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# An Experimental Investigation On Lox/lch4 Reaction Control Thrusters

Arturo Acosta-Zamora
*University of Texas at El Paso*, aacosta29@miners.utep.edu

# AN EXPERIMENTAL INVESTIGATION ON LOX/LCH4 REACTION CONTROL THRUSTERS

ARTURO ACOSTA-ZAMORA

Department of Mechanical Engineering, ME

APPROVED:

Ahsan Choudhuri, Ph.D., Chair

Norman Love, Ph.D.

Felicia Manciu, Ph.D.

Benjamin C. Flores, Ph.D.
Dean of the Graduate School

## Dedication

This work is dedicated to my parents, family, and friends who have supported me throughout my entire education.

# AN EXPERIMENTAL INVESTIGATION ON LOX/LCH4 REACTION CONTROL THRUSTERS

by

ARTURO ACOSTA-ZAMORA, B.S. Mechanical Engineering

THESIS

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## Abstract

This work describes the development and preliminary testing of a thrust measurement system, in combination with a propellant feed and automation controls systems to test the performance of 8.9 to 35.6 N (2 to 8 $lb_f$) LOX/Methane reaction control thrusters. LOX/$LCH_4$ has come to be the main focus of next generation "green" propellants for future space exploration. As there is limited experience with this propellant combination, an effort is being conducted to research performance of rockets using these propellants. The development of a thrust measurement, propellant feed, and automation controls systems is necessary for proper testing and qualification of thruster performance. The propellant feed system includes three subsystems: (i) Liquid methane production and delivery subsystem, (ii) LOX delivery subsystem, and (iii) Propellants automated flow control and monitoring subsystem. A cart-based mobile liquid methane delivery system was designed in order to provide fuel to meet combustion requirements; a 2.2 L liquid methane production unit was also integrated within this system. Liquid methane production is accomplished with a condenser and utilizing liquid nitrogen as a chiller. Flow control and monitoring of the system is done remotely from a control room and is achieved by component commands sent through a LabVIEW program interface and a DAQ system. The program allows the automated execution of thruster experimental procedures and precision in control of timing and measurement. A torsional based thrust measurement system uses thrust to generate a moment upon a central axis, which induces displacement captured by a laser positioning sensor. Torsional pivots are used to provide a consistent and measureable resistance to thrust; displacement is correlated to a thrust value via the use of a calibration curve. Preliminary integration testing was conducted to ensure proper system functionality and response by firing a LOX/$LCH_4$ thruster at ambient conditions.

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# Introduction

This work described herein is the development and testing of a thruster performance analysis system and serves in partial fulfillment of graduate thesis work for a Master's Degree at The University of Texas at El Paso (UTEP). The Center for Space Exploration Technology Research (cSETR), a NASA University Research Center (URC), started the development of a cryogenic propulsion system for diverse rocket testing applications. This system included the communications system for control of instrumentation inside the bunker facilities, as well as the development of a cryogenic propellant delivery system. The design and development of these systems was started by former students at the center, however little to no testing was conducted on them on the order of what is presented here.

Being a NASA URC, partnerships with NASA engineers exist for specific projects. One such project is the subject matter for this work, which is a collaborative NASA-UTEP effort started to test a cryogenic bi-propellant reaction control system (RCS) thruster. The thrusters, referred to hereafter as the "Pencil Thruster," were provided to the Center for performance testing, as well as design improvement based on performance analysis. The Pencil Thruster is a unique type of RCS thruster as it was developed or retrofitted using a design for an Aerojet engine igniter; hence, specific performance and design data was limited.

The introduction of a thruster experimental setup in the laboratory facilities of the University posed a new challenge for the Center as it introduced unique and new levels of safety and control requirements in order to meet thruster testing demands. The Pencil Thruster is a 35.6 N (8 $lb_f$) bi-propellant reaction control thruster, having liquid oxygen (LOX) and liquid methane ($LCH_4$) as its propellant combination.

In order to provide the propellant combination required, a methane condensation system was designed, developed, and tested prior to integration with the thruster test setup. A thrust measurement

system was also designed and both systems were designed to meet the Pencil Thruster requirements. Finally, a set of individual systems was integrated and tested with a fully-automated controls system.

Testing and validation of a previously designed LOX system, the design and development of a methane condensation system, as well as the development of a thrust measurement and an automation and control systems were all part of the work to be described in this paper. All of these efforts were done to provide a thruster performance analysis system. Preliminary integration and performance testing was conducted on these systems by firing the Pencil Thruster at two different test stages: one for a gas-gas propellant combination and another for liquid-liquid combination.

This thesis is divided into 7 chapters: the first 4 chapters exploring the individual subsystems (LOX, LCH4, thrust measurement, and automation controls) design and development, followed by an explanation of the integration of such systems as a unit, finalized with results and discussion, summary and conclusions, and future work pertinent to the project.

# Chapter 1: Liquid Oxygen (LOX) Subsystem

The liquid oxygen (LOX) subsystem will be introduced in this chapter. A system description followed by the procedure used when preparing the delivery system will also be discussed.

## 1.1 Background and Introduction

The LOX delivery line, found in the bunker facilities of the Goddard laboratory in the college of Engineering at UTEP, was designed and developed by a former student from the Center [1]. 304 stainless steel ½"OD tubing was used as the propellant carrier. Cryogenic and LOX compatible valves and instrumentation were placed at different points in the propellant line. The system schematic as it was used for the Pencil Thruster setup is shown in Figure 1.1. A liquid methane ($LCH_4$) line was also designed though no production tank was ever included in the system. This line then served as a gaseous nitrogen purge for the experimental setup of the Pencil Thruster. The LOX and $LCH_4$ lines developed in the cSETR by former students contains the two main propellant feeds (red/green and blue respectively in Figure 1.1), with their respective liquid nitrogen ($LN_2$) line cooling supply and gaseous nitrogen purge. The LOX line is supplied via the use of a self-pressurized tank with 2 MPa (300 psig) pressure limitations. The line could only be subjected to 1.4 MPa (200 psig) as the relief valves were set to 1.4 MPa and solenoid valves are only rated to 1.6 MPa (230 psig).

In order to test the Pencil Thruster under liquid-liquid propellant combinations, the LOX line had to be validated and shown to be capable of delivering oxygen in its liquid form before injection to any test article. As mentioned before, the system was designed and assembled yet no testing or validation with liquid oxygen was done. Therefore validation experimental trials were conducted to analyze system cool-down characteristics. These trials provided a way to estimate line cool-down techniques and times to deliver oxygen in its liquid form. It is important to remember special storage, handling, and safety actions must be taken when dealing with LOX cylinders due to the volatile nature of the cryogen. [2]

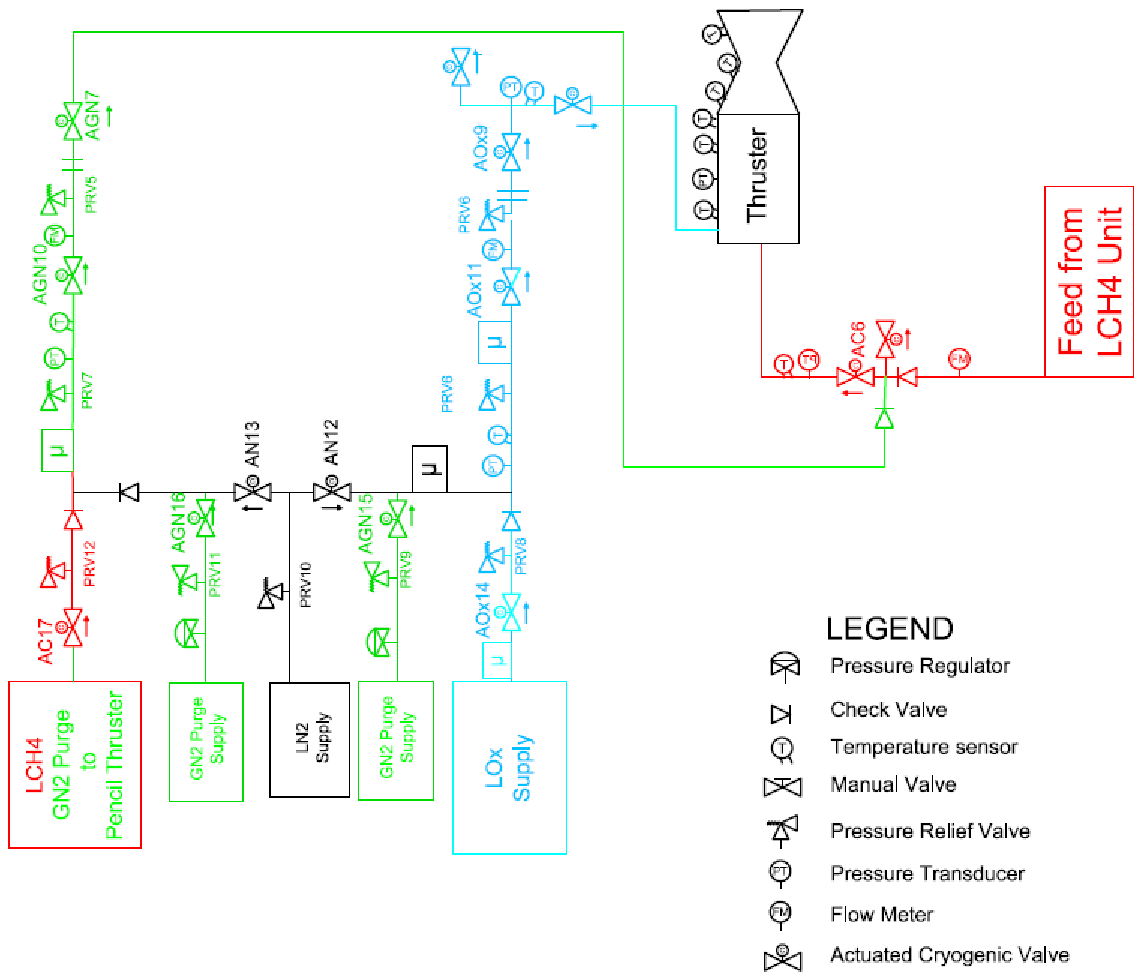


Figure 1.1: LOX Line Schematic

### 1.1.1 Cool-Down and Operating Procedure

In order to achieve liquid oxygen delivery to any test article, the delivery line and all of its components must be cooled to cryogenic compatible temperatures to avoid LOX gasification at any point in the line. Initial cool-down is done by flowing liquid nitrogen ($LN_2$) through the system. If the test article should not be cooled or restricts flow with holes smaller than 1/8" OD then a "bleed" valve must be positioned as close as possible to the test article in order to bring down line temperature of the delivery line. Fast (5-10 minutes) cryogenic cooling requires high flow rates. Therefore, whenever instrumentation having orifice size limitations is introduced to the system a by-pass line section must be added to speed the cooling process. In the case of the Pencil Thruster, combustion chamber injection

holes of 0.25 – 0.5 mm (0.01-0.02") in diameter were a limiting factor. As such, there was a need for the introduction of bleed valves in both propellant lines.

Once liquid nitrogen is seen coming out of the aforementioned valve, $LN_2$ may be run through the test article if needed and possible. It is important to mention that the user must cycle the bleed valve to avoid valve freezing. Even though all of the valves in the system are cryogenic rated, freezing was a common problem during the experimental procedures of the Pencil Thruster and valve cycling was determined to be an efficient way to avoid this phenomenon. Cycling repetition and timing is determined by the user's experience and familiarity with their system.

Once the desired temperature of the test article is reached, $LN_2$ flow may be halted and the system must continue to be cooled with oxygen. The user will notice a temperature increase upon start-up of LOX flow through the system, which is due to the fact that the oxygen is starting to flow from the tank. After a couple of minutes, the temperature should begin to drop again and the user should be able to see LOX coming out through the "bleed" valve and/or the test article. Steady state temperatures of -155 to -158 C (-247 to -252 F) were the target for this setup at an injection pressure of 100 to 150 psig (0.7 to 1 MPa).

**Cool-Down Validation and Characteristics**

A major requirement for appropriate testing was the characterization of line cool-down timing as well as validation of LOX flow at the end of the thruster assembly. Initial cool-down procedures for the line were initialized using liquid nitrogen ($LN_2$) flow, once liquid nitrogen was seen coming out of the thruster nozzle, LOX was now ran through the system. Both $LN_2$ and LOX were allowed to flow through the system, one at a time, by opening the bleed valve for the line, once a constant stream of liquid was seen coming out of the bleed, the thruster propellant valve was opened and the bleed valve was cycled.

Upon start-up of LOX flow, the temperature in the line raises due to the fact that LOX is now coming out of the tank and starting to flow. Figures 1.2 and 1.3 show the pressure and temperature data recorded during the cool-down and validation process of the LOX system. The intent of this validation

was to ensure proper functionality of the system, as well as to prove oxygen in its liquid form could be delivered to the thruster.

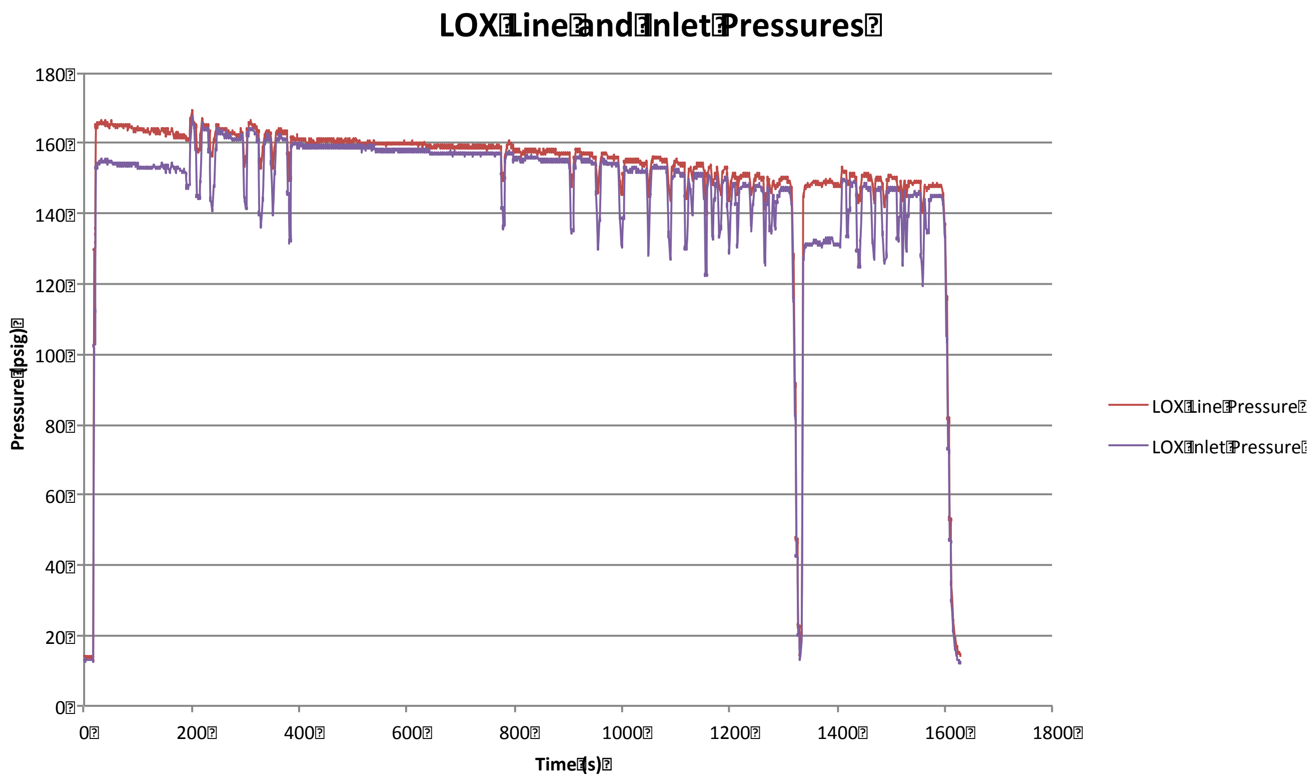


Figure 1.2 LOX Line and Inlet Pressures during cool-down validation

The pressure drops and rises correspond to user manipulation of valves (bleed and thruster) in the system, activating the flow of LOX through the line. It may be noted that these pressure drops correspond to a temperature drop as well, again indicating flow of LOX and cooling of the system. It will be discussed in the controls section that this process relies on the user's instinct and experience for appropriate system cool-down. Experimental trials showed repeatable cool-down behavior requiring 15-25 minutes for line cool-down time, starting from initial $LN_2$ flow and ending when LOX was seen coming out through the thruster's nozzle. Line pressure was measured at the middle section of the main propellant line, while inlet conditions were measured right before the thruster propellant valve.

