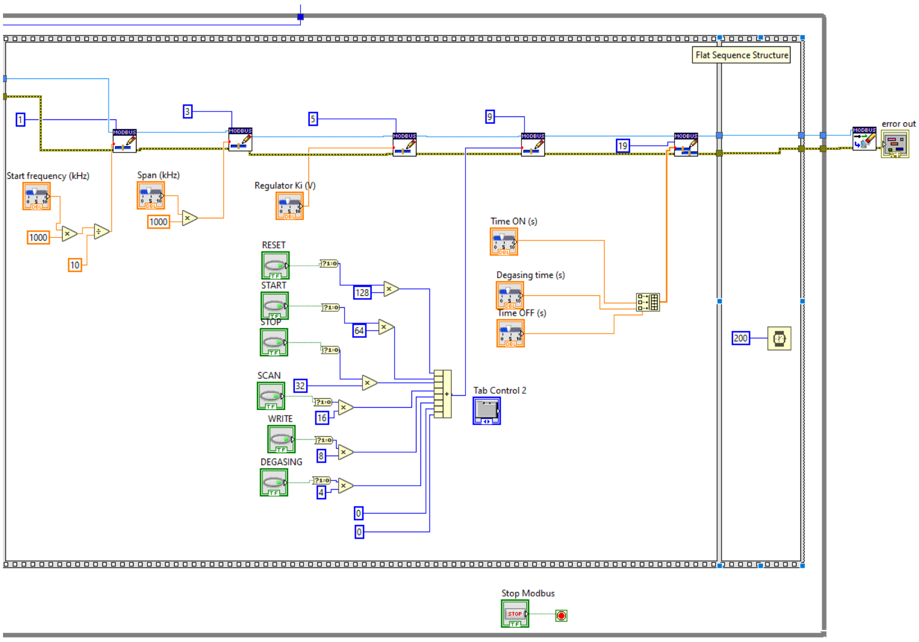


Figure 4.6 – Second part of the Modbus generator code

4.2 Graphical interface

In the front panel of the application, the DAQ used can be controlled and the data captured by it is shown.

The interface developed has the inputs and outputs present there divided into 4 tabs.

The first one is the DAQ tab, shown in Figure 4.8. Initially, to connect the DAQ with the program, it is necessary to input the IP address of the Kistler device (192.168.202.22), the IP port (6789), and the measurement ID (1). After this, by pressing the “Connect button” the communication between the DAQ device and the program is established.

On the top left of the display, there is an indicator that lights up to indicate that the connection is made, with is labeled “Connected” (or “Not Connected” when there is no connection). There is also an indicator that lights up when the DAQ is measuring its inputs (“DAQ running”) and another indicator that lights up when a value of maximum temperature is surpassed.

In the left side of the screen, there is a window with 5 sub-tabs that presents different information regarding the DAQ device.

The first sub-tab consists of a display of information of the DAQ device, which contains its type, description, name, serial number, and versions of the software, platform, bootloader, field programmable gate array and hardware.

The second sub-tab has configuration settings for a start trigger and a stop trigger to cause the DAQ measurement to start. These settings are the type of trigger, time, pre/post-trigger, duration (stop trigger only), threshold, channel number, edge and channel type.

