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Development of test stand for experimental investigation of chemical and physical phenomena in Liquid Rocket Engine

Abstract: *The main objective of this work was to present the specification of an experimental firing test stand for liquid rocket engines (LRE) and develop a program for control and acquisition of data. It provides conditions to test rocket engines with thrust from 50 to 100 kgf. A methodology for laboratory work implementation using information technology, which will allow the automatic and remote functioning of the test stand, permits users to input the necessary data to conduct tests safely, achieve accurate measurements and obtain reliable results. The control of propellant mass flow rates by pressure regulators and other system valves, as well as the test stand data acquisition, are carried out automatically through LabVIEW commercial software. The test stand program is a readable, scalable and maintainable code. The test stand design and its development represent the state of art of experimental apparatus in LRE testing.*

Keywords: *Experimental firing test, Liquid rocket engine, Data acquisition.*

LIST OF SYMBOLS

A_a: outlet area of nozzle, m^2

A_{cr}: critical section area, m^2

C^*: characteristic velocity, m/s

F: thrust, kgf

F_H: thrust in atmospheric condition, kgf

GN_2: gaseous nitrogen

GOX: gaseous oxygen

I_{sp}: specific impulse, s

k: adiabatic exponent

km: mixture ratio

$\dot{m}$: mass flow rate, kg/s

$\dot{m}_F$: fuel mass flow rate, kg/s

$\dot{m}_O$: oxidizer mass flow rate, kg/s

P_a: outlet static pressure, bar

P_{ch}: pressure in combustion chamber, bar

P_H: ambient pressure, bar

R: gas constant, $J/kg.K$

T_{ch}: temperature in combustion chamber, K

W_0: velocity in the combustion chamber, m/s

W_a: outlet velocity of nozzle, m/s

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INTRODUCTION

The Brazilian Space Agency (AEB) through National Plan of Space Activities (PNAE) (2005) has invested in the formation of specialists in technology of calculation, design and construction of liquid rocket engines. In the next scheduled version of the Brazilian Vehicle Launcher of Satellite (VLS), the liquid rocket engine (LRE) will only be utilized in the upper stages, but in future versions, it will be employed in other stages of the vehicle.

The advantages of LRE in relation to the solid propellant rocket motor justify the investment in this area. Among the advantages of LRE are its long operating time, thrust control and high achievable specific impulse.

LREs are subjected to tests in installations known as test stands before they are put into operation. Test stands are oriented in determining the specific operating parameters and achievable performances of LREs.

On September 17th, 2005, the Institute of Aeronautics and Space (IAE) performed the first firing test of a liquid rocket engine of 5 kN of thrust (named L5 engine). The tests were carried out in a test stand located at the Liquid Propulsion Laboratory (LPL) in São José dos Campos, which has capacity to test engines up to 20 kN.

The L5 engine was designed to operate with liquid oxygen (LOX) and kerosene but in the preliminary phase of the tests it used ethyl alcohol as fuel. The injector head

consists of bipropellant centrifugal liquid injectors of holes in the periphery of the fire bottom responsible for the film cooling formation.

Currently, the IAE has been working in two new projects in the liquid propulsion field. The L15 engine is a bipropellant LRE of 15 kN of thrust that operates with liquid oxygen and ethyl alcohol, which will be used in the VS-15 sounding rocket. The other project under development is the L75, a bipropellant LRE of 75 kN of thrust, which will operate with a turbopump feed system using the propellants: liquid oxygen and kerosene.

This work has resulted in two master's dissertations in the Aerospace Engineering course of liquid propulsion area of Aeronautics Institute of Technology (ITA). The first one developed test stand specifications, design of a LRE, and a test methodology (Alves, 2008). The second one developed a program for a test stand data acquisition and control system (Andrade, 2008).

The IAE decided to build this test stand, which is in the final phase of assembly. Once completed, it will be used as an educational tool in the formation of new groups of the master's degree course of ITA, in order to train IAE technical personnel, to evolve LRE research and to acquire liquid propulsion knowledge for application in satellite launch vehicles.

The apparatus under development will make available for laboratories to verify the influence of mass flow rate (object of this work) and nozzle expansion ratio in the thrust force of the LRE. With small changes in the thrust chamber, it will be possible to carry out additional tests to study the heat flow through the engine. Using an automated data acquisition and control system, the user will be able to remotely operate the engine and do measurements of several parameters, like pressure, temperature, mass flow rates and thrust.

THEORETICAL BASIS OF LIQUID ROCKET ENGINES

The LRE consists basically of one thrust chamber, tanks to store the propellants, a feed system to force the propellants into the thrust chamber, a power source to supply the energy for the feed system, piping to transfer the liquids, a structure to transmit the thrust, and control devices to initiate and regulate the propellant flow and control thrust (Sutton, 2001). The thrust chamber is the main part of a rocket engine (Sutton, 2001). It is usually formed by an injector head, a combustion chamber, a nozzle, a cooling jacket, and an ignition system according to Fig. 1.

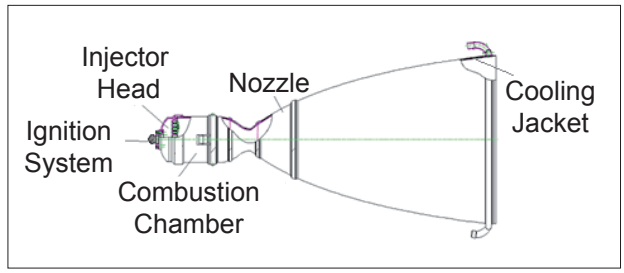


Figure 1. Thrust chamber.

The injector head consists of injectors distributed along the surface of a plate placed at the inlet of the combustion chamber and a set of ducts that guarantee a uniform distribution of propellants. The injectors are the key elements of the thrust chamber because they determine the behavior of propellants in the combustion chamber. It injects and atomizes the propellants into the combustion chamber, mixing them homogeneously and in well defined ratios of fuel and oxidizer, before it is vaporized and quickly ignited.

The injectors are classified as centrifugal or jet. They can be monopropellant or bipropellant (in case of bipropellants, for a better homogenization of the mixture) and can be used as a coaxial centrifugal injector.

The combustion chamber is the part of thrust chamber in which the combustion of propellants occurs at high pressure and temperature. The process of combustion can be characterized in three zones (Kessaev, 2006): 1) gasification zone (warming-up, evaporation), 2) burning zone, and 3) combustion product mixing zone. Internal cooling of the combustion chamber is made to protect the inner shell from contact with the high temperature gases. They can be of two types: by wall layer, which is constituted by a flow of combustion products with lower burning temperature along the wall; and a wall screen formed by the liquid fuel film.

The hot gases of combustion are accelerated from the stagnation to transonic velocity in the throat, reaching supersonic velocity in the exit of the nozzle (Barrère, 1960).