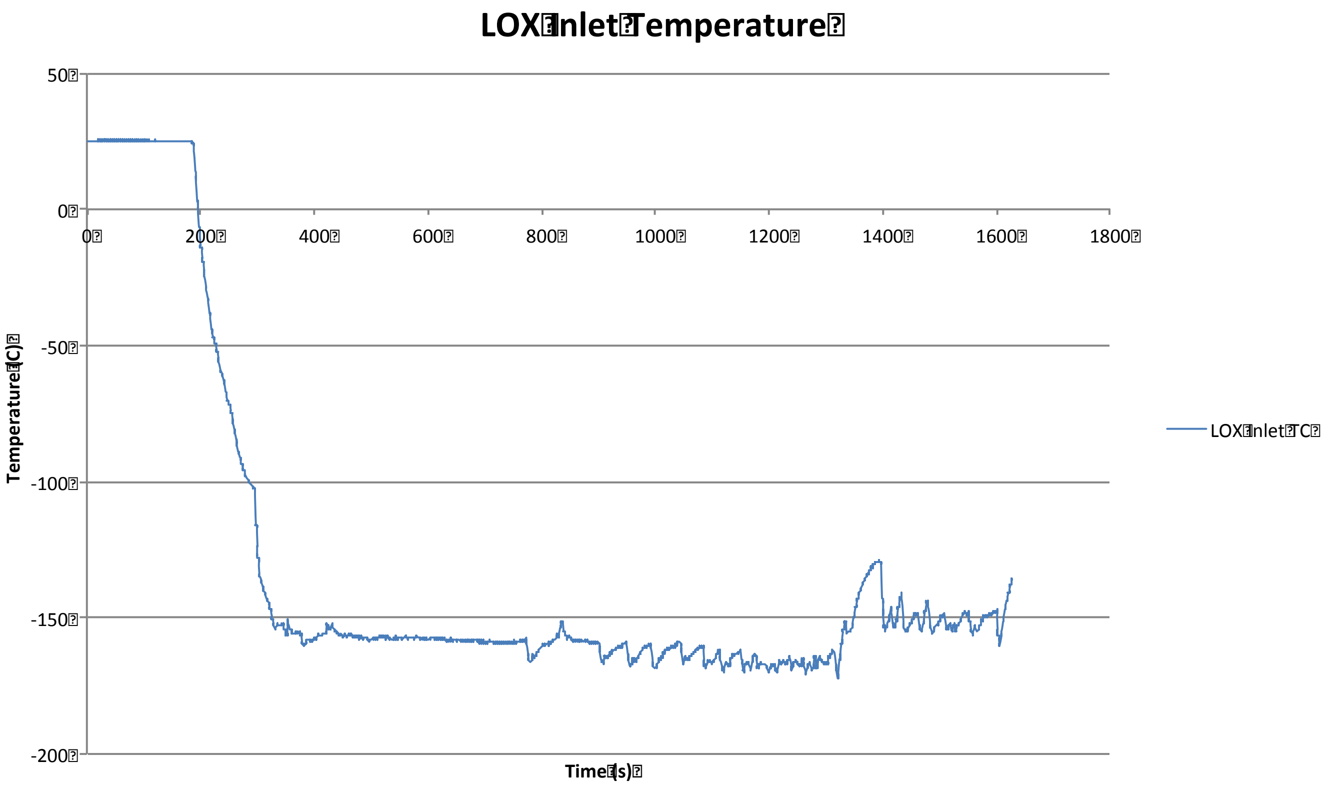


Figure 1.3 LOX Inlet Temperature

# Chapter 2: Liquid Methane Production and Delivery Subsystem

The following chapter introduces the methane condensing and delivery unit designed to produce liquid methane and supply the Pencil Thruster with fuel. Focus on the individual subsystem is presented in this chapter. Integration of this system with other subsystems and the experimentation when combined is discussed in the Experimental Setup section of this work.

## 2.1 Background and Introduction

The cSETR focuses on the research of alternative "green" propellants thus making methane in its liquid form ($LCH_4$) of particular interest for the Center. Liquid methane has become a major research focus, especially when combined with LOX, due to the fact that together they are a non-toxic, high density system [3]; yet this propellant combination has no flight history and very limited ground-test history. This combination also offers higher ISP compared to current systems, without the volume and power increases introduced in LOX/LH2 and MMH/NTO systems respectively [4]. However, this fuel is not readily available in the El Paso, TX area, and where it is available, industrial quantities are the minimum purchasable amounts. For safety and logistics reasons, storing such large quantities of flammable fuel in-campus was discarded; therefore an effort to condense gaseous methane into a liquid state within the laboratory was conducted.

An initial feasibility study was started by former students [1] , this consisted in modifying a 1L vacuum insulated *dewar* into a small scale open condenser, where liquid nitrogen ($LN_2$) was to be used for cooling purposes. A coil, through which $LN_2$ was flown in and out, was designed and placed inside the said *dewar,* while gaseous methane was flown into the same container though a different orifice. Gradual cooling of the methane inside the *dewar* was achieved, leading to methane condensation. This study proved to be successful; therefore a similar scaled approach was taken to produce a second generation higher capacity system capable of supplying $LCH_4$ to the "Pencil Thruster" for thruster testing.

### 2.1.1 System Requirements Definition

The design and development of the liquid methane propellant system was centered on meeting the requirements detailed in Table 2.1. These parameters were set by requirements of the "Pencil Thruster," and served as the basis for the determination of total propellant mass and volumetric flow required at maximum thrust level, thus providing a sizing parameter for the system. The propellant system was designed to produce a total of 2.2 L of liquid methane in a double ended stainless steel cylinder and a maximum operating pressure of 2.5 MPa (370 psig). A system description will be provided in the following sections.

Table 2.1: Methane production unit requirements

| | |
|---|---|
| **Thrust** | 8.9 to 35.6 N (2 lbf to 8 lbf) |
| **ISP** | >150s |
| **Flow rate** | 0.003 – 0.01 kg/s (0.006 – 0.05 lb/s) |
| **Mixture Ratio** | 1.5 - 2.4 |
| **Propellant State** | Gas, two-phase, and liquid |
| **Run time** | 2 min at 50% duty cycle |
| **Altitude** | $1^{st}$ phase at ambient |

## 2.2 Technical Approach

The design constraints provided to the team for the propellant requirements were presented in Table 2.1; based on such requirements the following relationships were used in order to determine the amount of propellant required for the experimental procedures, hence providing means to size the system. Equation 1, was used to compare a theoretical Isp calculation knowing a required Isp>150s must be achieved and knowing a thrust level, while equation 2, provides means of estimating total propellant flow required for a given thrust:

$$Isp = \sqrt{\frac{2kRT_c}{g(k-1)}} \qquad Isp = \frac{F}{\dot{m}_t} \qquad (1, 2)$$

$$\dot{m}_{total} = \dot{m}_{oxidizer} + \dot{m}_{fuel} \qquad MR = \frac{\dot{m}_{oxidizer}}{\dot{m}_{fuel}} \tag{3, 4}$$

It is important to note that the combustion parameters such as the gas constants k and R, and molecular weight, as well as chamber temperatures were obtained via use of both CHEMKIN and NASA's Chemical Equilibrium with Applications (CEA) software yielding similar results. Pressurization requirements were estimated by determining an approximated chamber pressure (Equation 5), followed by line pressure drop calculations and adding them up to determine an estimated propellant injection pressure. Pressure drop across the injector was also estimated, however due to the fact that limited data for the design parameter was available, this value was used as a base value for design purposes. Still, inlet propellant conditions were set by NASA requirements, an injector pressure drop of 30 psi was assumed.

$$w_p = \frac{P_c A_t k g_c}{\sqrt{k g_c R T_c}} \left( \sqrt{\frac{2}{k+1}} \right)^{\frac{k+1}{k-1}} \tag{5}$$

As it was previously stated, an initial proof–of-concept iteration was conducted to test methane condensation feasibility in the laboratory. The theoretical analysis for the original condenser design was based on a simple resistive heat transfer model, taking into account both natural and forced convection from the $LN_2$ to the coil and the gaseous methane surrounding , as well as the conductive heat transfer from the inside coil running in and out of the condensation tank.

The coil running through the inside of the condensing tank was determined to be 1/8" OD X 0.028" wall thickness, having 3 meters in length. A linear extrapolation of the previous iteration was determined to be sufficient for the cooling purposes required. Due to the nature of cryogenics and their variability in properties very sensitive to temperature and pressure, theoretical values were treated as base estimations for the condenser requirements and final design was based more on experimental results.

### 2.3 System Description

A cart-based mobile liquid methane delivery system was designed in order to provide fuel to meet combustion requirements of the Pencil Thruster. The design is inspired in a previous experimental

design done in the Center which used a vacuum insulated flask with a coil inside to condense methane. Successful methane condensation was achieved, however several problems limited the usability of such system, where pressurization of the liquefied methane virtually impossible. After successful condensation trials were accomplished, a linear scaling factor was approximated to design this 2$^{nd}$ generation liquid methane production system, which seeks to resolve the issues encountered with the first trial.

There are three main components of the system: 1) liquid nitrogen manifold 2) the liquid methane production tank and 3) the run tank. The liquid nitrogen manifold present in the system allows the user to connect a self-pressurized liquid nitrogen tank to the system with a flexible hose, giving the system capability of being placed in different positions for convenience. Two identical double ended stainless steel cylinders were utilized in the system, one to serve as a condenser for liquid methane production, while the other serves as a container which may be pressurized up to 9.7 MPa (1400 psi) for propellant delivery.

Liquid methane production is accomplished with a condenser, utilizing liquid nitrogen as a chiller. A coil, 3m (10ft) of 1/8" OD 316 stainless steel tubing, was designed and installed in the production cylinder where liquid nitrogen is routed through the coil, while gaseous methane surrounds it. This results in the gradual cooling of the methane, thus allowing for the production of liquid methane to be accomplished within the mobile unit itself. The condensation tank consists of a 2.25L Swagelok 304 Stainless Steel double-ended cylindrical tank, which was machined and re-welded in order to introduce the aforementioned coil for $LN_2$ flow. The top (welded) dome of the original cylinder was removed, an inlet and outlet hole were machined on this dome. Swagelok bulkhead fittings were inserted and welded to avoid any leaks; then, the designed coil was attached to the inside of the dome via the use of Swagelok compression fittings.

Thermocouple inlets were machined in the remaining bottom section of the tank; these E-type thermocouple probes serve as a way to determine the liquid level on the inside of the tank. These thermocouple inlets are provided via the use of 1/8" stainless steel bored-through bulkhead tube fittings, which allow the introduction of type E thermocouples into the middle of the tank to assure propellant

quality. Hence, $LN_2$ flows in and out of the tank through the coil, while gaseous methane is allowed in through the main port of the tank and its condensation level is measured by the thermocouples inserted into the tank. Figure 2.1 shows a graphical representation of the machining process undergone by the condensation tank.

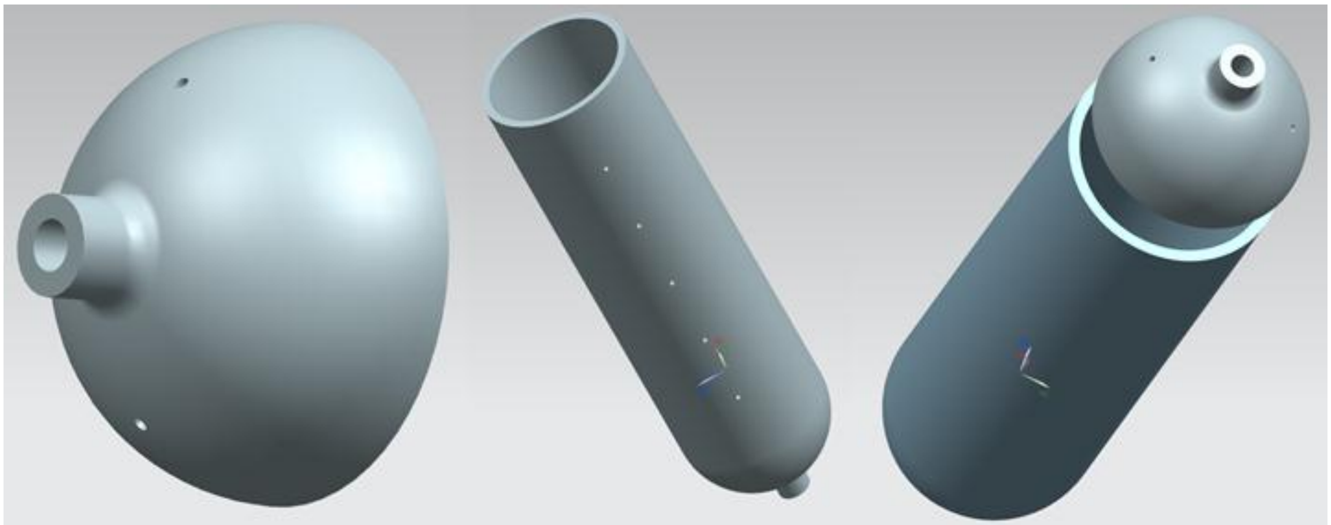

Figure 2.1 Condensation Tank Modifications.

Machining and re-welding the condensation tank, in order to install the coil on the inside, as well as to install thermocouple inlets in the sidewalls, for temperature measurements inside the tank, derived in the loss of its pressurization capabilities (originally rated for 1400 psig MOP). Therefore, a second identical tank was introduced to the system with the sole purpose of storing the liquefied methane for pressurization. The introduction of such tank added complexity to the system, however; transferring the condensed methane to the run tank became a necessity. In order to achieve liquid transfer without pressurization, a vertical stand was designed to fit both tanks, one underneath the other, therefore allowing gravitational forces to aid the transfer from the condenser tank to the run tank. Transfer is controlled via the use of a manual cryogenic rated valve. Both the condensation tank and the run tank have an additional copper coil following the tanks' cylindrical contour on the outside wall; these coils allow the flow of $LN_2$ through the outside of the tank, therefore speeding the cooling process. The rate at which liquid nitrogen flows through these coils is controlled via the use of manual cryogenic valves

connected to both of the coils; the user determines when and which valve to open or close. Figure 2.2 shows the assembly at an early stage as well as the outside coil configuration.

Figure 2.2 Liquid methane production and delivery subsystem integration

Once the cryogen is obtained, it is transferred to the second cylinder, for safety purposes, to allow pressurization for delivery, thus a vertical position was chosen for these cylinders to facilitate the transfer of the liquefied methane from the production tank to the run tank with the aid of gravitational forces. Vertical positioning of the cylinders is accomplished by placing the whole system to rest in a base consisting of a total of five stainless steel plates which support the tanks at both ends and attaches to the bottom of the cart; stainless steel nuts and washers are placed on both top and bottom sides of the plate to provide stability to the structure (Figure 2.2 middle). Four all-threaded stainless steel rods not only support these plates together and provide means of attachment to the cart base, but also allow the

user to adjust the system height by giving each plate independent movement capability, by simply moving the supporting nuts to the desired position; the system support base allows a maximum of 30 cm (12 in.) vertical displacement in any direction. The system was designed using ¼” OD X 0.035” wall thickness stainless steel tubing; appropriate cryogenic-rated instrumentation such as solenoid valves, relief valves, flow meter, thermocouples, and pressure transducers are placed in the system for monitoring and flow control. The liquid methane production and delivery unit schematic is shown in Figure 2.3.

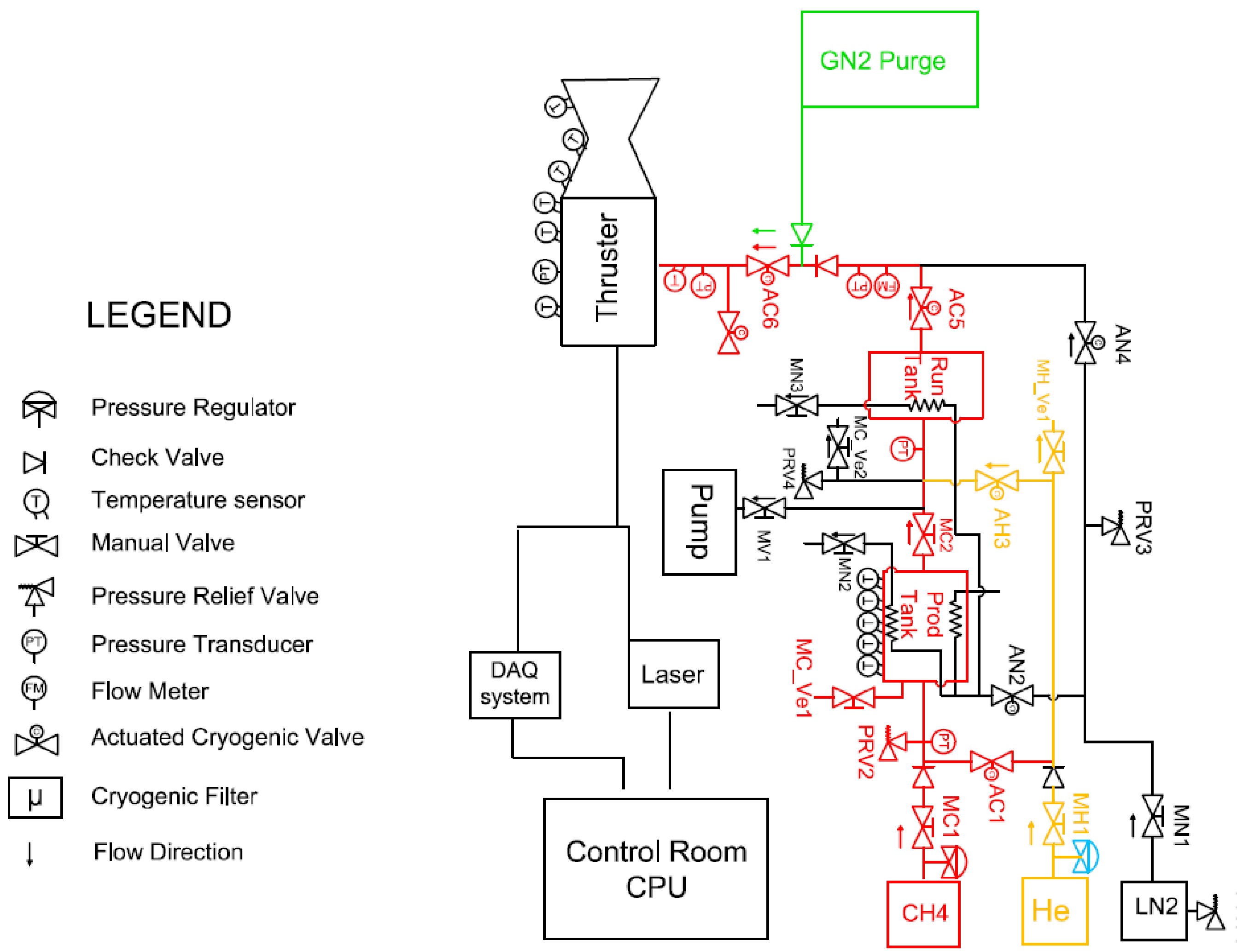


Figure 2.3 Liquid methane production and delivery subsystem schematic

Figure 2.4 Condensation tank, run tank, and final assembly of methane subsystem

A major advantage of the design of this system is its capability of being transported with ease. The mobility of this system allows the Center to be able to produce methane for use in different experimental setups without compromising the safety of the personnel or quality of the propellant. Such versatility is achieved by having a universal interface panel, to which all of the methane condensation system components (valves, transducers, etc.) are wired, which allows the user to connect the system to the main control room or independent setups' control systems. The system may be remotely managed form the control room found in the laboratory facilities of the university for thruster testing. A maximum operating pressure (MOP) of 370 psig sets the pressure limits on the system; every instrument used in the system is cryogenic-compatible to avoid temperature limitations.