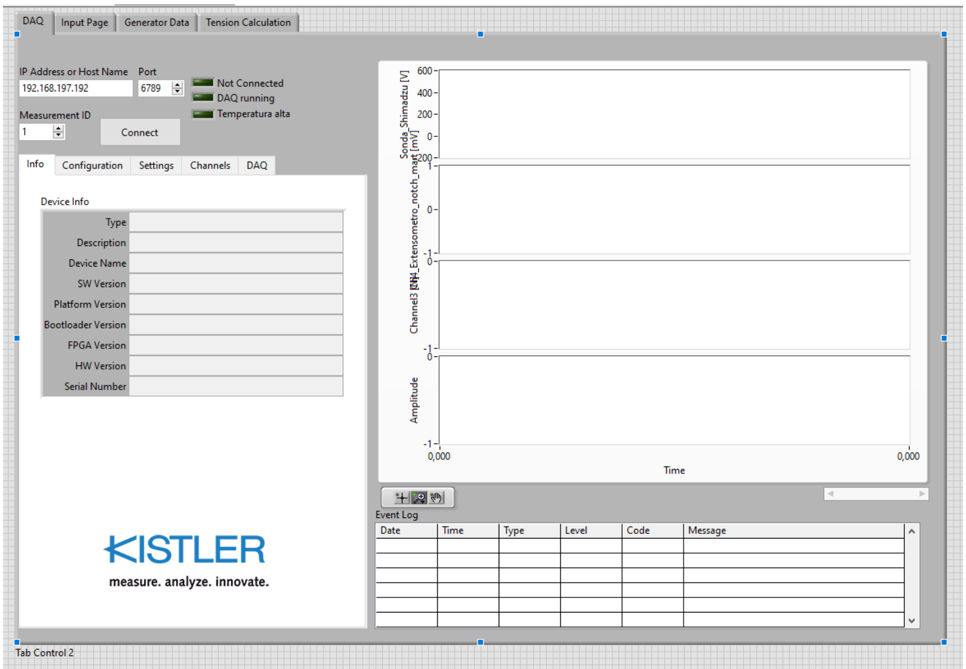
The third sub-tab has two buttons and two boxes. The first box is a selector of parameters of the DAQ and the second one is used to input or display the value of the selected parameter. The buttons have the functions of selecting setting the value of the selected parameter or getting its value.

The fourth sub-tab is used to get settings from an input channel of the DAQ that was selected in a combo box. The information displayed on the right part of the tab are the name of the channel, its type, the sensitivity (amount and unit) and range (amount and unit).

The last sub-tab is used to start the measurement once the DAQ is connected to the program. In the left side of the tab there are two buttons that are used to start the DAQ and to update its status. In the right side of the tab there is a display (DAQ status) that shows the stream status of the measurement and its frames, which is updated when the "Status" button is pressed. There is also an indicator that lights up when the measurement is running.

On the center of the display there are 4 waveform charts that display the variation of the 4 inputs of the DAQ with time and are titled and scaled based on the parameters of the DAQ that are input in the settings sub-tab.

Below these charts there is an event log that keeps track of the events that occur during the measurement, such as start and the end of it.