There are different types of nozzles, including conical, contoured, and ring nozzle. Conical nozzles are simple and relatively easy to manufacture but they are not the most efficient ones in terms of thrust for a given length. The type of nozzle chosen in this work was the conical one, due to simplicity and easiness to manufacture it.

The basic objective of the cooling jacket in a thrust chamber is to prevent its walls from becoming too hot, and enable them to withstand the imposed thermal loads and stresses. Most materials lose strength and become

weaker when temperature is increased. Cooling, thus, reduces the wall temperatures to an acceptable value (Sutton, 2001). The regenerative cooling is carried out by a cooling jacket around the thrust chamber by circulating one of the liquid propellants through it before it is fed to the injector head.

The propellants are combined inside the combustion chamber where they chemically react to form hot gases which are then accelerated and ejected at high velocity through the nozzle (Huzel and Huang, 1992; Kessaev, 2005).

The equation of thrust in atmospheric conditions (Eq. 1), as shown in Fig. 2, is given by:

$$F_H = m.W_a + A_a (P_a - P_H) \quad (1)$$

Where A_a is the outlet area of the nozzle, P_a is the outlet static pressure of the nozzle and P_H is the ambient pressure. This equation shows a balance between the created forces due to the mass ejected by the rocket and the force due to the effects of pressure at the exit plane of the nozzle. In space applications, the ambient pressure is considered zero (vacuum).

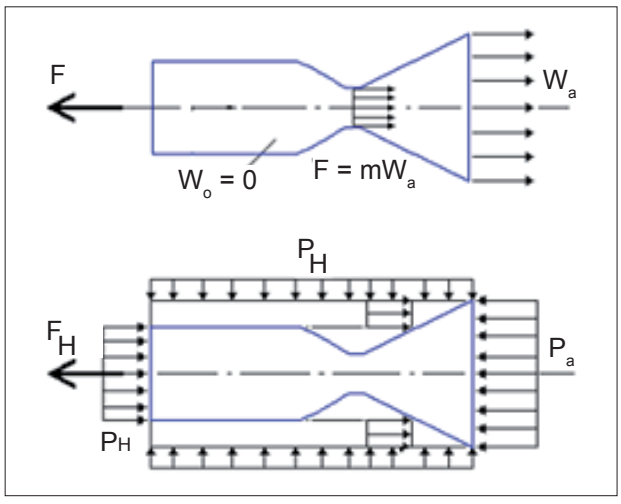


Figure 2. Thrust in atmospheric conditions.

The specific impulse Isp is the main performance measurement of an LRE. It is used as a base for comparison among propellants, combinations of propellants, and overall performance of LREs. The Isp can be calculated in two ways: experimentally, measuring the thrust (F) and the mass flow rate ($\dot{m}$) of the propellant according to Eq. 2 and from the thermodynamics properties of the propellants for a given expansion ratio Pa/Pch, according to Eq. 3:

$$Isp = \frac{F}{\dot{m}} = \frac{A_a (P_a - P_H)}{\dot{m}} \quad (2)$$

$$I_{sp} = \sqrt{\frac{2kRT_{ch}}{(k-1)}\left[1-\left(\frac{P_a}{P_{ch}}\right)^{\frac{k-1}{k}}\right]} \quad (3)$$

Equation 2 also shows that the Isp decreases with the increase of atmospheric pressure and the same is directly proportional to the thrust. Equation 3 shows that when the LRE is operating in vacuum, with the value of Pa tending to zero, the value of Isp is independent on the combustion chamber pressure.

The characteristic velocity, *C**, is a figure of thermochemical merit for a particular propellant and may be considered as an indicative of the combustion efficiency. It can be calculated in two ways: experimentally through the chamber pressure measurement (P_{ch}), critical area section (A_{cr}) and mass flow rate ($\dot{m}$) according to Eq. 4 and from the thermodynamics properties of propellants used according to Eq. 5:

$$C^* = \frac{P_{ch} A_{cr}}{\dot{m}} \quad (4)$$

$$C^* = \frac{\sqrt{RT_{ch}}}{\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{2k}{k+1}}} \quad (5)$$

Where:

R: gas constant in (*J/Kg.K*);

T_{ch}: temperature of combustion gases in chamber in (*K*);

k: adiabatic exponent.

The value of *C** empirically calculated considers a loss due to the friction and the movement of the combustion gases in the throat of the nozzle. This loss depends directly on the profile of the nozzle.

METHODOLOGY OF LABORATORY WORK

The experimental test stand was initially designed to carry out firing and cold flow tests of liquid propellant rocket engines using a pressurized propellant feed system. The LRE will use ethyl alcohol (C_2H_5OH) as fuel and gaseous oxygen as oxidizer.

The choice of the propellants (ethyl alcohol and gaseous oxygen) was made based on requirements for low cost, ease of acquisition, and non toxic

combustion product. Gaseous oxygen can be readily and inexpensively obtained in pressurized cylinder in almost all communities because it is used in oxy-acetylene welding. With reasonable precaution, it is safe to handle and for rocket test stand use. The alcohol is readily available in some communities. Safety precautions are already known by the most responsible personnel due to wide use of the fuel in internal combustion engines for automobiles and other power machines. The combustion chamber will be water cooled. The pressurization of the fuel tank and the pilot lines that feed the pressure regulators, as well as the purging of the fuel lines, will be made with gaseous nitrogen (GN_2) from pressurized cylinders at 200 bar.

The test stand allows tests of rocket engines in different regimes of operation by enabling the variation of parameters such as chamber pressure, mass flow rate, and firing time. It provides measurements of several physical variables associated with these regimes. The test stand will be controlled automatically by a computer (PC) that will enable real-time measurements during the rocket engine firing, allowing remote control and more safety to the operator.

The tests will be carried out in four different regimes of operation with constant mixture ratio (km) – ratio between the mass flow rate of oxidizer and mass flow rate of fuel. The change of regimes will be obtained by the variation of propellant feed line pressures, mass flow rates, and chamber pressures. The firing time will also be varied, limited only by the size of the fuel and oxidizer tanks. The number of operational regimes can be extended calibrating the system with additional values of feed line and chamber pressures. The tests will be conducted sequentially according to a pre-defined operational regime. The system will also allow the user to choose one unique regime of operation among four available options. Figure 3 shows a test with four regimes of operation carried out sequentially, and Fig. 4 illustrates an example of choice for an only regime that can be sometimes replied to survey statistics.

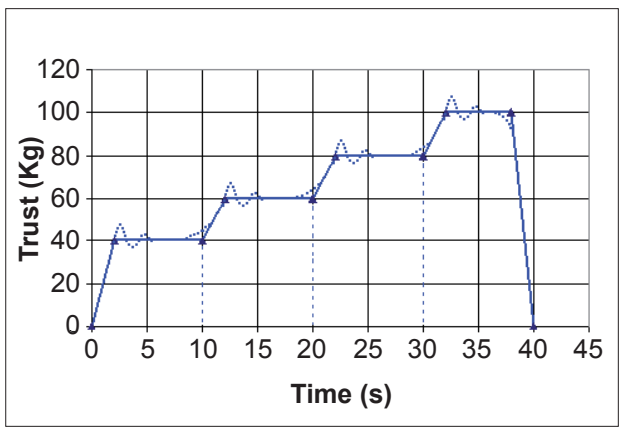


Figure 3. Sequential regimes.