Insulation is a very important system component, as it avoids heat gain in the system. Aerogel cryogenic insulation was chosen for this purposes; this insulation is commonly used for industrial cryogenic applications. Figure 2.4 also allows us to observe the insulating layers of Aerogel that were utilized to avoid heat leakage throughout the system. Preliminary test runs suggested heavy insulation was required for such a system to work properly and achieve a cryogen-friendly state. Experimental trials to determine appropriate insulation techniques and thickness were conducted in order to improve

the efficiency of the system. It was determined that two layers of Aerogel insulation provided enough insulation to maintain the liquefied methane at -168 C (-270 F). The insulating process is simple, first, a piece that fits the surface that the user wants to insulate is cut; the next step is to use duct tape to tighten the insulating piece around the tube section and hold it in place, it is not necessary to completely cover the Aerogel piece with duct tape; finally aluminum tape is used to cover the whole insulated section. If more layers are to be introduced to the insulation of a given system, the process is repeated for as many layers the user wishes to include.

## 2.2 System Instrumentation

As it was mentioned before, appropriate cryogenic-compatible instrumentation, including solenoid valves, relief valves, flow meter, thermocouples, and pressure transducers are placed in the system for monitoring and flow control. Table 2.2 summarizes the list of components and capabilities of the methane subsystem.

PX1005L1-250AV thin film cryogenic pressure transducers from Omega Engineering were chosen for this system. These transducers require a 10V excitation voltage and output 30mV; therefore requiring an amplification box, model DP25B-E in this case from the same vendor. The location of these transducers may be seen in the schematic presented before.

Cryogenic solenoid valves from GEMS Sensors & Controls were used for both the flow control in the methane production system as well as for the main propellant valves attached to the Pencil Thruster itself. These valves are fast-acting solenoid valves having a response time of 4-20ms depending on operating conditions. An excitation voltage of 12 V is required to operate the valves at manufacturer specifications.

Manual cryogenic globe valves were used to control the flow of liquid nitrogen through the outside coils in the condensing and run tanks, as well as to control the transfer of liquid methane from one tank to the other. These valves have a brass body construction with a MOP of 4.1 MPa (600 psig).

Temperature measurements are taken not only at the condensation tank, but also in the delivery line. Lakeshore temperature diodes were placed in the surface of the delivery line in order to analyze the cooling of the delivery line before experimental procedures. The temperature diodes require an

excitation signal of 10 μA and an output a signal of 15V DC. These diodes are connected to a temperature monitor, from which readings are routed to the DAQ system for redundancy

## 2.3 Operation Procedure

The procedure for liquid methane production will be described in this section. This process may vary slightly every time depending on the user, environmental conditions, and liquid nitrogen availability; nonetheless, an overall description will be presented here. A detailed step-by-step experimental procedure is appended to this work.

The initial step in the condensation process is to pull vacuum in both the condensation and run tanks. This prevents the condensation, and eventual freezing, of air inside the tanks during the process. A vacuum pump is connected to the system as shown in the system schematic (Figure 2.3) and vacuum is pulled.

The next step is to open the liquid nitrogen tank and the system valves controlling the flow through the inside and outside coils. Once liquid nitrogen is running through the system (inside and outside of condensation tank, and outside of run tank) gaseous methane is let into the condensation tank at a pressure of 34 KPa (5 psig). It is important to note that, at this point, the transfer valve (valve between condensation and run tanks) is closed; therefore only the condensation tank is being filled, however the run tank is being cooled as well by the outside coil. Depending on the amount of liquid methane desired, the duration of this process varies. The level of liquid methane is gauged via the thermocouple probes found inside of the condensation tank. The liquefied methane reaches a temperature of -168 C to -170 C (-270 to -274 F), if the temperature continues to drop freezing might occur; hence, the user must regulate the flow of liquid nitrogen though the system's coils.

Upon completion of the desired condensation, $LN_2$ flow is stopped and the transfer of the liquefied methane into the run tank may begin. Due to the fact that the section of line between both tanks was not cooled at all other than by the convection found between the liquefied methane and the tank inner surface, and subsequent conduction from the tank to the line, there are liquid losses through the transfer process. This surface temperature change causes the methane to vaporize, therefore creating vapor bubbles in the system. In order to avoid a "vapor-lock," in which gasified methane would not

allow the liquid to flow down to the run tank, a manual valve (valve MC_Ve2 on Figure 2.3) is opened on the run tank to allow the vaporized methane to come out of the system, while the liquid flows down to the run tank. The transfer process may take from 15-25 minutes to complete; transfer level from the condensation tank is gauged via the use of the thermocouple probe in the condensing tank. The user may see an increase in temperature in each of the thermocouples as the level of liquid methane decreases. Unfortunately, there is no way to measure the amount of liquid actually transferred to the run tank. Delivery line cooling with $LN_2$ should begin in parallel with the transfer process; this is done by opening valve AN4 (Figure 2.3) and the thruster valve as well.

An additional thermocouple is attached to the run tank skin, to approximate surface temperature of the tank on the top dome. Run tank temperature should be monitored at all time and ensure that it is below -75 C (-103 F) to minimize liquid losses. If the temperature of the tank increases during the transfer, the $LN_2$ flow may be reactivated and focused to flow through the outside coil of the run tank preferably.

Once the last thermocouple (lowest positioned TC in the condensation tank) reaches a temperature of -150 C (-238 F), the user may close the transfer valve, as most of the liquid should be in the run tank at this time; the flow of $LN_2$ through the delivery line should be stopped as well. With all the valves in the system closed, the helium tank should be opened and set to the desired test pressure. At this point, the liquid methane is ready to be delivered to the test article. Further discussion of this procedure geared specifically for the Pencil Thruster experimental procedures will be presented in the Experimental Setup chapter.

# Chapter 3: Thrust Stand Measurement Subsystem

The following chapter introduces the thrust measurement subsystem designed and developed to measure thrust generation of the Pencil Thruster. Similarly to the last chapter, a focus on the individual subsystem is presented here; however integration with the other subsystems will be discussed in the Experimental Setup section of this work. A torsional-type thrust stand was designed and developed for RCS thrusters.

## 3.1 Background and Introduction

The development of a thrust-measuring device is necessary for accurate and repeatable thruster performance analysis. A previous smaller scale iteration of a torsional thrust stand at the Center was developed by a different group of students, for evaluation of thrust up to 5N (1.1 $lb_f$) having successful results [4]. There are, however, some issues found with the application of this type of thrust stand in lower thrust levels including sensitivity and calibration issues, as well as noise overwhelming the system response; still, torsional-type thrust stands have been successfully used in micro-Newton class thruster applications as a high resolution and repeatability option [5].

The principle behind a torsional thrust balance is to create a moment arm upon a central rotating axis containing frictionless pivots allowing rotation, by using thrust as the rotation driver; a counterweight arm is included across the axis, thus balancing the thruster weight. This work represented a novel effort to extend the application of this measurement technique to a higher thrust class, and develop a torsional thrust measurement stand to analyze the performance of the Pencil Thruster, an 8.9 to 35.6 N (2 to 8 $lb_f$) reaction control thruster. With higher thrust production, noise problems are considerably diminished when comparing the displacement induced; also, larger thruster implementation is enabled by a stronger construction. Preliminary test results, in which the effects of increasing thruster weight were explored, will be further discussed in the results section of this thesis.

### 3.1.1 System Requirements Definition

Table 3.1 details the requirements that served as the basis for the design and development of the torsional thrust stand. These parameters were adjusted to meet criteria required by the Pencil Thruster and served to determine total mass and stiffness required at this thrust level, thus providing a sizing

parameter for the system. The technical approach section will discuss details on the calculation of the system requirements.

Table 3.1: Torsional thrust stand requirements

| | |
|---|---|
| **Thrust** | 8.9 to 35.6 N (2 $lb_f$ to 8 $lb_f$) |
| **Application** | Steady state and pulsing |
| **Run time** | 2 min at 50% duty cycle |
| **Resolution** | 0.09 N (0.02 lb) |

### 3.2 System Description

A torsional thrust balance design was chosen due to its applicability in low thrust situations as previously mentioned. The operating principle of a thrust balance is to use thrust to generate a moment. A thruster is placed at a known distance from a fixed rotating axis; a known resistance or stiffness is provided by such axis through the use of torsional pivots. Hence, the moment generated during thruster operation produces a moment arm displacement. In turn, this displacement can be measured in various ways; in this case, by an optical laser; calibration curves are used to correlate this displacement measurement to a thrust value.

The use of frictionless torsional pivots was selected to provide system stiffness; these pivots possess two mounting cylinders; one is fixed to the stationary object, while the other to the oscillating object. A flexible tab provides resistance to the induced moment as it is being strained, therefore providing stiffness. A total of four frictionless torsional pivots manufactured by The Riverhawk Company was selected, considering the mass used for design purpose;. Each pivot induces a stiffness of 7.52 in-lb/deg, providing a total spring rate of 30.08 in-lb/deg. These pivots are positioned inside the base (Figure 3.1) which serves as the axis of rotation for the system and through which setscrews are inserted to fix the stationary ends of the pivots. The base, holding the entire assembly, can be bolted to a solid structure or surface. The dynamic ends of the pivots are secured, by means of setscrews, to a secondary moment arm block (Figure 3.2), to which the moment arm is attached; therefore, the block is

allowed to oscillate, while the housing remains stationary. The use of these pivots eliminates any tare forces that would have been generated by using traditional bearings.

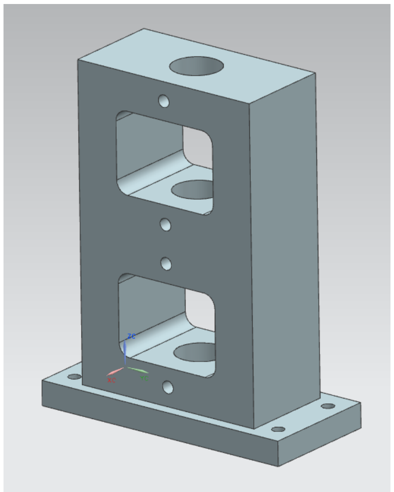

Figure 3.1 Base and rotating axis of thrust stand

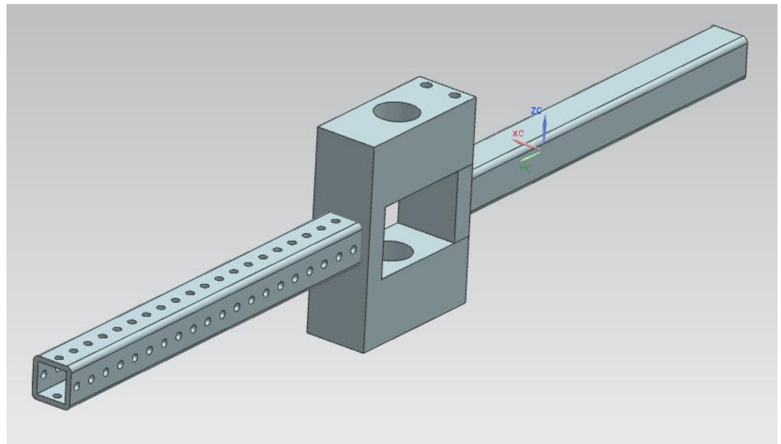

Figure 3.2 Moment arm block with counterweight and moment arm assembly

The small angle assumption was used for the design of this stand, therefore the amount of deflection induced by a given thrust level must not exceed 5 degrees. Therefore, in order to keep a consistent displacement at lower and higher ends of thrust, thruster location along the moment arm is important. For the maximum thrust level (fifteen pounds) the thruster should be placed closer to the pivot axis (3.5 inches), generating less moment; at 35.6 N (15 $lb_{f,}$) and a distance of 8.9 cm (3.5 inches), a displacement of 2.71 mm (0.11 in )is expected. Likewise lower thrusts can be measured with the same resolution and produce a similar displacement when position on the far end of the moment arm away from the base. The moment arm (Figure 3.2), which is attached to the base and is 25 cm (10 inches) long, possesses mounting holes on all four faces of the bar at half-inch intervals to facilitate thruster mounting. For weight reduction purposes, the both the moment and counterweight arms were made out of hollow bars.

In order to counteract the moment generated by the thruster weight on the moment arm, a counterweight arm (Figure 3.2) was developed to balance forces on the vertical direction acting on the pivot axis. The counterweight arm is 25 cm (10 inches) in length as well, however no positioning holes

were machined in it, instead a custom-made counterweight may be positioned anywhere along this arm and fix to a position via the use of a set-screw. Depending on the test article mounted on the stand, different counterweights at different lengths may be needed.

### 3.3 Technical Approach

One major consideration for the design of the thrust stand was the natural frequency of the system, as it limits the frequency capabilities of the stand. . An unloaded natural frequency of 10.3 Hz (Equation 6) was determined for the stand. Figure 3.3 shows the complete thrust stand assembly model. Moment of inertia estimations for individual dynamic components of the system were calculated using Equation 7.

$$w = 2\pi\sqrt{\frac{k_t}{I_t}} \tag{6}$$

$$Moment\ of\ Inertia = I = \frac{m*l^2}{12} + m*c^2 \tag{7}$$

$Note: Momemt\ of\ Inertia\ is\ taken\ for\ each\ dynamic\ component\ of\ the\ torsional\ thrust\ stand$

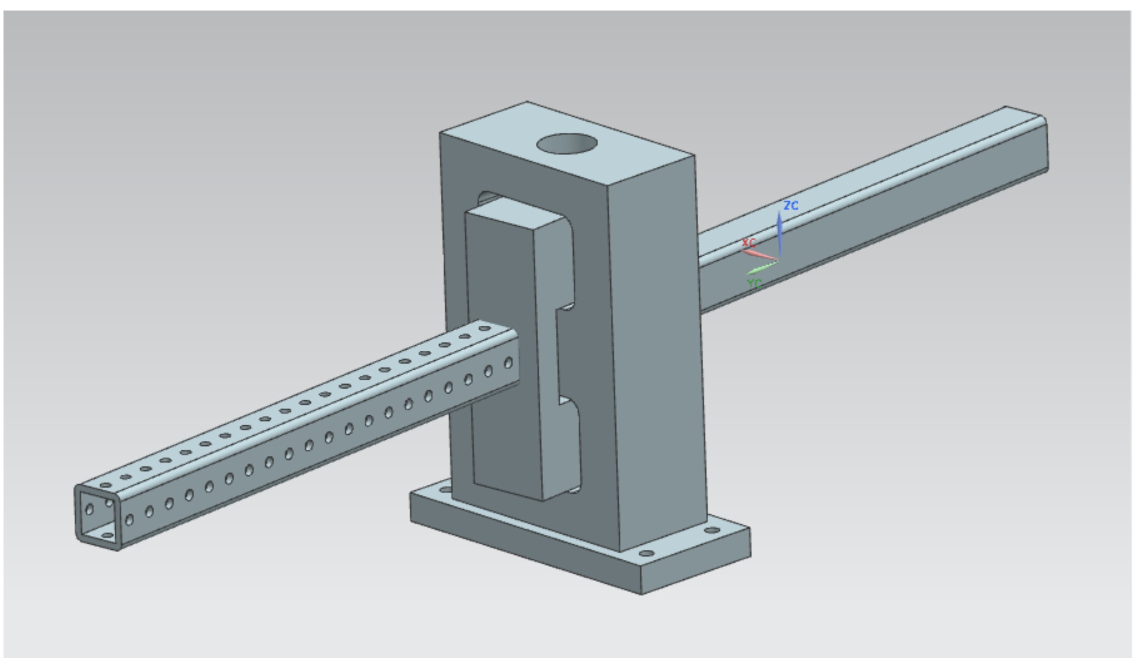

Figure 3.3: Torsional-type thrust stand assembly

Due to the fact that this stand would possibly be in contact with LOX, 304 stainless steel was the material of choice for construction. All components of the thrust stand were designed with this application in mind, with the exception of the torsional pivots, which are commercially available through The Riverhawk Company. Figure 3.4 shows the thrust stand with the Pencil Thruster mounted on top of it.; all of the main components are pointed out as they are positioned in the system.