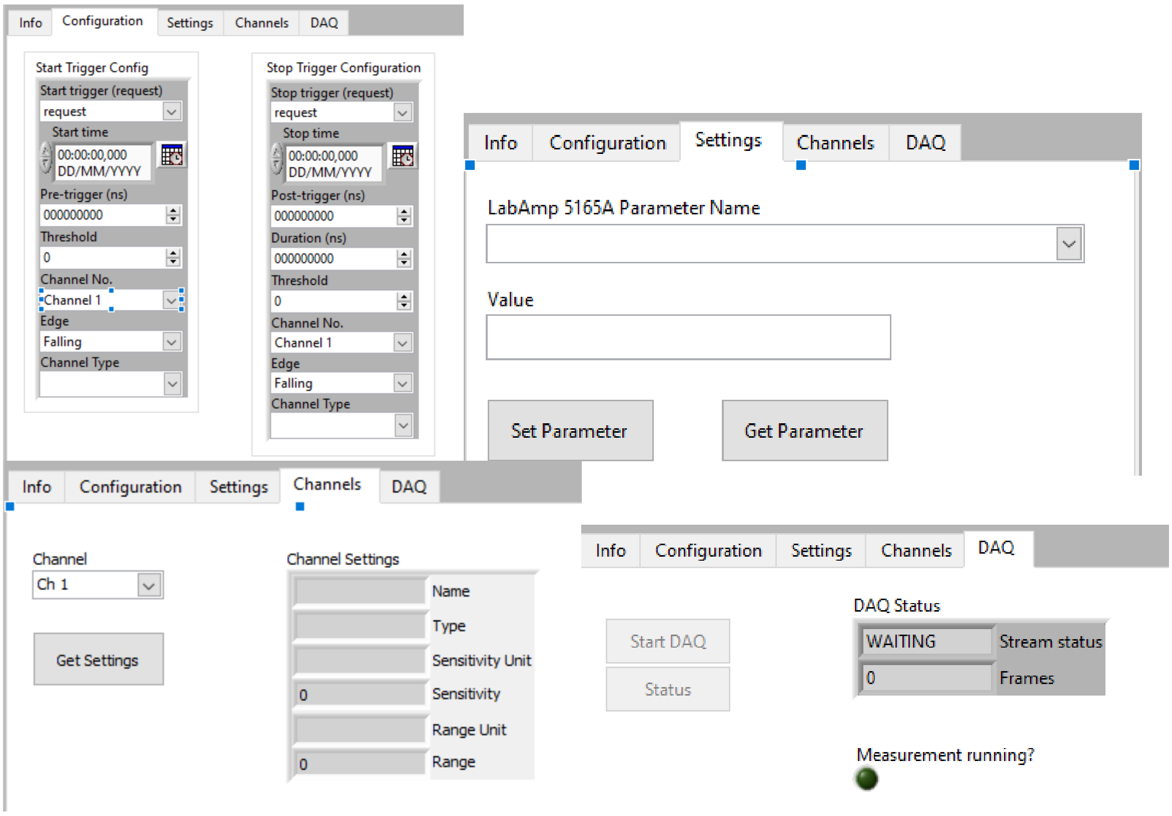


Figure 4.7 - DAQ tab of the program's interface (a - overall view; b- configuration subtab; c - settings subtab; d - channel subtab; e - DAQ subtab)

The second tab is the "Input Page" tab, shown in Figure 4.9. In this tab, the inputs that aren't related to either the generator or the testing specimen are set here. These inputs are the PC COM ports that connect to the generator and the Arduino board, the gains of the pyrometers (in ºC/V), the load cell (in N/V) and the transducer (in µm/V), the channel of the DAQ that measures the temperature and maximum temperature of the specimen (in ºC).

The inputs that aren't the COM ports were set to only accept values above 0, with the exception of the temperature channel input, which only allows values of 1, 2, 3 and 4.

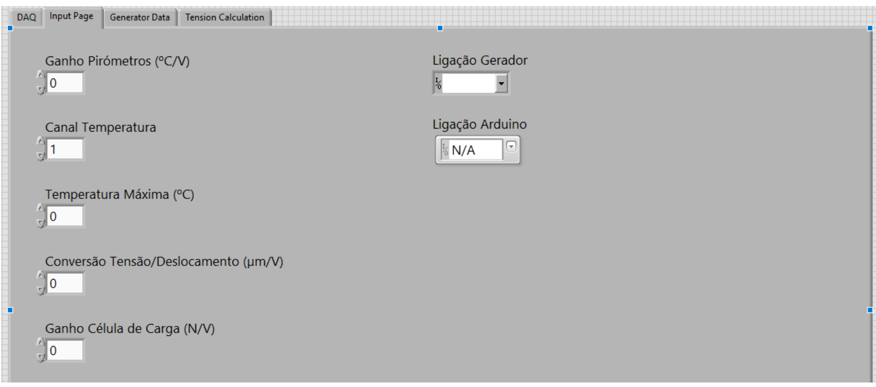


Figure 4.8 - Input Page tab of the program's interface

The third tab is the "Generator Data" tab, shown in Figure 4.10. In this tab, inputs and outputs related to the generator can be found.

The inputs present here are the 6 command buttons of the generator ("RESET", "START", "STOP", "SCAN", "WRITE", "DEGASING") and 6 sliding bars for the starting frequency (in kHz), amplitude of the ultrasonic wave (in V), frequency span (in kHz), time the generator will operate in the degassing mode (in seconds), time the generator will be turned on per cycle (in seconds) and time the generator will be turned off per cycle (in seconds). There is also a stop button to end the connection to the generator.

The outputs in this tab are 7 alerts of the generator ("On", "Overcurrent", "Overvoltage", "Overload", "Overheat", "No Load", "Frequency Error") and the actual frequency of the generator (in Hz), the difference between that value and the starting frequency (in Hz), the generator's output current (in mA) and its output voltage (in V).