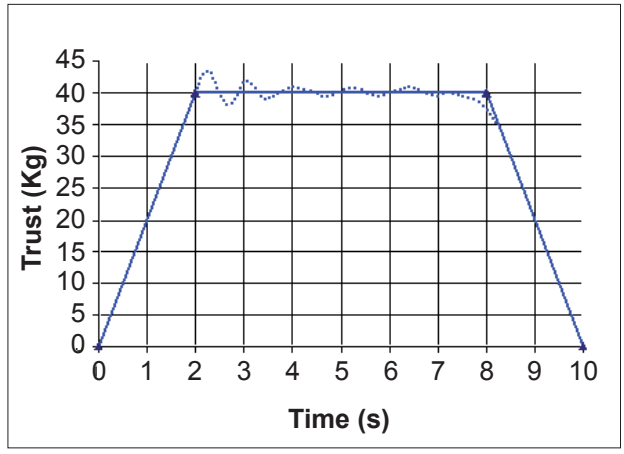


Figure 4. Representation of one unique regime.

The control system will basically work in three different conditions: set up, operation, and shut down; operation condition is subdivided into starting, test, wait and finishing.

The test is initiated with actions of opening and closing synchronized feed line valves, firstly to ignite the gas-dynamic igniter and then to provide the conditions to start the engine firing. During engine firing, the mixture ratio is kept constant by controlling the propellant line pressures with automatic pressure regulators (PID system). Initially, the pressures related to mass flow rates (fuel and oxidizer) are obtained by calculations but verified experimentally.

DEVELOPMENT OF TEST STAND INSTALLATIONS

The main requirements of the test stand and engine developed are:

a) propellants are ethyl alcohol and oxygen gas;

b) capacity of generating a 50 to 100 kgf range of thrust;

c) constant mixture ratio (km) for maximum specific impulse;

d) four regimes of operation with chamber pressure of 8, 10, 12 and 15 bar;

e) maximum admissible pressure of combustion chamber: 20 bar;

f) duration of each regime of operation equal to 10 seconds;

g) constant mass flow rate using pressure regulators in the propellant feed lines;

h) gas dynamic igniter for multiple ignitions;

i) water-cooled jacket;

j) automated data acquisition and control system;

k) acquisition of temperature values, pressure, mass flow rate and thrust;

l) system safety is automatic, safety routine program is to ensure that safety, consistent with mission requirements, is designed into systems, subsystems, equipment, facilities, and their interfaces.

Considering the mixture ratio km equal 1.6 to maximize specific impulse, the values for mass flow rates of propellants of the combustion chamber and their respective thrusts for four operational regimes were calculated and the results are shown in Table 1.

Table 1. Pressures in the combustion chamber (P_{ch}), mass flow rates ($\dot{m}_O$,$\dot{m}_f$) and thrust (F_H) values.

Regimes	P_{ch} (bar)	$\dot{m}_O$ (kg/s)	$\dot{m}_f$ (kg/s)	F_H (kgf)
1º	8	0.200	0.125	56.05
2º	10	0.250	0.157	70.22
3º	12	0.301	0.188	84.43
4º	15	0.376	0.235	105.78

Figure 5 provides an AutoCAD drawing in cross section of a thrust chamber, detailing the ignition system (detail 1) and the mechanical interface of the engine with the frame of the test stand (detail 2). The injector head will be made of stainless steel except the base plate (detail 12) and igniter ducts (detail 7), which will be made of copper. The combustion chamber will be made of stainless steel. On the inner shell (detail 6), there will be milling ribs that begin in the cylindrical part and finish in the throat; the cooling jacket is constituted of a double wall shell, without ribs. The inlet and outlet of the cooling system can also be seen in details 15 and 4. The nozzle is segmented in parts that can be removed during the laboratory work as configuration makes it possible to verify the influence of expansion ratio on thrust. Consequently, three conditions of expansion in the nozzle can be tested: under expanded, over expanded, and adapted. In the planned work, the tests to determine LRE thrust characteristics will be carried out only in three segments (details 16, 17 and 18 of Fig. 5) corresponding to an adapted nozzle at sea level.

The thrust measurement system is part of the test stand frame and it is constituted of an interface support that fixes the engine in the frame, a compression load cell (which measures the thrust force) and a calibration mechanism, as the system shown schematically in Fig. 6. Strain gages, load cell, were placed on the beam to convert strain to a voltage proportional to the thrust force. The calibration is easily effected by adding weights. In order to obtain a proper zero reading for all thrust measurements, it is necessary that the whole measurement system be pre-stressed with a pre-load of 5-10% of the expected thrust. The frame of the test bench is constituted of the parts shown in Fig 6.

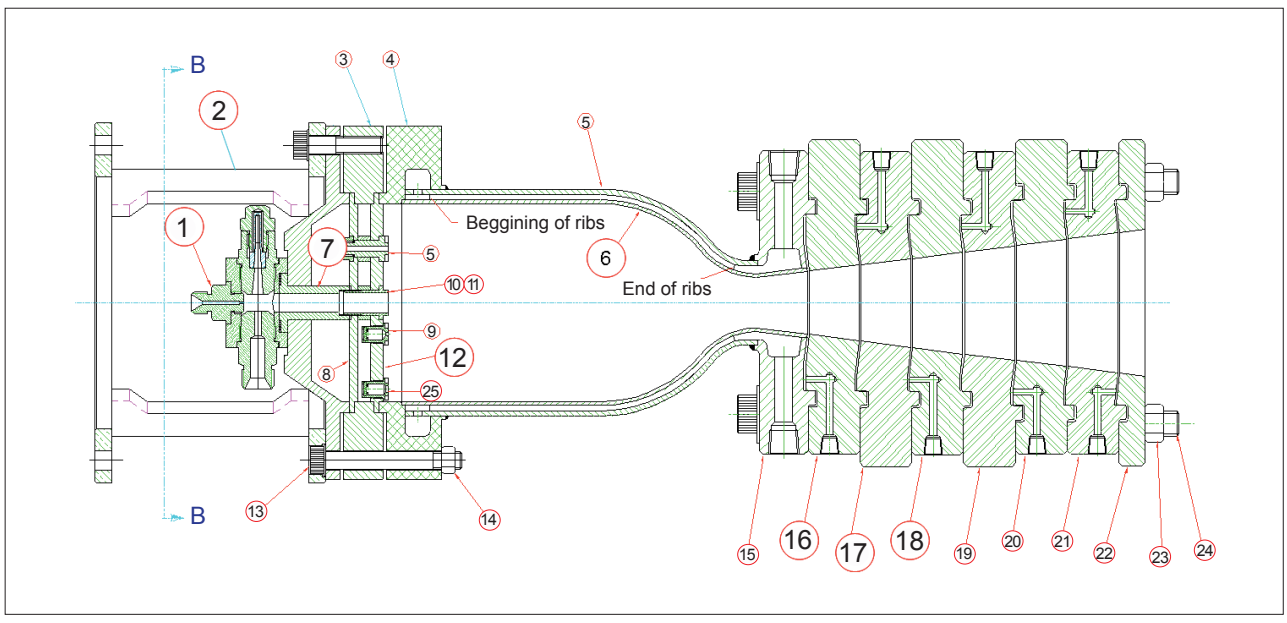


Figure 5. General drawing of longitudinal cross section thrust chamber.