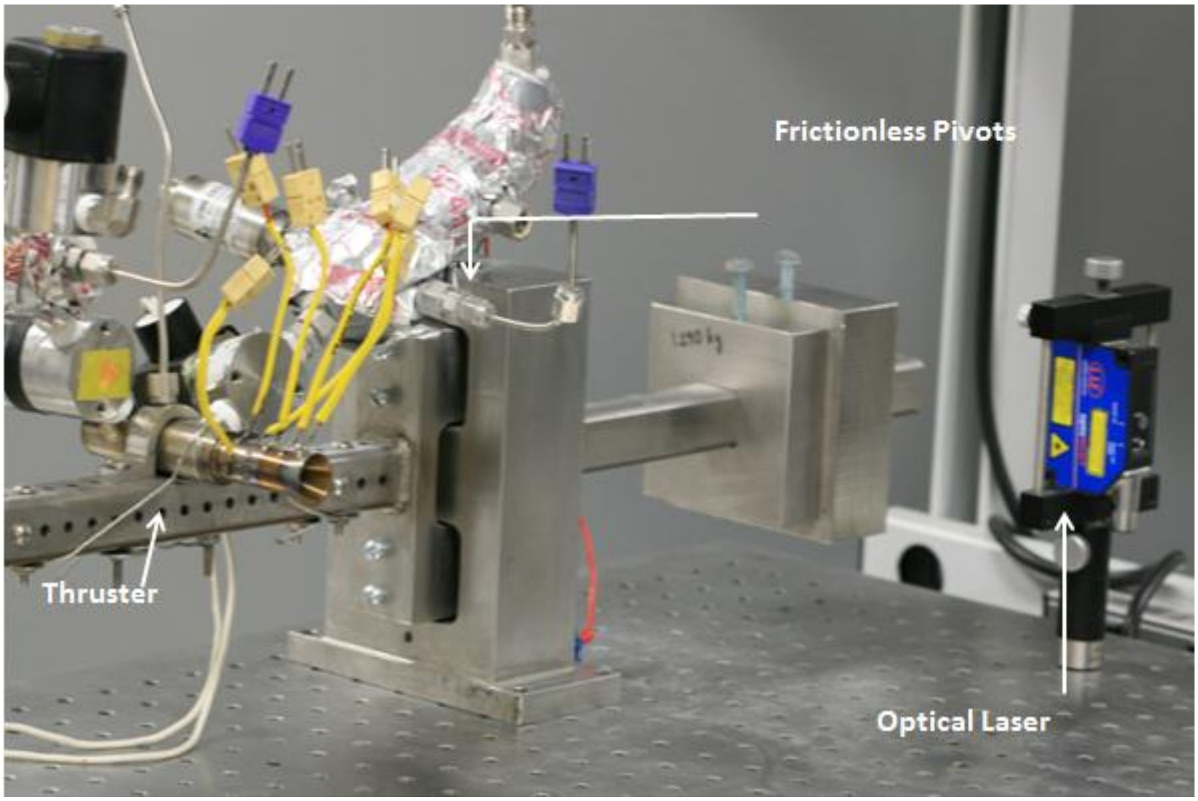


Figure 3.4: Thrust stand and thruster final assembly

### 3.4 Calibration

Calibration procedures are crucial in the development of a thrust stand; these ensure that the added stiffness of the propellant lines and thruster weight are taken into account for the displacement measurements from the laser. This process provides a curve by which all displacements, recorded by the laser system during thruster operation, can be correlated to a thrust level. Performance results of the thrust stand are closely related to the quality of calibration performed. Therefore, special attention was placed during this procedures; the process will be thoroughly explored in this section.

A calibrated mass set was utilized to provide a known force acting on the stand. A low friction pulley served to redirect the force such that it acted parallel and concentric to the thruster nozzle axis. This process seeks to simulate the thrust generated by a rocket under actual operation, providing a displacement relationship for each force applied on the moment arm.

As it was stated before, an optical laser, located on the counterweight arm of the stand (Figure 3.4), measures the displacement induced by each individual force applied. Individual masses ranging from 0 to 4 kg (0 to 9 lb) were placed in increments of 400 g (0.9 lb) , recording the displacement induced each time. Individual calibration trials consisted of runs starting at a natural state without weight, then gradually increasing the weight to 4 kg (9 lb) , and finally decreasing in the same gradual manner back to zero. Due to the laser resolution, the system's sensitivity to any alteration in a given experimental setup may prove to be significant; therefore calibration procedures took place before testing.

Typical calibration curves for the Pencil Thruster setup at different testing stages and therefore different weights are shown in Figure 3.5.These stages differ in the amount of instrumentation and feed lines on the thruster system, therefore affecting the mass at each stage. There is an increasing slope for the calibration curve as the mass supported by the stand increases, implying more force required to produce a lower displacement.

The only data recording taken directly from the thrust stand is the displacement of the moment arm; this is accomplished via the use of a Opto-NCDT 1402-100 displacement laser. This laser has a measurement range of 100 mm with a resolution of 0.02 mm which exceeds the resolution listed in the requirements table. The minimum force detectable for this system is 0.44N (0.1 $lb_f$)

Due to LabVIEW compatibility issues, the laser data was acquired using factory laser software, which allows for the establishment of a start point from which all displacements are to be measured. Displacement data can be recorded at a sampling rate of up to 1500 Hz and written to a data file. This data can then be plotted and the displacements can be correlated to a thrust value using the curve generated in the calibration process.

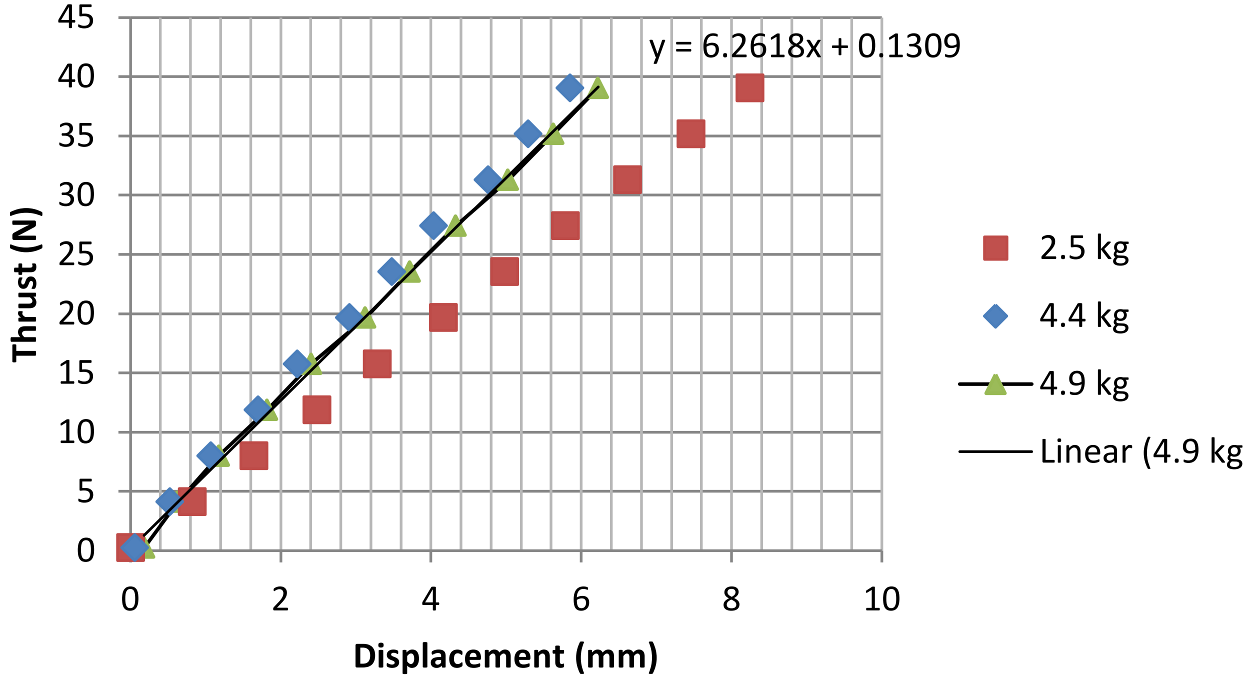


Figure 3.5: Pencil Thruster Setup Calibration Curves at different system weights

# Chapter 4: Controls and Data Acquisition Systems

Controls and data acquisition systems used to integrate all of the subsystems described in previous chapters are introduced in this section.. This subsystem allows the compilation of subsystems into the Pencil Thruster experimental setup. Similarly to the last chapter, a focus on the individual subsystem is presented here; however integration with the other subsystems will be discussed in the Experimental Setup section of this work.

## 4.1 Background and Motivation

The Goddard laboratory bunker facilities and instrumentation were controlled via a system previously developed by a former cSETR student. While control via manual switches as well as user interaction with LabVIEW software was achievable with this system, this method and level of control proved to be insufficient for more elaborate and complex testing such as thruster tests. An unfortunate failure during initial Pencil Thruster ignition testing procedures, proved the system to be inappropriate for these types of tests. The need for a controls system capable of running a pre-set experimental sequence without human interaction was clear after this event, therefore an effort to develop such a system was conducted.

### 4.1.1 Pre-existing System: Analysis and Validation

The existing controls system in the laboratory facilities was designed and developed, but not tested extensively as it would have been ideal; a limited number of valves and instrumentation was utilized for the preliminary test of the control system, therefore only a limited number of channels in the system were tested.

The experimental setup for testing the Pencil Thruster required the usage of most of the channels available for valves and instrumentation, and even the creation of more of these. This experimental setup allowed for appropriate testing of the previously assembled controls system under actual operation for experimental procedures. Communications between the control room computer and the valve and instrumentation located inside the bunker was validated; the emergency stop was fixed and tested as well.

The previous control and instrumentation system consisted of a communications system that was established between the control room and the bunker, via direct wiring of signal channels between two connection boxes. These boxes housed female headphone jacks whose ends where wired from the bunker box to the control room box. Any instrumentation or data acquisition device is connected in the control room as well as in the matching channel in the bunker side. This type of construction gives the user versatility when using the system, by simply changing the appropriate audio connection for any given instrument the user wishes to control or acquire data from. Specific instrumentation and configuration details may be found in the work of Betancourt [6].

## 4.2 Controls System Structure

Discussion has been made about the Pencil Thruster experimental setup requirements of a large number of valves and instrumentation. The controls system has to control the three main subsystems within the setup:

1) LOX delivery and line subsystem
    - Cool-down and delivery
2) $LCH_4$ delivery line subsystem
    - Condensation and delivery
3) Thruster subsystems
    - Instrumentation, thrust stand, and ignition

While the LOX subsystem's control posed no major issue considering the fact that few valves and instrumentation were in need of control, the $LCH_4$ subsystem proved to be a major challenge to control remotely from the control room. This subsystem required manual control of 6 valves (with both DC and AC power requirements) during the methane condensation process; however it also required the automation control for the experimental procedures. The solution to this problem was found in making separate control programs for the condensation process and the experimental process. Nonetheless, the integration and timing of all of the systems described before posed the major challenge.

### 4.2.1 System Requirements

The requirements upon which the system was designed and developed will be described in this section. As it was previously mentioned, full automation was to be achieved; meaning that no user interaction would take place with the computer for control once the experimental procedure started. An additional requirement was to implement "redlines" or limits on the instrumentation readings during the experimental sequence; if such limits were surpassed at any stage of the experimental run, the program should automatically, without user interaction, trigger a pre-set emergency sequence. This emergency sequence would need to be an automated sequence as well, ran without any user interaction and triggered only by instrumentation readings. Derived requirements coming from the aforementioned included: time delay of less than 40ms, no slow-down of system due to over usage of computer buffer, and capability of controlling the system in both manual and automated modes with LabVIEW.

### 4.2.2 Condensation Manual Control System

As it was mentioned in the subsystem description, methane condensation is a process that may not be automated, unless smart system integration took place. This process requires the user's instinct and experience to cycle (open/close) valves when needed in order to achieve condensation of the gas to the desired conditions. An additional requirement for this process is the simultaneous cool-down of both the LOX and $LCH_4$ lines, where the user determines when to cycle specific valves to make the process efficient to avoid waste of $LN_2$.

For this section, what is referred to as "manual control" is a program in which the user controls valves and instrumentation through LabVIEW virtual switches, not physical manual switches as the word might imply.

**Programming Structure**

The structure and programming of this program is relatively simple. Overall, there are two main WHILE loops; one houses all the analog inputs to the system (all of the instrumentation being utilized), while the other houses the digital outputs (ports and lines used for valve control). DAQ Assistant functions are used for this program, requiring one of these per data acquisition device in use.

Figure 4.1 shows the valve control mechanisms; as stated before, these are housed in a WHILE loop in the form of switching controls working on a true or false statement activated via a virtual switch that a user is able to activate or deactivate. Since individual valves are operated, no logic control is required for this system. It is important to note that there is no limitation programming–wise as far as which or how many valves may be open at any time, however there are some hardware and power supply limitations. Individual DAQ Assistant functions are introduced per device in use.

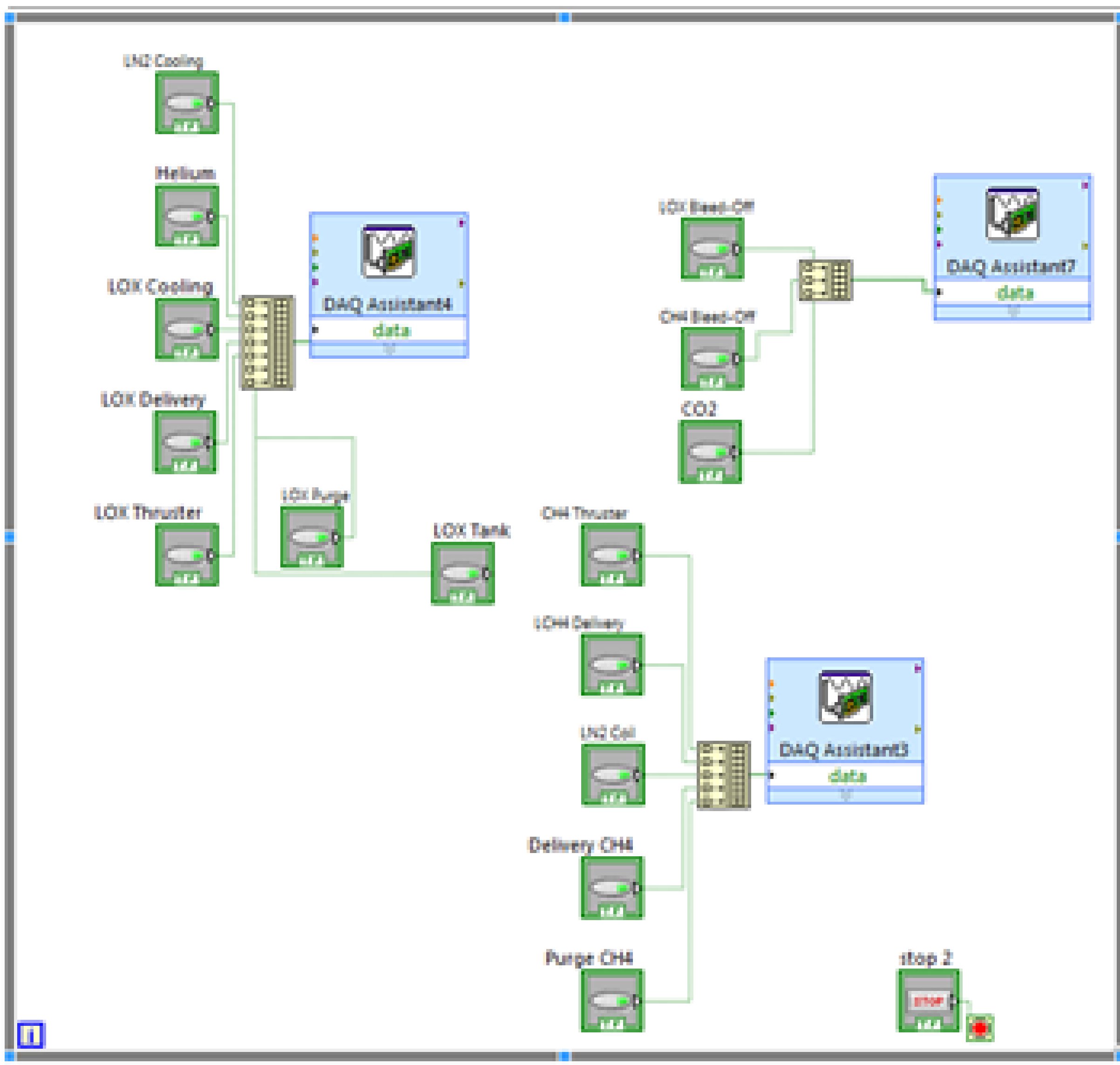


Figure 4.1: Condensation Valve Manual Control Programming

A second WHILE loop houses all of the instrumentation devices and indicators. Figure 4.2 shows the graphical user interface (GUI) for this program. The bottom shows the systems that needed

control: Condensation system, thruster valves, LOX line propellant system, and an emergency carbon dioxide ($CO_2$) line.