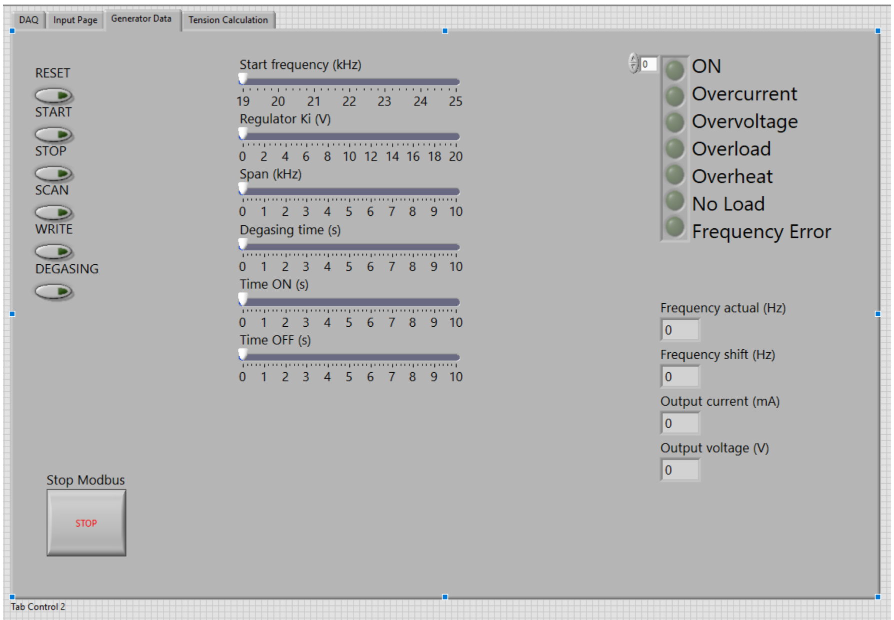


Figure 4.9 - Generator Data tab of the program's interface

The fourth tab is the "Stress Calculation" tab. In this tab, the inputs and outputs related to the specimen's stress and displacement can be found.

The inputs are the Young Module (in MPa) and density (in g/cm^3) of the specimen's material, the specimen's total length, its L2 length and its diameters at the thinnest and widest parts (all in mm).

The outputs are the L1 length of the specimen (in mm), the force (in N) and stress (in MPa) applied on it during the pre-load, the stress (in MPa) applied on it and its displacement (in µm) during the testing.