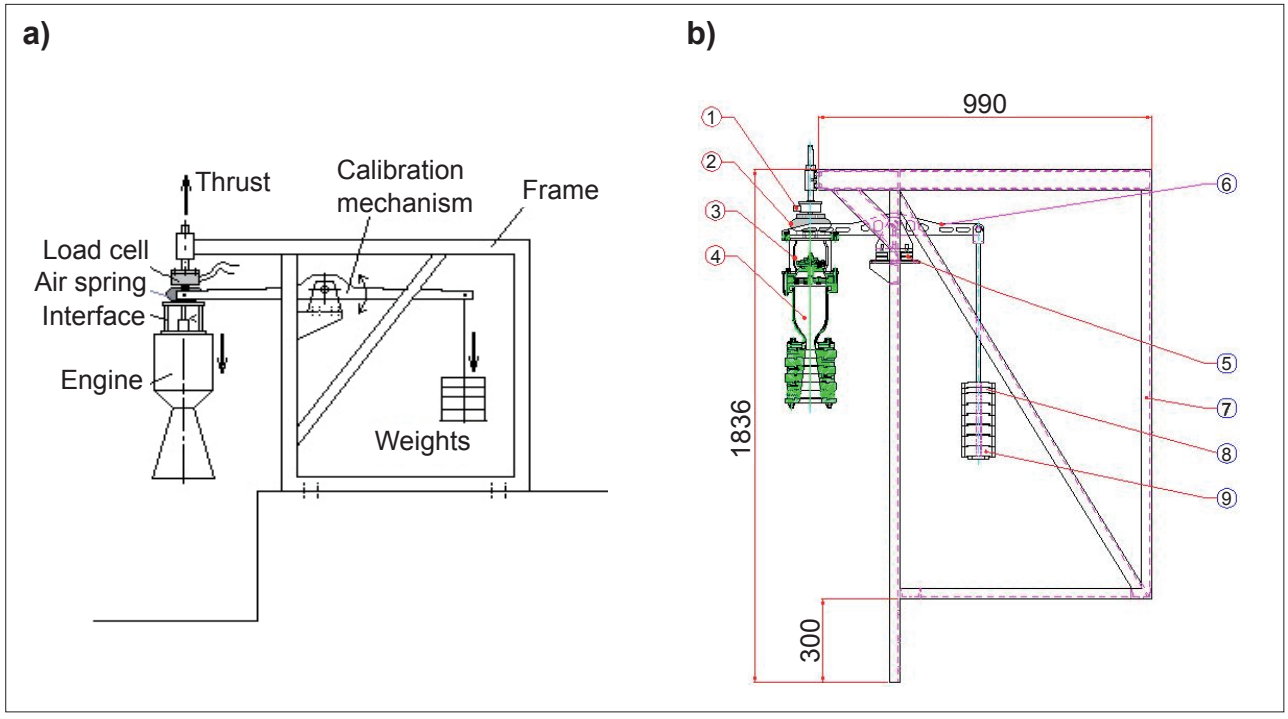


Figure 6. Thrust measurement system: (a) lateral view of scheme test stand and (b) design in CAD. 1: load cell (thrust force measurement); 2: air spring (pneumatic spring); 3: support to fix the engine in the frame; 4: rocket engine; 5: damper; 6: balance beam; 7: body; 8 and 9: counterweights (5 and 10 kg).

A structural analysis of the test stand frame, using the finite element method, was carried out to evaluate the linear static behavior and modal to steel ASTM-A36. The main results of the analysis are listed below and Fig. 7 shows the mesh and Von Mises stress. The values of stress are below the admissible stress in the analyzed models and no problem was found in the screws of the frame and in the bearings of the load cell. Table 2 shows the natural frequency of the frame test stand.

Table 2. Natural frequency.

Frequency number	Frequency (seconds)
1	0.7136914E-01
2	0.4997758E-01
3	0.3089837E-01
4	0.2763159E-01
5	0.1987037E-01

According to Fig. 7, the maximum stress was obtained where the engine was fixed. The results to stress, displacement, and values to steel ASTM-A36 are:

- admissible stress=150 MPa;
- maximum vertical displacement=0.45 mm;
- maximum stress (Von Mises)=83.9 MPa;
- safety margin=(admissible stress – maximum stress)/ maximum stress=79%.

The feed system is constituted of an hydropneumatic installation illustrated in Fig. 8, composed of piping lines, a series of valves, provisions for filling and removing (draining and flushing) the liquid propellants, and control devices to initiate, stop, and regulate their flow and operation.

GOX passes from a stored cylinder through a pressure regulator, where its pressure is reduced and feeds the engine when electric valves are opened. Part of the GOX is also used in the ignition unit. GN2 from a stored cylinder is reduced by the pressure regulator and pressurizes the fuel tank to feed the engine. The scheme also shows the cooling water inlet in the throat region of the engine and the exit from the mixing head. Figure 8 also shows temperature, pressure, and thrust measurement cell load sensors.

The layout of the test complex is shown in Fig. 9, which gives an overview of the arrangement, equipment of control and data acquisition system. The interface between the test stand and the control room will be carried out by signal transmission cables represented by the black dotted line in Fig. 9. The propellant and pressurization gas will be located in three separated bays, and the engine rocket will be installed in the frame of test stand. Figure 9 also shows the control room which not only serves to protect test personnel from a possible combustion chamber or tank explosion, but also contains the equipment controlling for test operation and data acquisition equipment.