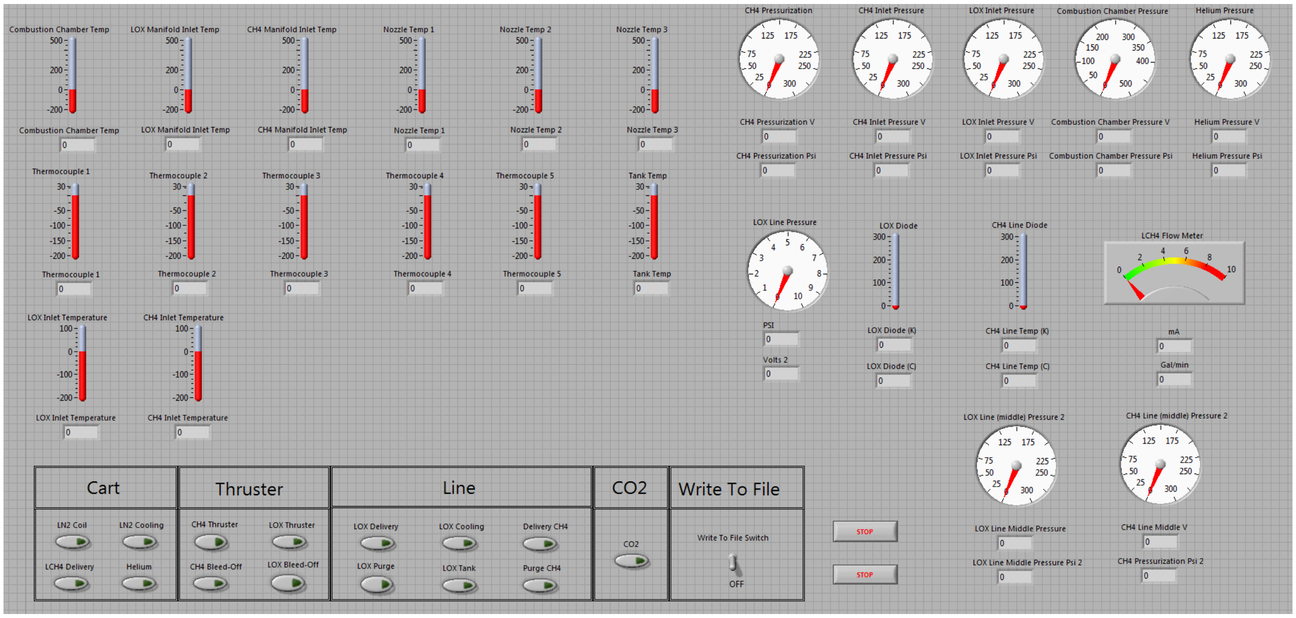


Figure 4.2: Condensation Program Graphical User Interface (GUI)

### 4.2.3 Automation Control System

The software of choice for the development of the automated controls system was National Instruments' LabVIEW; this software was readily available in the laboratory and was the basis for the previous control system development as well, therefore making it a logical choice. LabVIEW offers a wide range of programming capabilities, making it a suitable software choice for this type of application.

The overall goal of the development of this program was to avoid user interaction during experimental sequences and, therefore, eliminate human error during experimental procedures. The program allows the user to develop and record an experimental sequence, indicating at what time any given valve opens or closes. This is recorded through a text file, which is later read and activated by the automation program. Also, temperature and pressure limits were set as triggers for an emergency sequence, whenever any of these parameters were surpassed from the preset limit. No user interaction is

needed upon selection of the text file to read. The operating principles will be further discussed in detail the following sections.

**Programming Structure**

The automation programming structure is by far more intricate than the condensation control described in the previous section. However, it will be simplified into three main parts for discussion, all of which will be thoroughly described in this section: 1) instrumentation loop, 2) automation loop, and 3) emergency loop. These will all be described in the order listed.

**1) Instrumentation Loop**

The instrumentation loop will be described first; this loop contains all of the instrumentation in the subsystems utilized during experimental firings of the Pencil Thruster, which are all of the subsystems described in the previous three chapters of this thesis. A WHILE loop, conditioned by a manual virtual STOP switch, contains all of the indicators for pressure, temperature, and flow present in the LOX and liquid methane subsystems, and thruster body. Measurements are continuously read and/or recorded, at a previously set rate, upon the startup of the program and activation of the record switch. Due to space constraints and for ease of discussion, the structure will be broken down into sections, providing an explanation of the functions used at each step. Figure 4.3 shows the first loop structure to be discussed, in which DAQmx functions initiate data acquisition.

As it may be noticed, unlike the manual control program, the regular DAQAssist function was not utilized; instead, for more intricate level of control, the DAQmx functions were used. First, a virtual channel is created for each of the different types of measurements in the system (i.e. voltage, current, temperature, etc). It is at this point where the user indicates the software which devices and channels data will be gathered from. Function specifics may be searched on the LabVIEW help catalog under “Create Virtual Channel” function. After the creation of a virtual channel, the “Stark task” command is used; this function is automatically started by the DAQAssist manager, however with the DAQmx, the user must indicate the software at what point to start the task. It is important to note that for any one device, there may only be one task initiation; if more than one task is initialized for any single device, LabVIEW will return an error message.

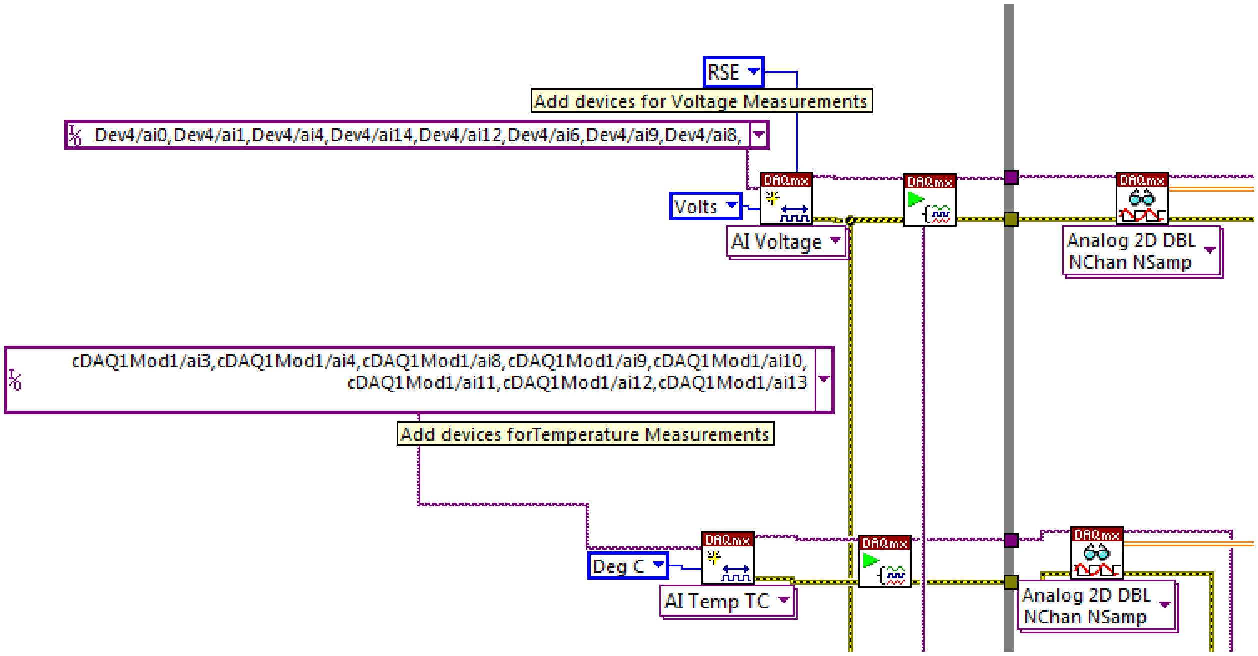


Figure 4.3: Virtual Channel Creation and Task Initiation

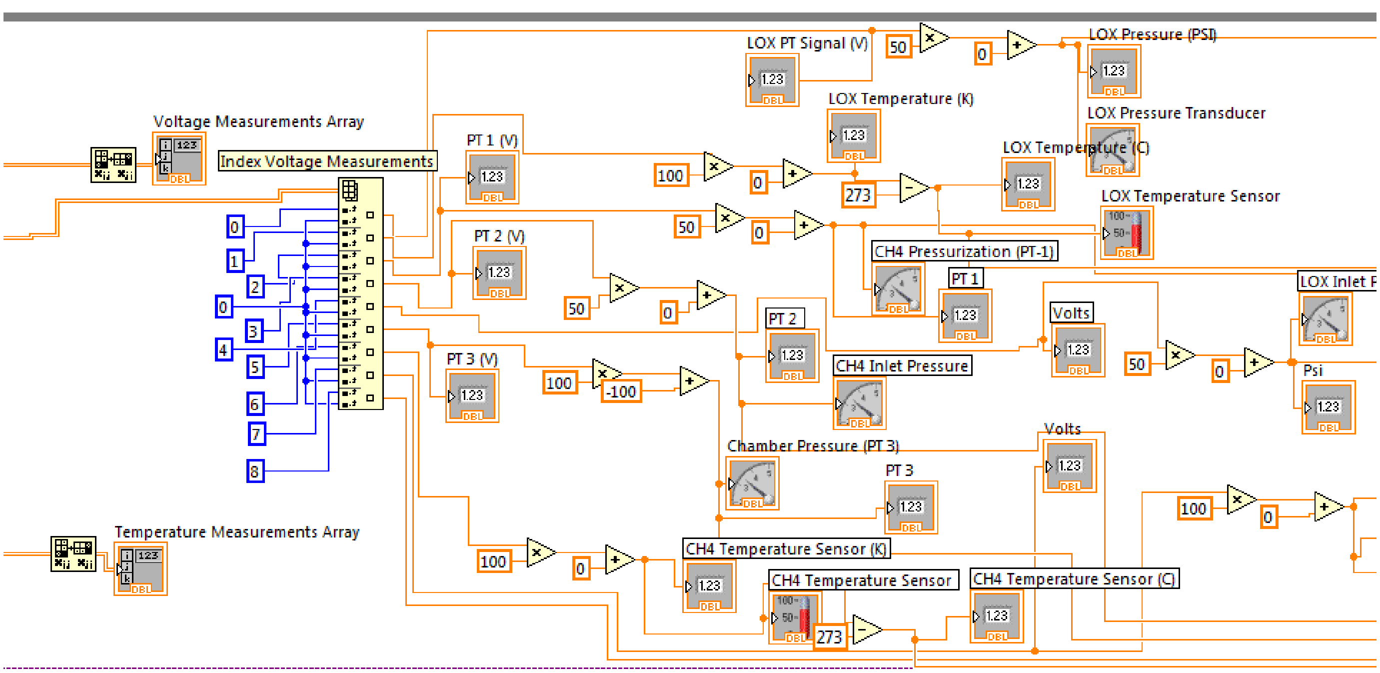


Figure 4.4: Data string separation and Instrumentation Indicators

Once the software is aware of what devices and channels data is to be gathered from, recorded data is compiled in a single string. Therefore, the next step is to separate each individual measurement.

This is done as shown in Figure 4.4, where the initial data array is separated into individual strings of data; this is accomplished using the Index Array function. This function allows the user to create sub matrices from the main data matrix by simply inputting the row and column to extract from the main matrix. Once individual strings of data are obtained, they are then connected to indicators for visual representation in the GUI.

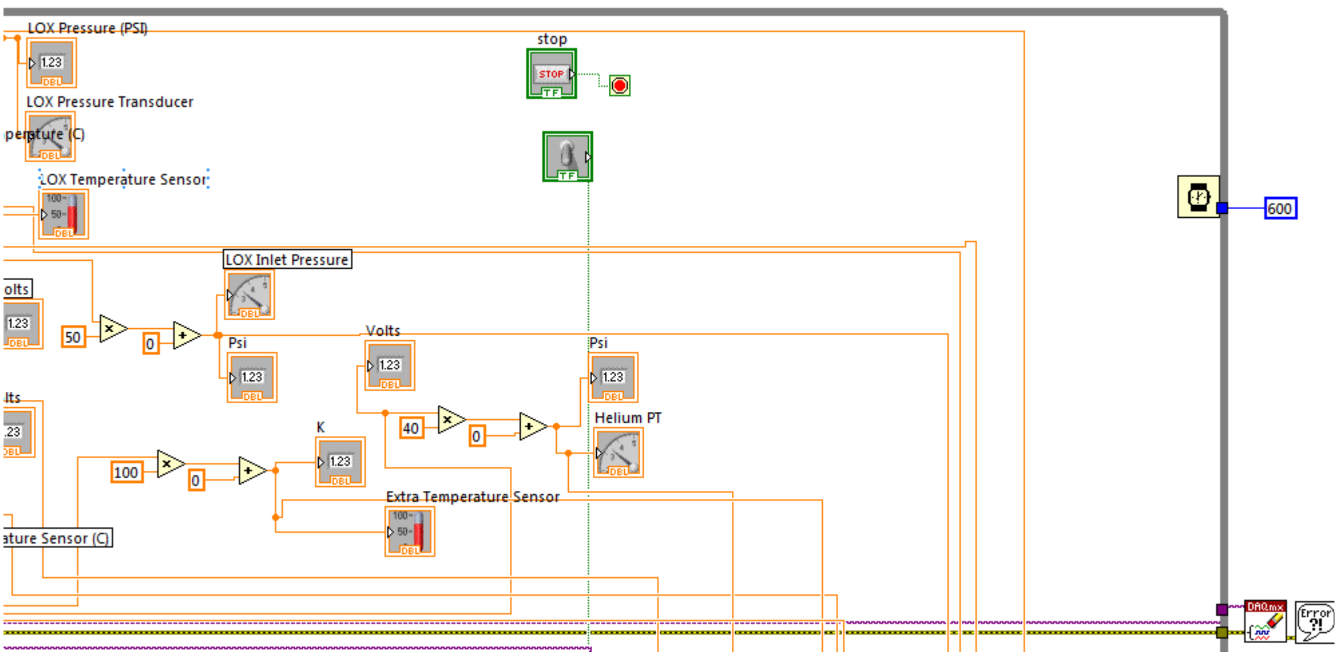


Figure 4.5: Task Termination and Time Delay

The loop is ended as shown in Figure 4.5; the last section of the loop consists of ending the task that was started when the WHILE loop was initiated. This is done by use of the “End Task” DAQmx function, an error visualization function is added as well. In case an error occurs at any point in the program, starting from the “Start Task” function, an error message description will be available for the user to troubleshoot. The user must indicate when to end the tasks that were initiated; otherwise errors will occur in the program if this is not specified.

**2) Automation Loop**

The automation loop functions as the controller during experimental sequences, reading a pre-set experimental sequence and activating relays at the appropriate time for valve control. Valve control is

achieved via the use of relays found in the PCI 6520 card inserted in the main computer in the control room. This card possesses 8 mechanical relays with 120 VAC/12 VDC capabilities. This loop may be split into two main categories; one for valve control, the other for continuous "redline" check and emergency sequence triggering.

A FOR loop, having an N number of iterations, determined by the script file executed, contains all of the programming for this sequence. A script file is utilized to set the experimental sequence the user desires to execute. This file has a simple structure containing a time column and a number of additional columns matching the number of valves to be used in the sequence. The time column is filled with time numbers in milliseconds, while the different valve columns are filled with 0's or 1's. These two digits work as a binary code, 0 indicating a closed state, while 1 establishing an open or active state for the valve. There is no limitation, programming-wise, as to how many valves may be opened individually or at the same time, however there is a hardware limitation that determines the number of valves that may be controlled at any given time. The current capabilities of the system allow relay control of 16 valves; however additional channels had to be created for this setup. Figure 4.6 shows a sample script used during one of the tests performed.

Test Sequence

| Time | LOX Tank | LOX Purge | LOX Thrust | CH4 Purge | CH4 Thrust | Igniter | CO2 | CH4 Bleed | LOX Bleed |
|---|---|---|---|---|---|---|---|---|---|
| 3000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5000 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 8000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9000 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| 12000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13000 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 13100 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 |
| 13200 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| 13300 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 13400 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 13500 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 13600 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13700 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13800 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13900 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14000 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 14100 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 |
| 14200 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| 14300 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 14400 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 14500 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 14600 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Emergency Sequence

| Time | LOX Tank | LOX Cool | LOX Purge | LOX Thrust | Helium | CH4 Purge | CH4 Thrust | Igtr | CO2 |
|---|---|---|---|---|---|---|---|---|---|
| 500 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 5000 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 10000 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 20000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 4.6: Sample experimental sequence text file

The experimental sequence is bounded by the two time columns (for experimental and emergency sequences respectively). As it has been implied, each valve is represented by each column in

the script. The emergency sequence is also included in this file, starting from the second time column until the end of the file. This sequence will be triggered and run if and only if any of the instrumentation limits mentioned before are surpassed. This instrumentation will be described in the Experimental Setup section of this work.

Upon star-up of the program, LabVIEW prompts the user to select the file to be executed; here is where the user must select the previously prepared file for a given sequence to be run (Figure 4.7). Once the file is selected, the programming was structured such that LabVIEW transforms the input file into a matrix via the use of the "Read From Spreadsheet VI" and the "Array Subset" functions. From this matrix, two matrix subsets were created; the first sub matrix establishes the first (left-most) column in the script file as the time column, while the sub matrix second establishes an independent matrix of 0's and 1's for valve operation, having the closed/open code for the valves (Figure 4.6).