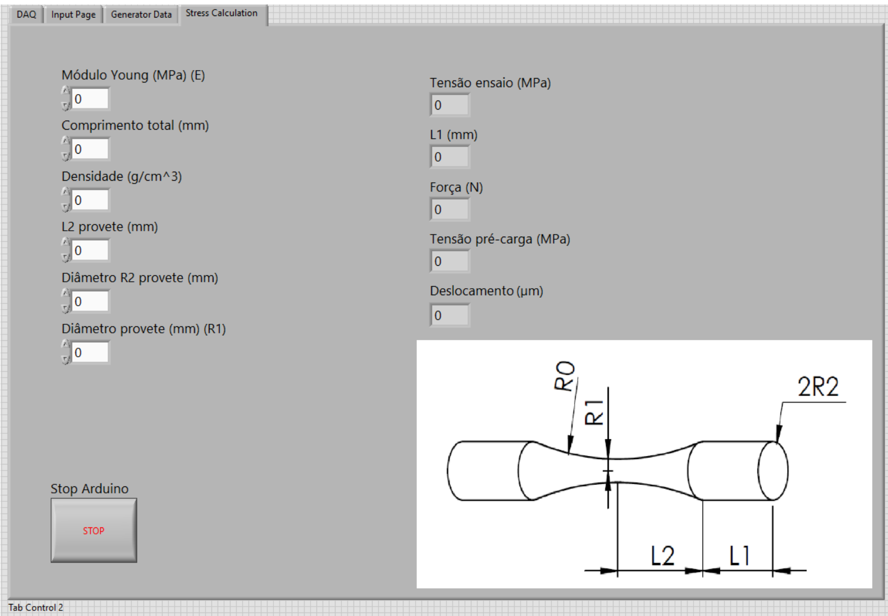


Figure 4.10 - Stress Calculation tab of the program's interface

5 Conclusions and future works

The work performed conceptualized a system of components and their technical requests and elaborated an integration procedure for them. This system will be used for the sensing of the ultrasonic fatigue testing machine that will be built at INEGI. Besides that, a software program was built to configure, control, and analyze the results of the fatigue testing procedures.

First, the intended purpose of the system was schematized, as seen from its physical perspective. Then, the functioning of the software of the generator used in this project was analyzed so that it was possible to understand how to change the settings of the testing parameters in it. The transducer used was also analyzed so that a better understanding of its necessary inputs was possible. After that, the various components used in this system were chosen and their functions in the project were set. The pyrometers, proximity sensor, strain gauges and the DAQ system used are components that are important for the functioning of the system that were already present at INEGI. The pressure switch, solenoid valve, pneumatic unions, pressure regulator, load cell, buttons, power supply and the Arduino Uno board are components that were chosen during this work and bought after its start, that will also be used for the control of the system. After all components were chosen, a schematic representation of the system from an electric perspective was shown and a bill of materials was elaborated.

After this, a LabVIEW program was developed that is capable of displaying the inputs of the DAQ system, read and write settings for the generator, calculate the stress during testing and pre-loading and establish logical connections in the Arduino board to automatically control the solenoid valve and stop the generator.

This dissertation presents a human-machine interface that can handle the requests of the ultrasonic fatigue testing machine that will be built.

In the future, it is necessary to assemble the components bought for the instrumentation and sensing of the machine and eventually change the LabVIEW program’s code based on future necessities. It also may be possible to add further components to the project, such as, for example, a thermal camera for the testing specimen.

References

[1] W. Macek, S. Zawiślak, A. Deptuła and R. Ulewicz, "Fatigue testing machines and apparatus," *Quality production improvement,* vol. 10, no. 1, pp. 80-108, 2019.

[2] S. Stanzl-Tschegg, "Very high cycle fatigue measuring techniques," *International Journal of Fatigue,* vol. 60, pp. 2-17, 2014.

[3] P. Ilie, X. Lesperance and A. Ince , "Development of an ultrasonic fatigue testing system for gigacycle fatigue," *Material Design and Processing Communications,* vol. 2, no. 6, 2019.

[4] Y. Lage, A. Ribeiro , D. Montalvão, L. Reis and M. Freitas, "Automation in strain and temperature control on VHCF with an ultrasonic testing facility," *Application of Automation Technology in Fatigue and Fracture Testing and Analysis (ASTM Special Technical Publication),* vol. 15, pp. 80-100, 2014.

[5] "USF-2000A," Shimadzu, [Online]. Available: https://www.shimadzu.com/an/products/materials-testing/fatigue-testingimpact-testing/usf-2000a/index.html. [Accessed 22 August 2022].

[6] "Very High Cycle Fatigue (VHCF)," 3R, [Online]. Available: https://3r-labo.com/en/mechanical-engineering/very-high-cycle-fatigue-vhcf/. [Accessed 22 August 2022].

[7] P. Costa, R. Nwawe, H. Soares, L. Reis, M. Freitas, Y. Chen and D. Montalvão, "Review of Multiaxial Testing for Very High Cycle Fatigue: From ‘Conventional’ to Ultrasonic Machines," *Machines,* vol. 8, no. 25, 2020.

[8] A. Messager, A. Junet, T. Palin-Luc, J.-Y. Buffiere, N. Saintier, N. Ranc, M. El May, Y. Gaillard, A. King, A. Bonnin and Y. Nadot, "In situ synchrotron ultrasonic fatigue testing device for 3D characterisation of internal crack initiation and growth," *Fatigue & Fracture of Engineering Materials and Structures,* vol. 43, no. 3, pp. 558-567, March 2020.