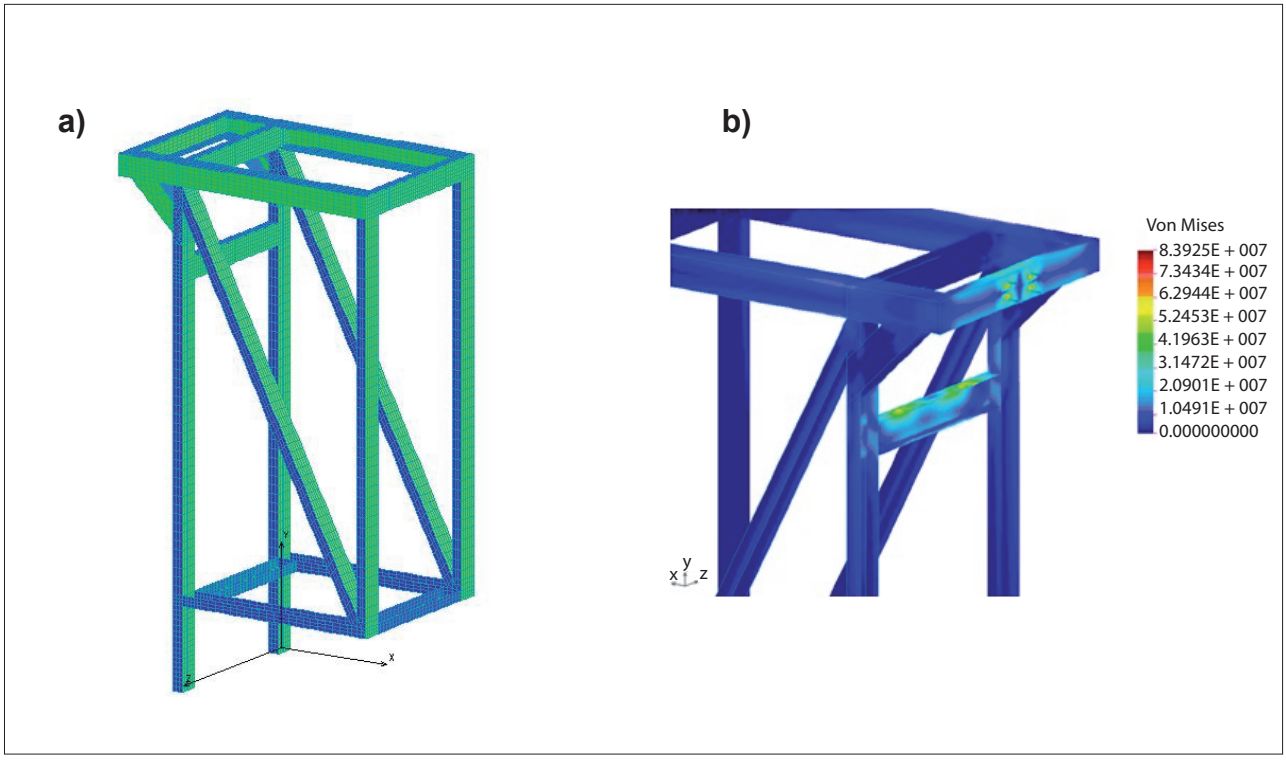


Figure 7. Results – (a) Mesh and (b) Stress (Von Mises).

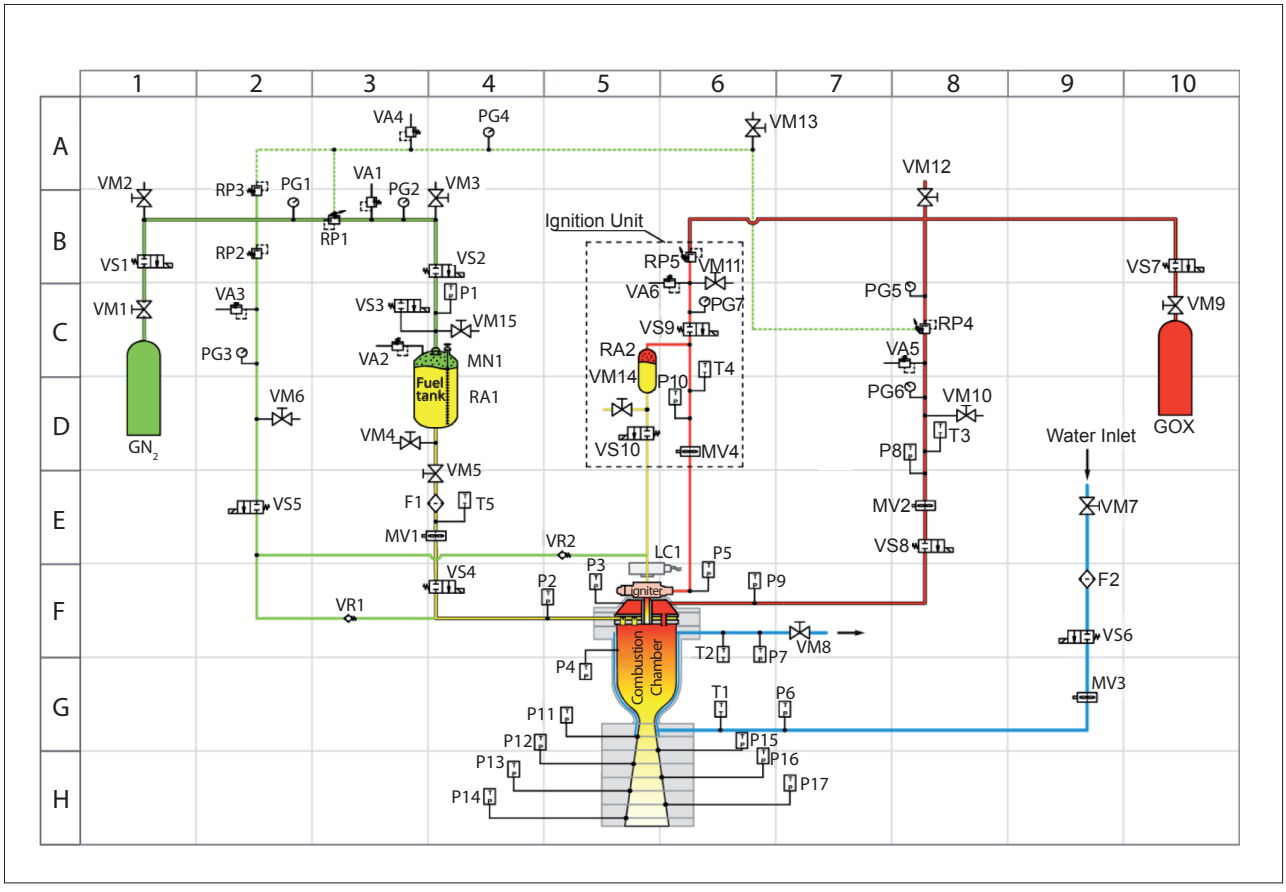


Figure 8. Hydropneumatic scheme. RP(n): pressure regulator (n=1,2,3,4,5), T(n): thermocouple (n=1,2,3,4,5), VA(n): relief valve (n=1,2,3,4,5,6), VM(n): manual valve (n=1,2,3,...,14), VS(n): solenoid valve (n = 1,2,3,...,10), MV(n): flowmeter (n=1,2,3,4).