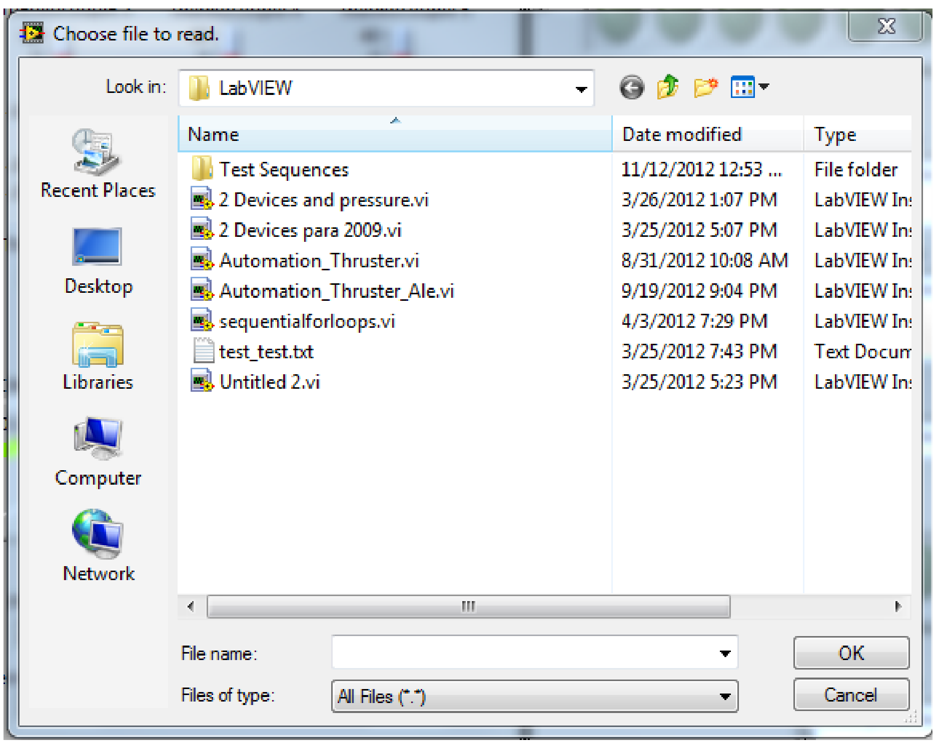


Figure 4.7: Program Start up – Experimental Script Selection

Figure 4.8 shows the "Read from Spreadsheet VI" and the array subset functions mentioned before. Also, we may now see the "Create Virtual Channel" functions used for digital output control.

This is the same function used in the Instrumentation Loop; however in this case it is used as a digital output function, hence the slight difference in device input format. However, the same rules apply, there may only be a digital output task initiation per digital output device, otherwise an error message will prevent the program form being run.

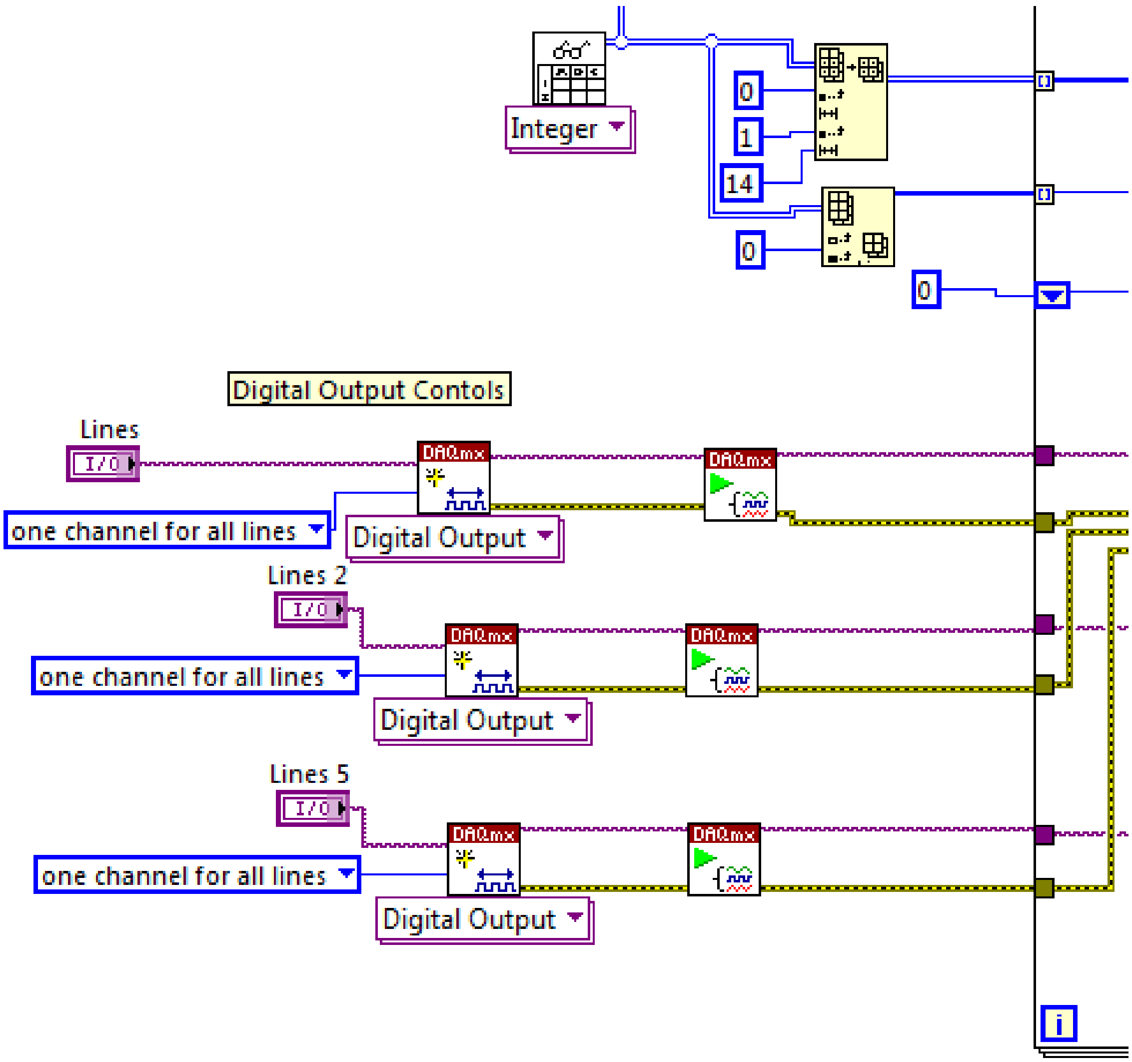


Figure 4.8: Read from Spreadsheet and Array subset Functions

Figure 4.9 shows how the output devices and lines are set. This is done in the Front Panel view, inputting the devices, ports, and lines to be used. LabVIEW notation is important when writing which lines to use. There are two general cases to be explored here. The first, whenever consecutive lines form any single device are to be used, the input may be simplified with the use of a semi-colon as follows:

Dev1/port0/line0:3; this indicates the software to use lines 0, 1, and 3 from device 1's port 0. The second, if it is intended to use spaced lines from a single device, commas should be used to separate the lines as follows: Dev1/port0/line0, Dev1/port0/line5. If inputted as the last example, the lines used would be 0 and 5 from device 1's port 0. Multiple devices might be used as well, as long as only one task is initiated for any one device, otherwise the software will return an error message; to do so, the user would use the second notation, changing the device name.

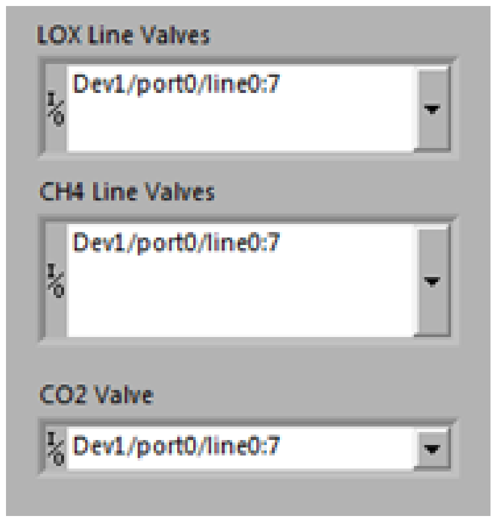


Figure 4.9: Input notation for output devices and lines

The next section in the automation FOR loop is shown in Figure 4.10. In a similar fashion to the Instrumentation Loop, the data arrays must be split if the user wants to incorporate indicators for valve actuation; this is accomplished through the "Array subset" function as shown in Figure 4.10. Following the task initiation comes the "DAQmx Write" function where the user chooses how to manage the data (1D, 2D strings, etc), function specifics may be found in the LabVIEW help catalog. Whichever choice is made by the user is shown underneath the function icon. The FOR loop is finalized with a "DAQmx Clear Task" function, just as it was done for the instrumentation WHILE loop, as well as with a "Simple Error Handler VI."

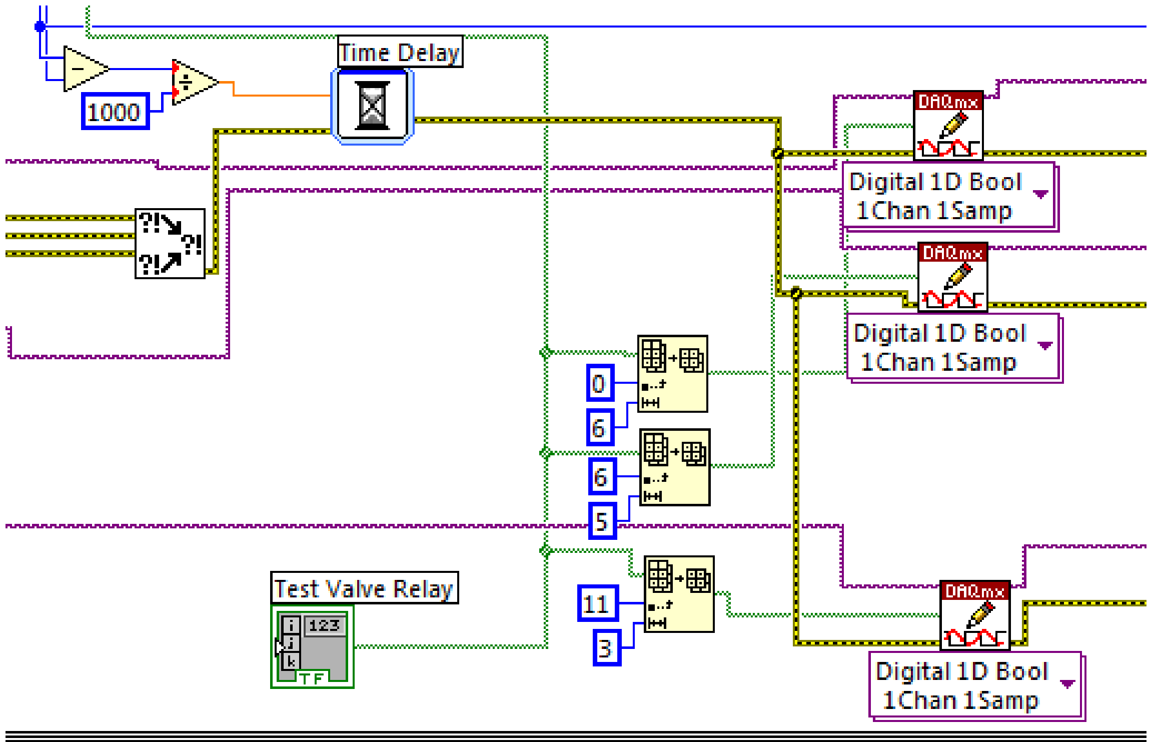


Figure 4.10: Array Subset and DAQmx Write Functions

The second main category in this loop is the section that checks whether or not instrumentation limits have been surpassed during any iteration. The way the FOR loop is put together makes each row in the script file, to be one loop iteration. Therefore, if more continuous instrumentation level checkup is required, more loop iterations may be added by having repeated sequence rows with identical valve operations, at more continuous time intervals. Doing this will not affect time response within the system or valve operation, but rather have more continuous instrumentation level checks. Figure 4.11 shows how the instrumentation levels are established. Thermocouples and pressure transducers placed in the thruster body and inlet propellant lines were chosen as the limiting instrumentation; these will be described in the experimental setup section.

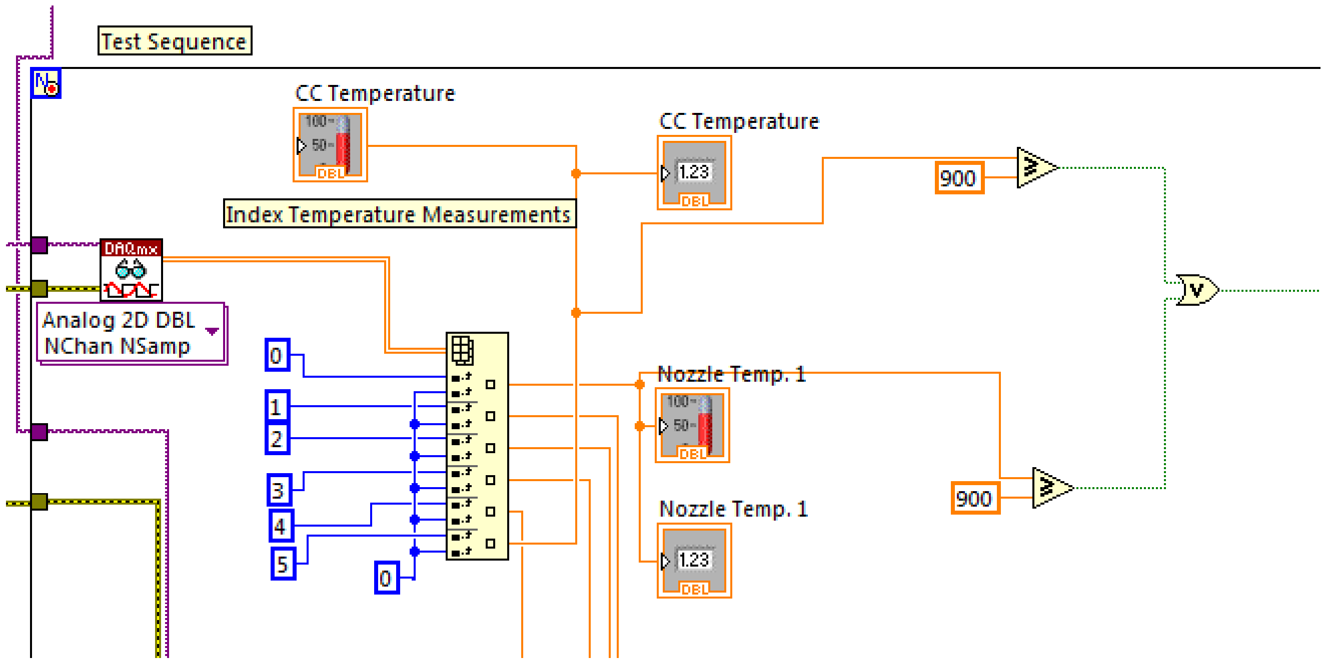


Figure 4.11: Emergency Sequence Triggering Programming

Since a task for the device containing the thruster instrumentation had already been started in the instrumentation WHILE loop, the task may not be initiated again for the FOR loop. Therefore, as it may be seen in Figure 4.11, the task is carried from the initiated task at the WHILE loop and inserted into the FOR loop, then a "DAQmx Read" function is used to read the data. The data array is divided into individual strings, and comparison functions are used to set the limit comparison to a chosen numerical value of temperature or pressure. AND or OR functions are used since any single instrumentation must trigger the emergency sequence, they are all compared and later taken out of the FOR loop to a comparison state in the emergency loop.

### 3) Automation Loop

The last section of the control program is the Emergency loop. This loop will only be run when triggered by any of the emergency instrumentation described in the previous section. If any of these instruments' readings surpass the user pre-set level, this loop will be activated and run the emergency sequence found in the initial script file, beginning from the second time column.

The compared data string shown in the right hand side of Figure 4.11 is taken as a true or false condition for a case structure. This case structure houses the emergency sequence; if indeed the true statement proves that any of the limits have surpassed, the original experimental sequence will be interrupted and the emergency sequence will be triggered; while no action is taken if the statement is false. Figure 4.12 shows the case structure housing the emergency sequence,

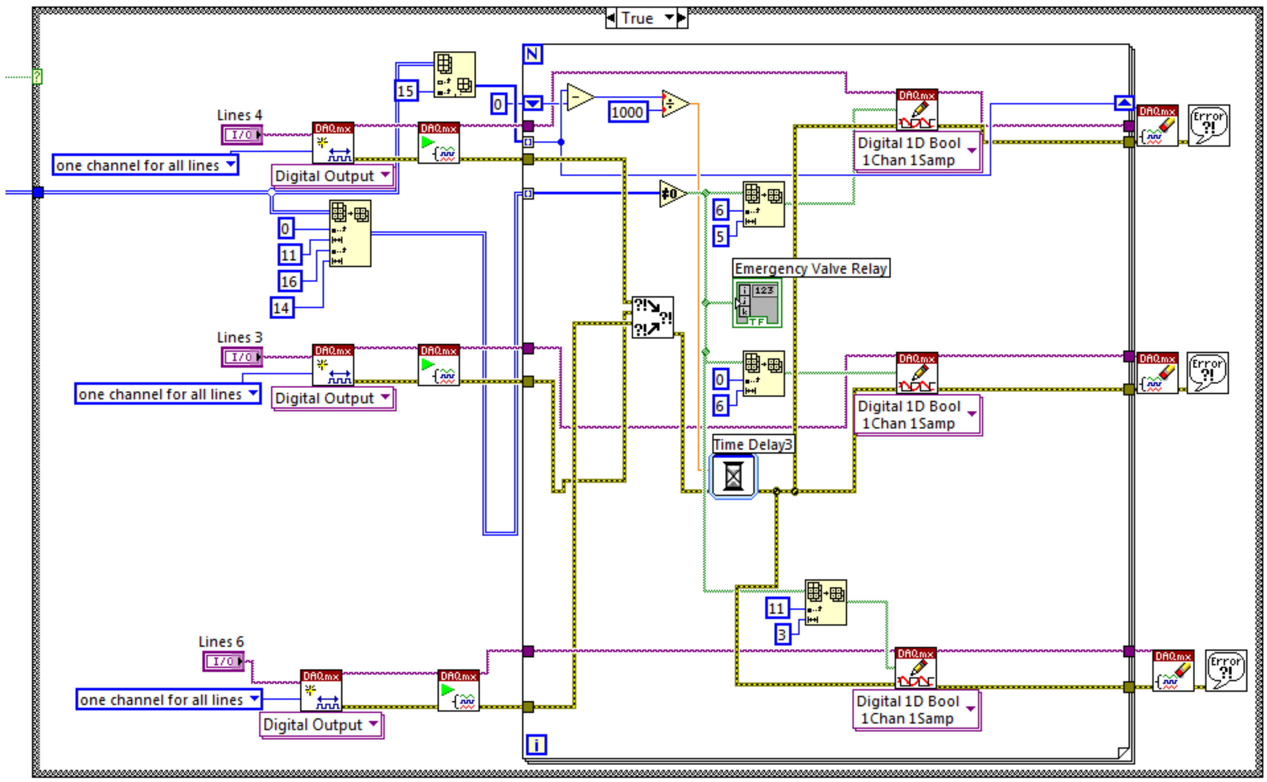


Figure 4.12: Emergency Sequence Case Structure

When triggered, the sequence works in the exact same way as the regular automation loop does. It is important to notice that, since the sequence is pre-set in the same text file script as the main sequence, the file is loaded once the automation is started. This may be seen in the figure, where the blue string of data coming into the FOR loop is the same matrix coming out of the “Read from Spreadsheet VI” from the automation loop. The user needs only to specify which set of rows and columns LabVIEW must read; this is done via the use of the array subset functions as before.