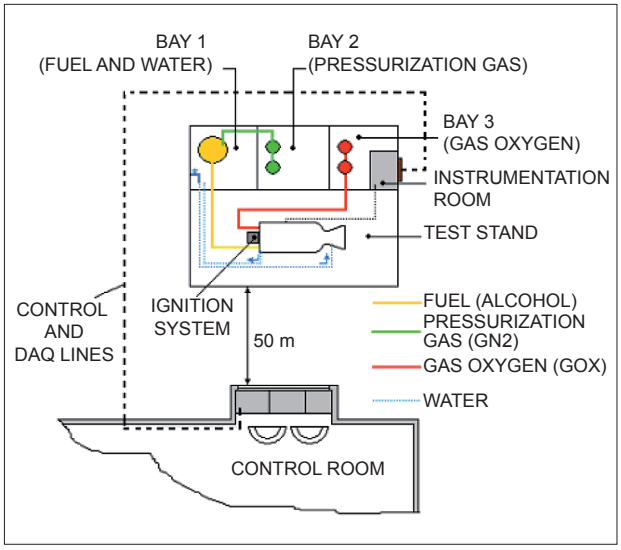
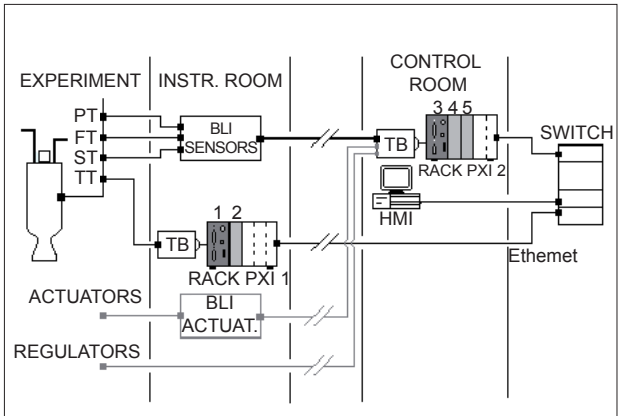


Figure 9. Layout of test complex.

The control and acquisition system in use in the test stand is composed by the elements presented in the system architecture (Fig. 10). The pressure transducers (PT), mass flow rate (FT), strain or thrust (ST) and temperature (TT), shown in Fig. 10, are sensitive elements that convert the physical phenomena of the experiment in electrical signal that will be conditioned and later analyzed. The signals will be conditioned and processed in the PXI platforms of instrumentation for measurement and automation of National Instruments.

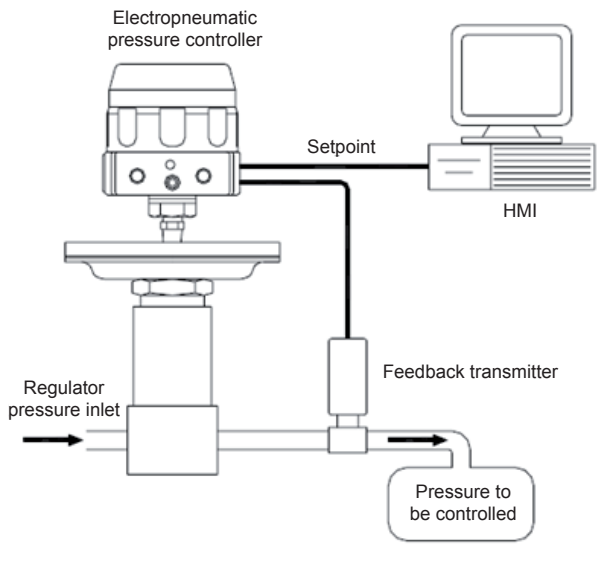


PT: pressure transducers; FT: mass flow rate; ST: strain or thrust; TT: temperature; HMI: human-machine interface. 1: controller system only for temperature data; 2: temperature peripheral module; 3: controller for other data acquisition and control; 4 and 5: pressure regulator.

Figure 10. Data acquisition system architecture.

In Fig. 10, item (1) is a controller system only for temperature data, (2) is the temperature peripheral module, (3) is a controller for other data acquisition and control and (4) is the pressure regulator. The interface with user or human-machine interface (HMI) is carried out by means of a personal computer connected by ethernet and a software that, in this case, will be the LabVIEW program. The control will be carried out through the opening and closing of the solenoid valves, also commanded by PXI racks.

It will be possible through the automatic system to control the pressure in the lines of fuel and oxidizer to keep the mass flow rate constant. It is done by a microcontroller-based device that implements a digital control algorithm (PID controller) to regulate pressure. PID controller involves three parameters of control: proportional, integral and derivative values that are obtained by test. The weighted sum of these three actions is outputted to a control element such as the position of the control valve. Figure 11 shows a scheme of control in pressure regulators using computer: the user is responsible for fixing a setpoint value to control the pressure.



HMI: human-machine interface.

Figure 11. Control in regulators by computer to keep the pressure constant.

METHODOLY AND DEVELOPMENT OF PROGRAM

The program developed for test stand control and data acquisition for LRE test uses the software LabVIEW because of its user interface and the readable, scalable and maintainable algorithm. The development of this program was possible due to a well defined development methodology. It consists of the phases shown in Fig 12.

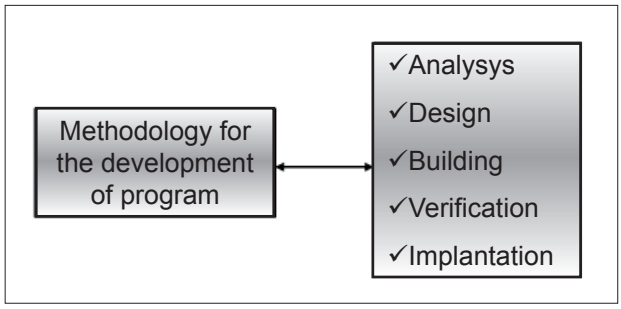


Figure 12. Phases of the methodology for the program development.

Analysis

In this phase, the investigation of the necessary data for the understanding of the design requirements was done. Hydropneumatic scheme was planned and developed with the schedule of all its activities from activation through shutdown of the test stand. Based on the hydropneumatic scheme shown in Fig. 8, the state machine was prepared, with the purpose of supplying and focusing on the development of the program (Shaw, 2003). Figure 13 shows the state machine of the hydropneumatic scheme of test stand.

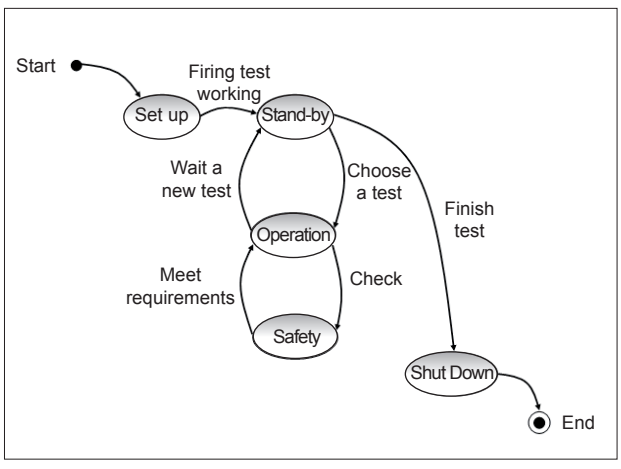


Figure 13. Test stand state diagram.

According to Fig. 13, during the set up phase, the test stand is checked, i.e, valves, pressure regulators, gas lines and so on, until the stand-by state, when it will be ready to choose a test. During the test stand work, safety routines are used to monitor some system parameters like pressure and temperature, in order to avoid incidents due to super heating or pressure higher than the one specified in the design. The safety routines are programmed to perform determined actions of system protection by executing routines like closing of valves, depressurization of lines, banks etc. The test is finished in the shut down state.

Design

In this phase, the interface between the user and the available infrastructure was described to meet the functioning of the LRE and installation of the hydropneumatic scheme, as shown in Fig. 8.

Building

In this phase, there was the interpretation of performed requirements resulting in the development of the LabVIEW codification. All codification sequence was made in a modular and scalable way, with comments inserted in the program. Figures 14, 15 and 16 show some LabVIEW screens developed to control the test stand.

Figure 14 shows the first screen of the program with its guides. This screen, called “Gravação”, allows the user:

- to choose the name and the folder where the acquired test data will be saved;
- to monitor and save the generated sensor data;
- to finish the check of sensors when they are being monitored;
- to determine the time of countdown of the test.

The guide screen “Canais” allows the user to choose the type of configuration and adjust the data channels for the valves or keep the default. Figure 15 shows the guide screen “Seleção das Pressões”, displaying chamber pressures available to the test stand.

Finally, Fig. 16 shows the guide screen “Ensaio”, where the user can perform and observe other options such as an elapsed time clock, a clock with countdown to the test, and the pressures of the combustion chamber carried out at the moment of the test. There is one visual alert when the internal pressure during tests exceeds the pre-established values.

Verification

This phase enables the user to identify and correct errors in the program. The following verification tests were performed:

a) software function test, in which one can verify if all requirements were contemplated in the codification;

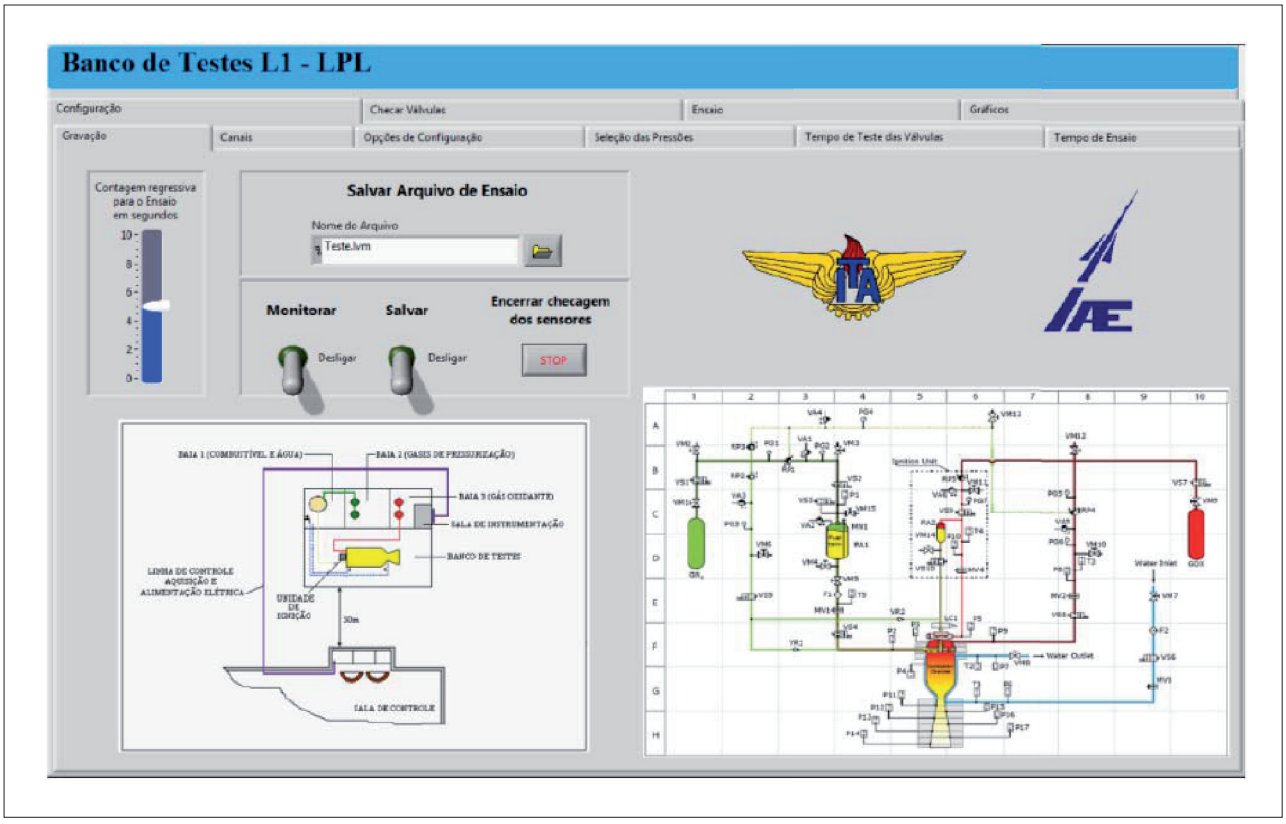


Figure 14. Initial screen of interface with user.