# Chapter 5: Experimental Setup

As it has been established throughout this work, the Pencil Thruster experimental setup is complicated due to the fact that it is a compilation and assembly of propellant feed, measurement, and control systems working in unison. It has been described that the final purpose of this project is to operate a thruster under pulsing and steady state conditions. The test article, in this case, the Pencil Thruster, is placed inside the vacuum chamber present in the Goddard laboratory facilities, on top of the thrust stand subsystem described in Chapter 3.  Further description of the thruster setup inside the chamber will be discussed in this section. Figure 5.1 shows an overall system distribution (top) and the respective schematic (bottom) for the integration of all the subsystems in the Goddard laboratory.

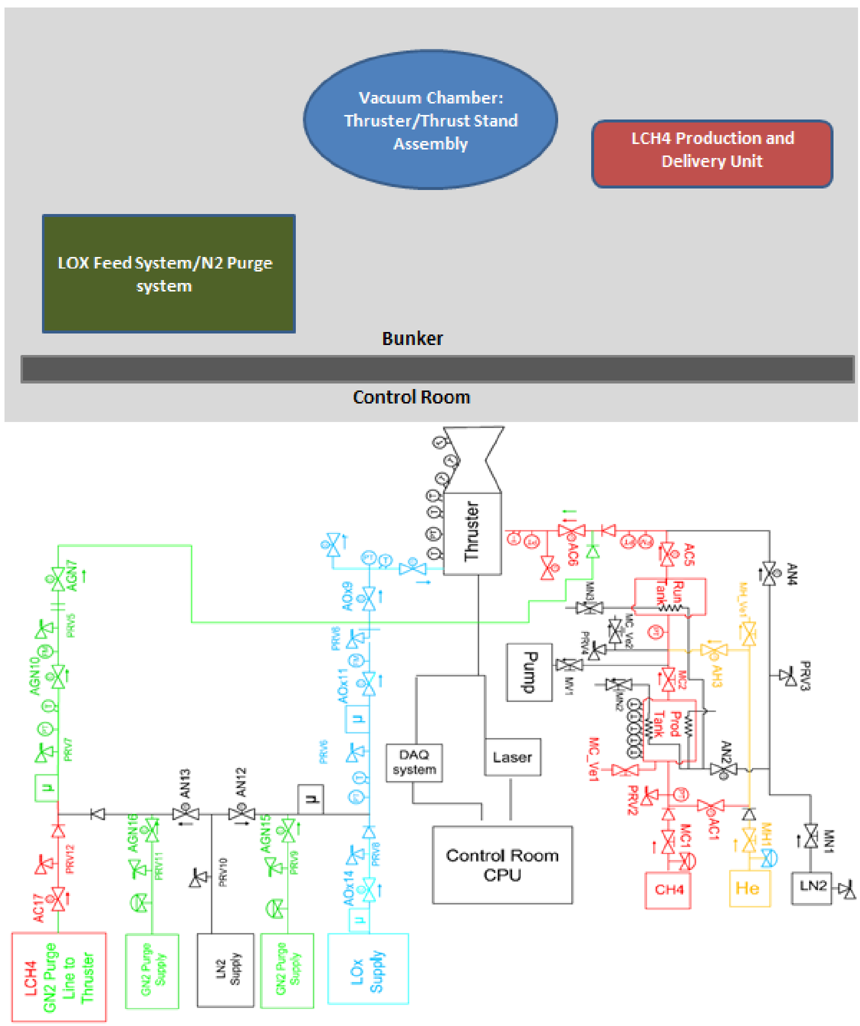


Figure 5.1: Subsystem location distribution and schematic in Goddard bunker

## 5.1 Thruster System

The Pencil Thruster is a 2- 8 lbf class reaction control engine (RCE) designed by the NASA JSC counterpart of this project. The thruster consists of 5 main separate sections: combustion chamber, oxidizer manifold, fuel manifold, nozzle, and the igniter; all of these parts are welded together, with the exception of the spark plug which screws at the back of the combustion chamber. This RCS engine is meant to work on the Morpheus Lander under NASA's Project Morpheus. A coil-on-plug ignition system is used for the thruster [2]. The thruster uses a film cooling system, in which excess fuel is injected through separate injection holes, downstream of the ignition point to protect the thruster walls.

### 5.1.1 Instrumentation

The thruster contains the instrumentation that sets the "redlines" or limits described in the controls section (Chapter 4), E-type thermocouples were welded to the thruster body in the combustion chamber and the nozzle. Also, there is a pressure transducer connected to the thruster chamber via 1/8"OD 304 SS tubing that is welded to a hole in the chamber. A total of 6 thermocouples are welded on the thruster body, three on the combustion chamber at 90 degrees from each other; while the rest are welded to the nozzle.

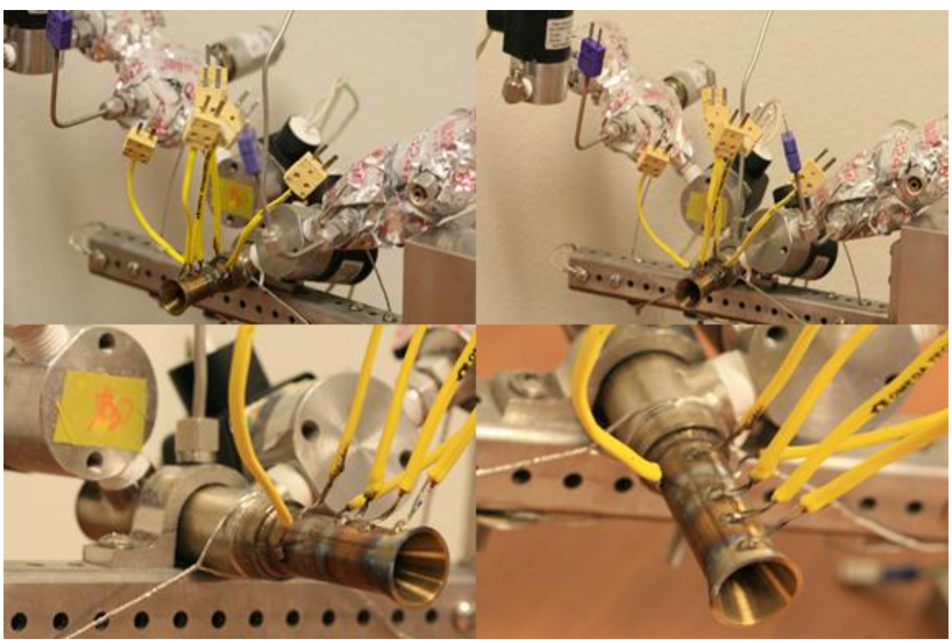

Figure 5.2: Subsystem location distribution and schematic in Goddard bunker

Additional instrumentation for characterization of propellant inlet conditions is also shown in Figure 5.2; this includes two thin film cryogenic pressure transducers and two E-type thermocouple probes. These transducers are the same ones used in the methane unit; Omega engineering cryogenic thin film pressure transducers which require 10 VDC excitation signal and output 30mV which must be amplified before inputting to the DAQ system. All of these instruments set the limit which triggers the emergency sequence from the controls program if any of the values read surpass the pre-set limit. This instrumentation will be a major component of graphs shown in the Results section.

### 5.1.2 Ignition System

A major component of the experimental setup for the Pencil Thruster is the ignition system. Thruster ignition is achieved via the use of an automobile ignition system, with a spark plug and an MSD ignition coil. However, the spark plug has been modified to have an extended electrode tip and spark to the thruster inside wall. The electrode tip extension shape and geometry was defined by the NASA counterpart for the project, to adjust to their specific needs, no modifications where done to its geometry in any form.

As it was stated before, the spark plug was modified in order to achieve sparking further down the thruster combustion chamber. Pre-specified requirements stated the need for sparking to occur 0.01" downstream the fuel injection holes in the chamber. Figure 5.3 shows the sparking position required in the thruster chamber cross-section. In order to meet this requirement, an electrode tip was machined and welded onto the pre-existing electrode on the spark plug as shown in Figure 5.3.

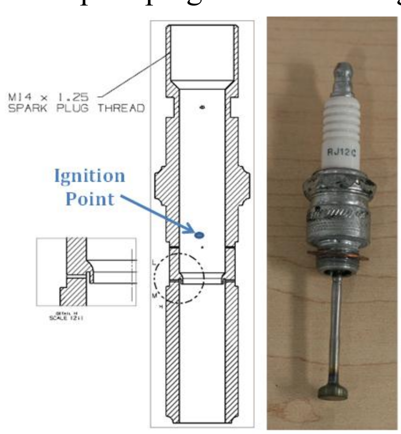


Figure 5.3: Combustion Chamber cross-section and modified spark plug

**Spark Plug Electrode Tip Welding Fixture**

Welding the electrode tip extension to the spark plug is a major challenge, as there is very limited spacing between the tip diameter and the inner wall of the thruster 0.025". Spark plug electrode and the extension tip must be perfectly aligned to avoid a major displacement towards the top of the extension due to its length. Therefore, machining a custom welding fixture to accomplish this task is a necessity. The fixture consists of a 1X1 304 SS square bar in a vertical position, with a hole in the center of the top face threaded to fit the spark plug's reach. A secondary through hole, concentric to the threaded hole, is sized to have a tight fit for the electrode extension's larger diameter. A slot is created from one of the lateral sides of the bar to allow welding instrumentation and filler wire in. The spark plug is positioned by the threaded hole in the bar, while the electrode tip is inserted from the bottom side of the fixture and pushed up until the extension and spark plug electrode touch; the extension is kept aligned by the tight-fit hole. Once in the right position, the fixture may be rested on a flat surface to prevent the extension from coming out of the fixture. After welding is done, the modified spark plug may be removed from the fixture by simply unscrewing it out. Figure 5.4 shows the welding fixture utilized to ensure proper alignment of the electrode extension.

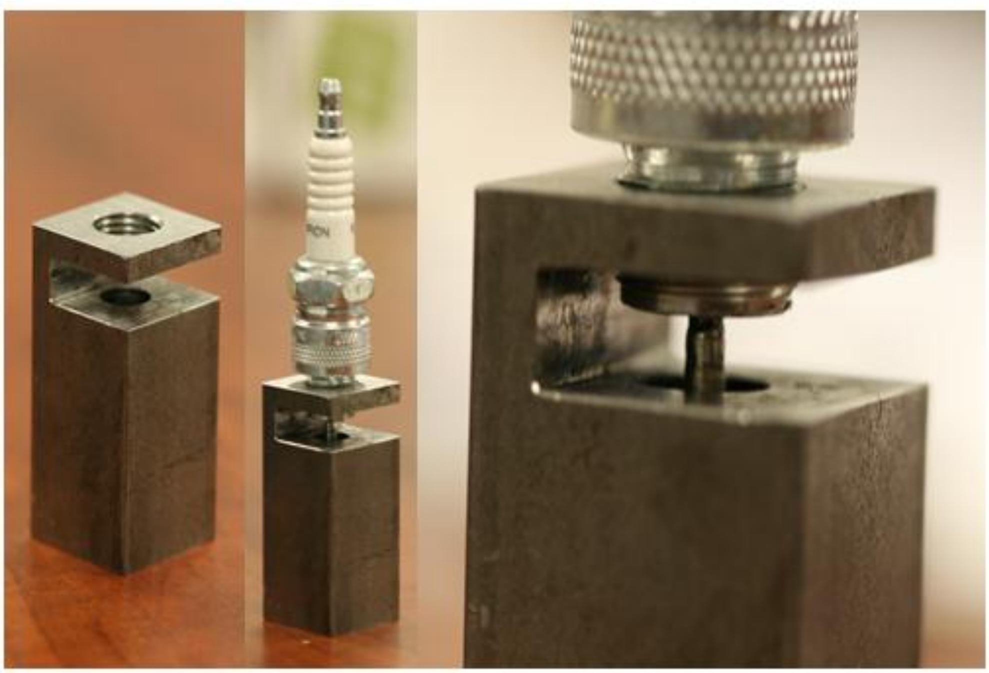

Figure 5.4: Electrode Tip Welding Fixture

**Spark Plug Selection**

Ideally any spark plug would be able to be utilized for this ignition system, the only constraint for this particular application is the thread size and reach on the plug housing which is determined by the thruster threading. In this case the required thread is a special metric thread: M14X1.25 thread. The required thread size is 14 mm with a 0.375” thread reach; with this in mind Champion Spark plug RJ12C was selected for use in this project. Alternative spark plug options are listed in Table 5.1; spark plug cross-references are available online as well.

Table 5.1: Spark plug cross-references

| Spark Plug Alternatives | |
|---|---|
| **Brand** | **Model** |
| AC Delco | M47, C49 |
| Autolite | 458, 308 |
| Bosch | WR9EC, W9EC0 |

**Ignition Coil**

Following previous discussion, the ignition system consists of a MSD high performance ignition coil and a Champion spark plug assembly. MSD 8247 ignition coil model was used to generate the spark on the plug. This performance coil has a maximum dwell time of 4 ms at 12V input according to specifications provided by the manufacturer; this coil is typically found in LS2 engine models and is shown in Figure 5.5.

The igniter coil requires a 12V excitation voltage and a TTL 5V signal to trigger spark generation. The pin-out for this device is presented in Figure 5.5; the 12V power is received from a lawn mower battery, while the TTL signal is sent from a BK Precision 4003A 4MHz signal generator in the form of a 100Hz square wave. It is important to note that there is one pin not being used in the coil, manufacturing industries produce several models of this items in mass and therefore the redundant pin. The reason behind the selection of a car battery as a power supply is derived from the fact that the coil has an 11A current draw at 12 V. his level surpasses by far the amperage capabilities of common power supplies.


Figure 5.5: MSD Ignition Coil and Pin-out

**Working Mechanism**

As it has been stated before, the igniter is controlled in the same way valves are operated by the LabVIEW software. This is accomplished by controlling the TTL signal coming from the BK signal Generator; this signal is routed to a NI CB-37FH connector block; this connector block is controlled by the use of a NI PCI-6521 card. This computer card has 8 mechanical relay outputs with 150VAC/VDC capabilities; additional specifications may be found from the manufacturer website. Upon release of the signal by activation of the PCI relays, it is sent to a manual switch and then wired to the ignition coil in the bunker. It is important to mention all of this equipment is found in the control room, while the coil sits inside the vacuum chamber in the bunker facilities.

As an additional safety measure, the igniter signal is routed through a manual switch before being sent to the coil, therefore is this switch is not manually operated to the ON position, the signal from the generator will never reach the coil even if the relays are activated by the software. The coil is constantly receiving power form a lawn mower battery which is placed underneath the vacuum chamber in the bunker. No sparking will occur until the TTL signal is received, which is controlled by the automated sequence in the software.

Physical connections to the coil pins will be described in this section. Pin A (Figure 5.5) is connected to +12V from the battery. Pin B receives the 5V 100 Hz TTL signal from the generator and manual switch. Pin C is not used; hence no wire is connected to this pin. Finally, Pin D receives both ground from the car battery and the negative signal of the TTL generator.

## 5.2 LOX Subsystem

The LOX line runs through the bunker main propellant feed system and is terminated at a manifold entering the vacuum chamber. The line is fed propellant from a self-pressurizing tank which is connected to the main feed for the system; the tank has pressurization limitations of 300 psi, therefore the user is also limited on LOX inlet pressure conditions. It is important to remember as well that the propellant line has relief valves and cryogenic valves rated a 225 psi. Hence, pressure limitations are an influential factor for thruster testing, in case high inlet pressures are required. In this regard, the Pencil Thruster is designed to work, under actual operating conditions, at inlet pressures of 300 psi, a pressure value that far exceeds the system's limitations, therefore further pressure improvements must be made to the system; the main LOX line entering the vacuum chamber is shown in Figure 5.6.