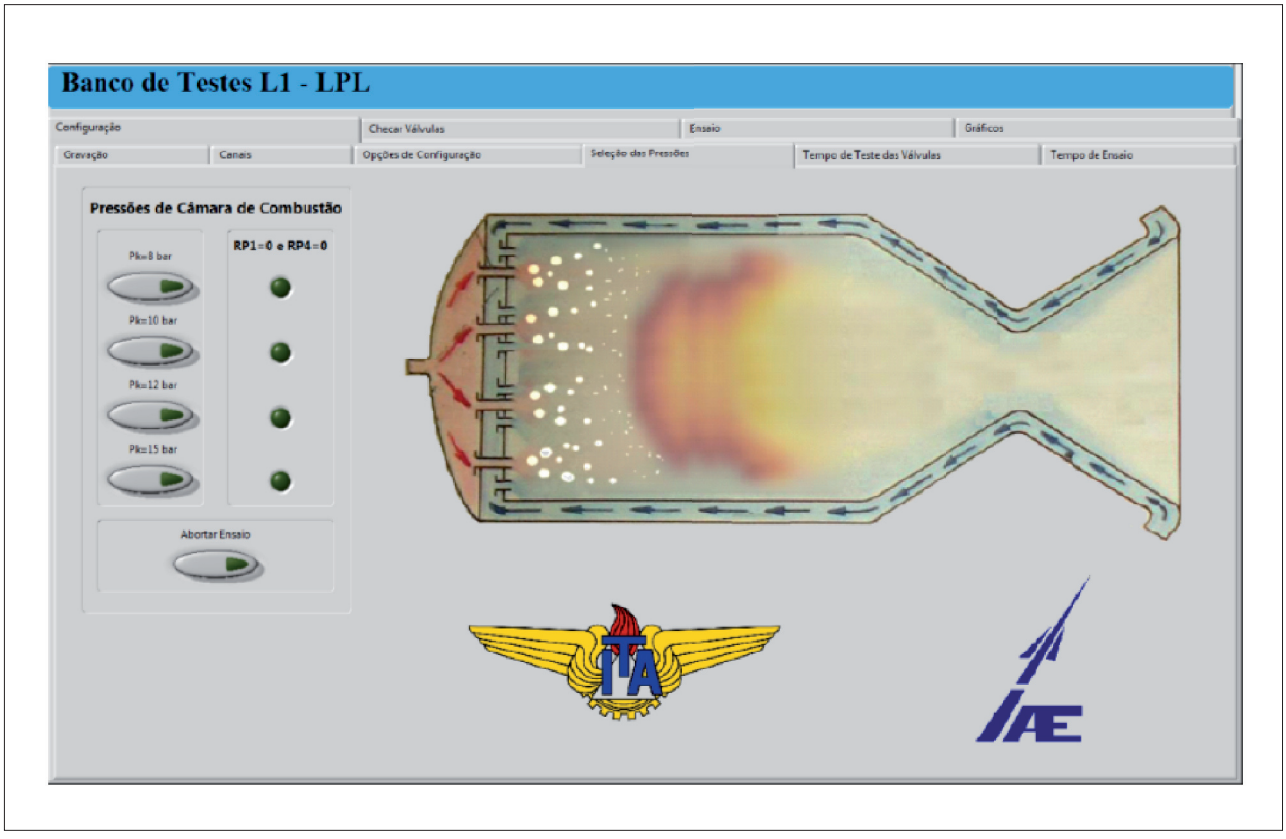


Figure 15. Guide screen “Seleção das Pressões”.

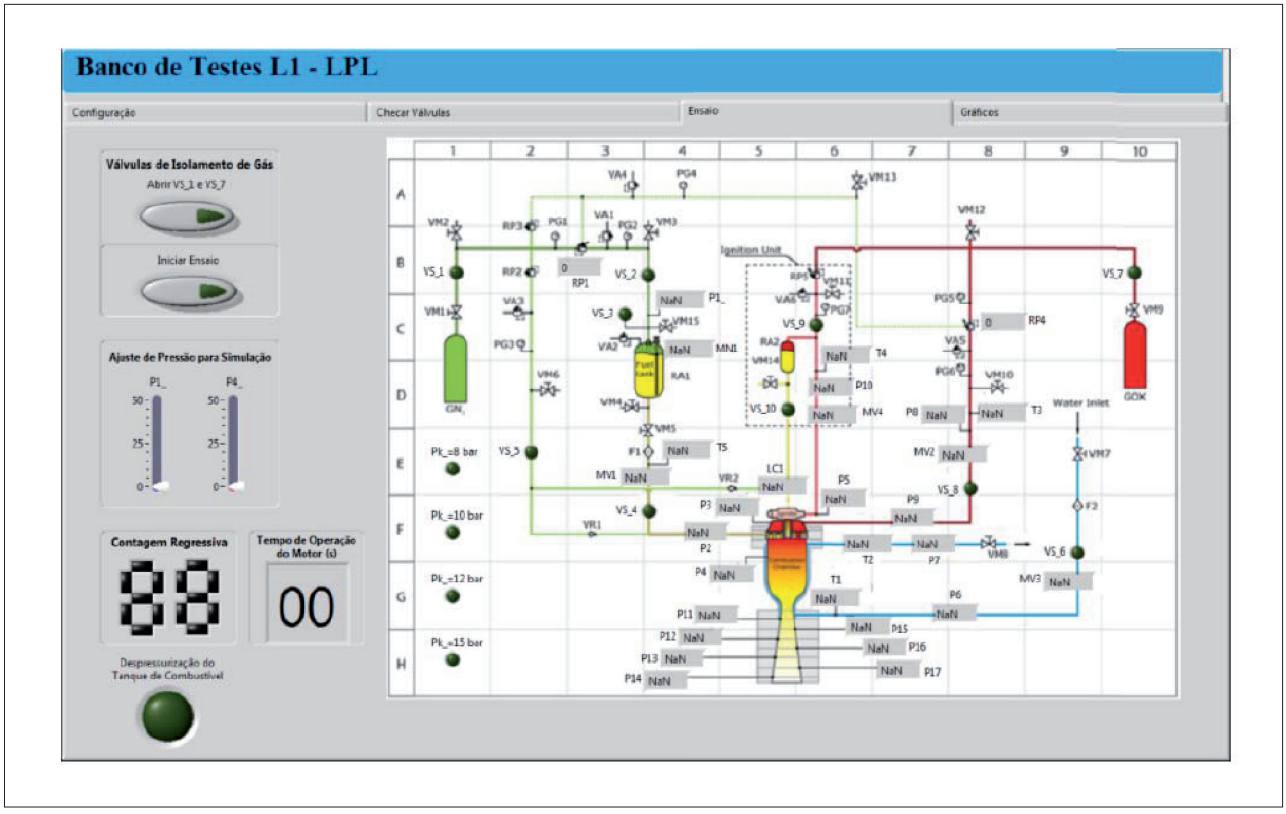


Figure 16. Guide screen "Ensaio".

b) black box testing of the functionality of software and its interaction with the user;

c) white box testing, in which the source code was tested in detail and all transitions of the program demands were verified;

d) integration testing, in which the architecture of the program and its communication with external interfaces were tested.

Description of test

The objective of test was to simulate the parameters through the computer in ambient Windows using the National Instruments Data Acquisition System. In order to simulate the opening and closing of the solenoid valves, a schematic panel of the hydropneumatic system was used with leds representing the state of the valves. These leds turn on/turn off at a determined time, representing the open/close state of the solenoid valves during the tests. To verify the data acquisition system, a device called DAQ-Acessory was used to supply a square wave as analogical input and was displayed and stored by program.

Implantation

In this phase, it was defined the position of the control hardware on the test stand inside the control room in the LPL (Fig. 9). The responsibility level of each operator during the test is in accordance with the standards of IAE.

This standard requires an IAE qualified professional to be the test supervisor and manage the step operations of the test stand.

CONCLUSION

This work presented the specification of an experimental firing test stand for a LRE and the apparatus to its development in order to carry out the laboratory work. The design of a hydropneumatic scheme and a LRE led to the development of a program to control and acquire data, providing conditions to the engine work in agreement with parameters of design.

All the phases of this project were done with two major aims: the excellence required in the field of Space Engineering and the state of the art of several Engineering fields like electricity, mechanics, thermodynamic, heat transfer, propulsion, combustion. These aims result in

higher knowledge and aggregate value to the development and investigation of LREs.

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