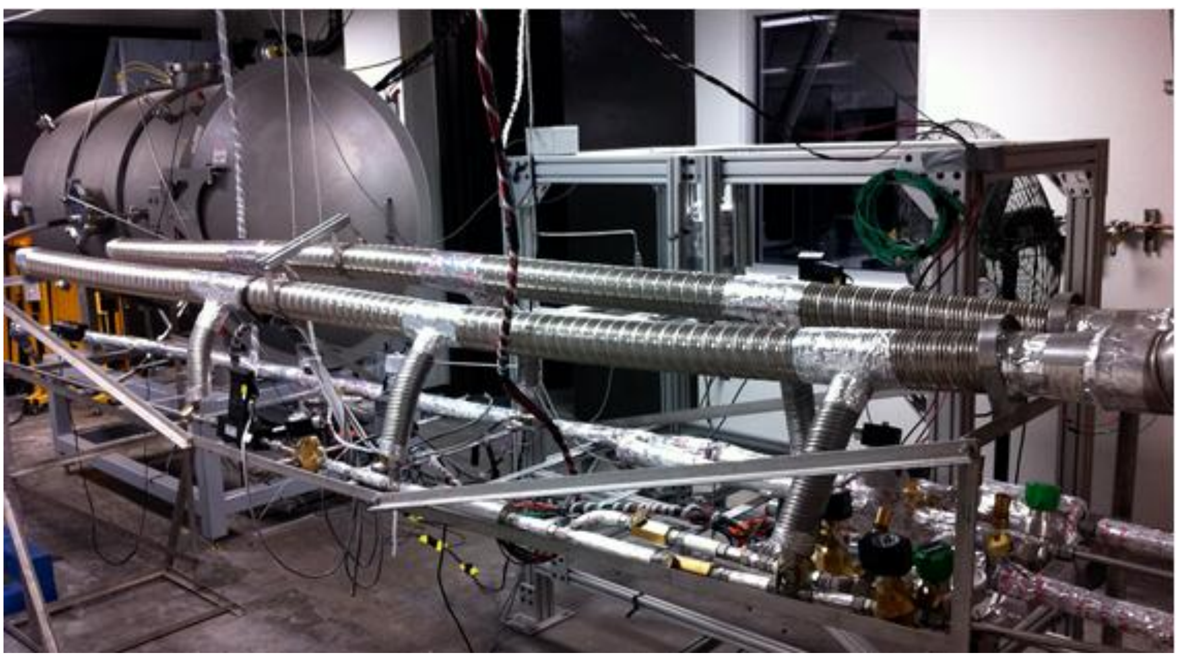

Figure 5.6: LOX Main propellant line

## 5.3 $LCH_4$ Production and Delivery Subsystem

The next main component is the $LCH_4$ production unit, which is placed right beside the vacuum chamber and feeds propellant to the thruster via the vacuum chamber line inlet ports. The design and development of this system was described in Chapter 2. For safety purposes, a Kevlar barrier is placed in between the methane condensation and delivery unit and the vacuum chamber. The location of the

unit is far away from the LOX tank, closer to the secondary entrance to the bunker facilities, while the LOX tank is placed near the main entrance to the bunker. All of the valves and instrumentation in the methane production unit are powered and controlled from the control room in the laboratory. The wiring necessary to accomplish this is run through wire trays found in the laboratory and separated from the rest of the wires running through there as well. Data and power cables are run through separate trays to avoid interference in data signals caused by the power cables being close to the data transmission cables. Figure 5.7 shows the methane condensation and delivery unit in position for thruster testing inside the bunker facilities.

Figure 5.7: $LCH_4$ production and delivery subsystem

### 5.4 Thrust Stand and Thruster Final Assembly

As it was mentioned before, the thruster rests on the thrust stand which is attached to a base plate inside the vacuum chamber. Material compatibility with LOX is a major issue when dealing with oxygen systems, therefore the base plate was machined out of 316 Stainless Steel to avoid material

compatibility issues in case of a LOX spill inside the chamber. The base plate was machined as an optical table, where multiple holes are available enabling multiple setup mounting configurations. Figures 5.8 and 5.9 shows the thruster-thrust stand assembly inside the vacuum chamber, with the respective LOX and $LCH_4$ feed lines. A 12 V car battery and thermocouple data acquisition devices are placed and secured in a table underneath the vacuum chamber. All of the experiments were conducted at ambient conditions.

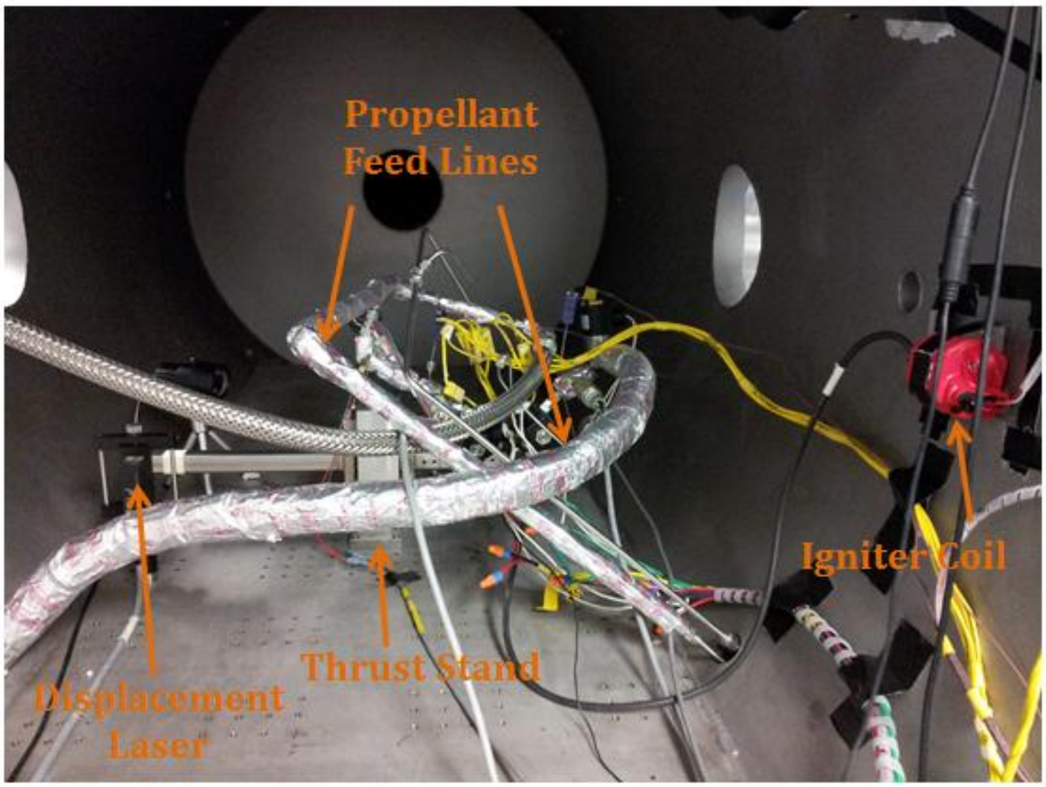


Figure 5.8: System assembly inside vacuum chamber – rear view

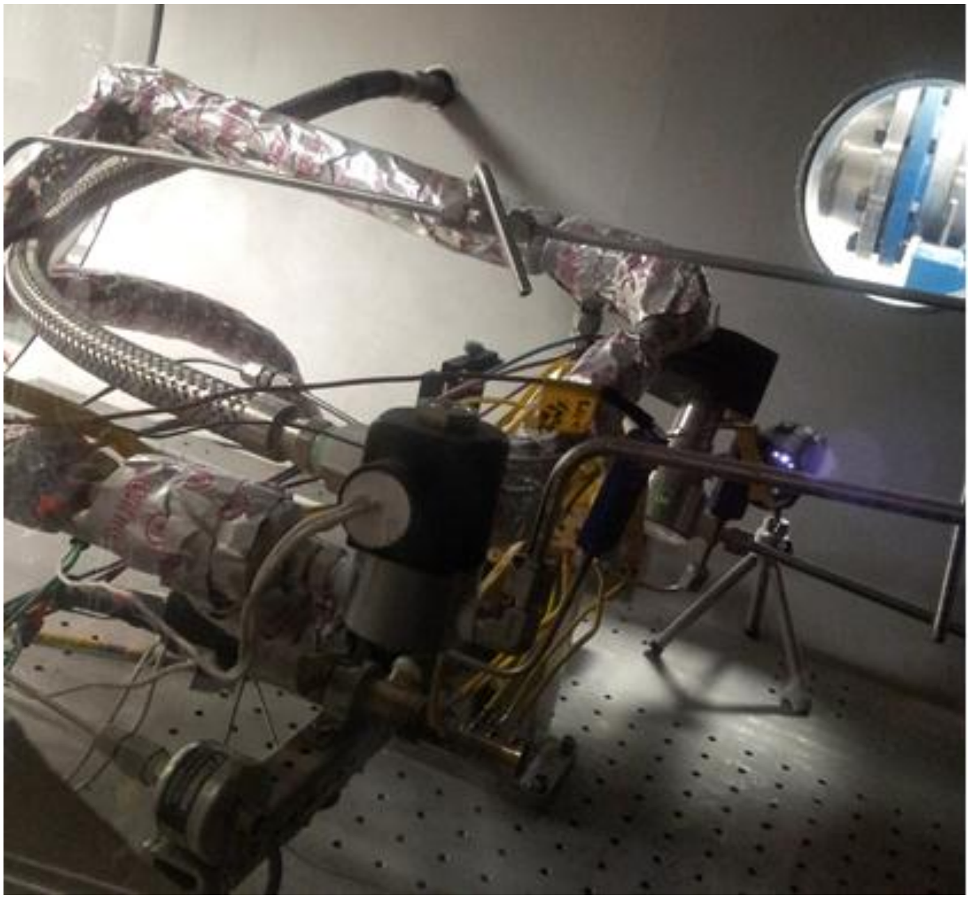

Figure 5.9: System assembly inside vacuum chamber - side view

## 5.5 System Integration: Operating Procedure

Specific operation has been explored for each individual subsystem in the past chapters. A step-by-step procedure is appended to this thesis for the experimental trials of the Pencil Thruster testing. However, an overall summarized description of the steps followed during testing is provided in this section. The main actions followed during these procedures were as follows:

- Thruster Assembly and Installation
  - Thrust stand subsystem setup inside vacuum chamber
  - Thruster attachment to stand
- Bunker Safety Check
- Check LOX, $CH_4$, and $LN_2$ tanks
  - Ensure enough gas/liquid is available for testing procedures

- Pencil Thruster Instrumentation, Component and Controls, Igniter Check
    - Ensure control system works properly
- Pre-test Instrument, Component, and Controls Engagement
    - Test control system, ignition system
    - Ensure all valves and instruments in system work properly
- Methane Condensing Sequence
    - Begin methane condensation procedures (45 – 60 minutes)
- Thruster and LOX lines pre-chill
    - Initiate LOX line and thruster cool-down (15-20 minutes)
- $LCH_4$ tank transfer to run tank
    - Transfer condensed methane to run tank (15-25 minutes)
- Bunker Safety Check
    - Ensure no foreign objects are present, check oxygen level inside the bunker
- Supply tank regulators set to testing pressures
    - Pressurize liquefied methane to desired test pressure
    - Set LOX tank pressure to desired test pressure
- Safety personnel overview of procedure
    - Positioning of personnel to designated areas for testing
- Initiate Testing Sequence, simultaneously recording data and video
- End test  sequence and post-test maintenance

# Chapter 6: Results and Discussion

As it was mentioned before, preliminary system integration and functionality was tested by firing the Pencil Thruster at ambient conditions in two stages: gas-gas combination and liquid-liquid combination. These tests focused on validating systems functionality and integration, experimental procedures, ignition reliability, and experimental sequence automation. These tests also provided a way to analyze individual systems' response and detect weak features with room for further improvement for future rocket testing.

## 6.1 First Stage Testing: Gas-Gas Propellant Combination

The first testing phase consisted in firing the thruster in a gas-gas propellant combination. This phase was also divided in two phases, one with the original thruster, the last with a second thruster iteration (discussed later). The intent for this testing was to analyze automation control for the system, and overall system functionality; therefore low pressures were used for these tests. Inlet pressures of 40 psig and 94 psig for oxygen and methane respectively were used.

### 6.1.1 Gas-Gas Ignition Testing: Original Thruster Configuration

Initial ignition and system integration tests were conducted for system validation purposes. With the inlet conditions of 40 and 94 psig low thrust (<1 lb) was expected. The system weight at this stage was 2.5 kg and the line tension was considerably less than it would be in the second stage testing. It is important to note thruster instrumentation had not been installed at this stage as well as the automations control system had not been developed yet, therefore test data was limited. The focus of this testing stage was to analyze thruster and system behavior.

**Thruster Response and Modifications**

Initial gas-gas ignition tests visually showed non-uniform heating of the thruster nozzle and chamber with the apparition of "hot-spots" on these sections of the thruster as seen in Figure 6.1. Thruster temperature became a concern, and therefore, and effort was conducted to make slight modifications on thruster design in order to have a more effective cooling. In order to address this issue, a simple heat transfer analysis was conducted to get an estimation of thruster temperature at different

mixture ratios under gas-gas and liquid-liquid propellant combinations. Initial ignition tests were conducted at a mixture ratio (MR) of 2.47, hence, this ratio was used as the higher end and the ratio was dropped at intervals until 1.5; Table 6.1 summarizes the theoretical temperature approximations that served as parameters for MR selection.

Figure 6.1: Thruster regional "hot spots" and non-uniform heating

Table 6.1: Theoretical thruster body temperatures at varying mixture ratios

| | GOx- GCH4 | LOx-LCH4 |
|---|---|---|
| **Mixture Ratios** | **Surface Temperature (K)** | **Surface Temperature (K)** |
| **2.48** | 2904 | 2826 |
| **2.16** | 2734 | 2619 |
| **1.92** | 2516 | 2345 |
| **1.72** | 2251 | 2050 |
| **1.5** | 1864 | 1644 |

It is important to note that these values shown in Table 6.1 give a theoretical estimation to show temperature behavior at the different mixture ratios, under actual working conditions thruster temperature would not raise to these values. Steady state heat transfer relationships for cylinders were used for this analysis, no transient analysis was conducted. Chamber and fuel manifold cross-sections were used to develop a resistive heat transfer model, then the following heat transfer relationships were used to determine Reynolds, Nusselt, and Prandtl numbers, as well as heat flux, heat transfer, and coefficients.

$$Reynold's\ Number = Re = \frac{\rho V D}{\mu}$$

$$Nusselt\ Number = Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)}{\left[1 + \left[12.7\left(\frac{f}{8}\right)^{.5} + (\mathrm{Pr}^{\frac{2}{3}} - 1)\right]\right]}$$

$$Friction\ Friction = f = (0.790 \ln(Re - 1.64))^{-2}$$

$$Nusselt\ Number = Nu = CRe^{m}Pr^{n} = \frac{hD}{k}$$

$$Heat\ Transfer = Q = \frac{T_{\infty i} - T_{\infty o}}{R_{tot}}$$

Based on these results, it was determined that the fuel injected for film cooling was not staying close enough to the wall, and thus was not working as it was intended to. In order to address this problem an internal ring was designed to be machined on the inside wall of the combustion chamber protecting the film cooling fuel injection holes. Figure 6.2 shows the original combustion chamber configuration (left) and the modified configuration (right). The latter configuration was the machined for a second thruster, which was used for the second gas-gas and liquid- liquid test runs. No other component of the thruster was modified, except the combustion chamber.

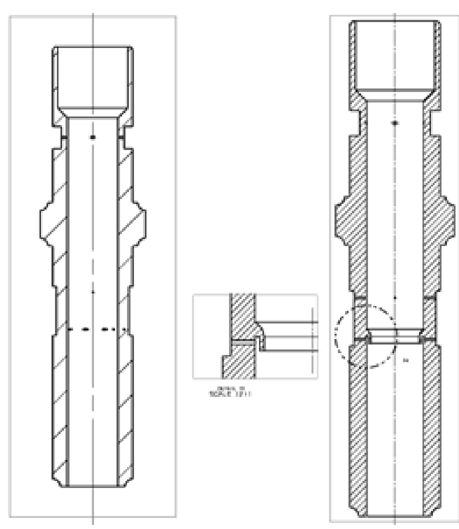

Figure 6.2: Original and modified cross-sectional views of thruster combustion chamber

### 6.1.2 Gas-Gas Ignition Testing: Modified Thruster Configuration

Upon completion of the machining and assembly of the modified thruster configuration, a second validation test series was conducted. Thruster instrumentation was included this time, adding weight and stiffness to the system, as well as providing means of analyzing thruster status. Again, the purpose of this test was to validate the integration of all the subsystems. This test series was the first one to integrate all of the subsystems described in this work with the automation controls system. Thus, the focus of the test was to validate proper integration and functionality of the systems and analyze thruster response; therefore, the same low pressures were used again for this series. The test matrix for these runs is detailed in Table 6.2.

Table 6.2: Gas-Gas Ignition Tests – Test Matrix

**Test Matrix: Thruster Gas-Gas Ignition Tests**

**Steady State Testing**

| On Time [s] | Off Time [s] | Pulses | Duty Cycle | Duration [s] | P Inlet - Ox [psig] | P Inlet - Fuel [psig] | MR | Ox Temp [°F] | Fu Temp [°F] |
|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 0 | 1 | 100% | 0.5 | 40 | 94 | 1.5 | Gas | Gas |
| 0.5 | 0 | 1 | 100% | 0.5 | 40 | 94 | 1.5 | Gas | Gas |
| 1 | 0 | 1 | 100% | 1 | 40 | 94 | 1.5 | Gas | Gas |
| 3 | 0 | 1 | 100% | 3 | 40 | 94 | 1.5 | Gas | Gas |
| 5 | 0 | 1 | 100% | 5 | 40 | 94 | 1.5 | Gas | Gas |

**Pulse Testing**

| On Time [s] | Off Time [s] | Pulses | Duty Cycle | Duration [s] | P Inlet - Ox [psig] | P Inlet - Fuel [psig] | MR | Ox Temp [°F] | Fu Temp [°F] |
|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 2 | 33% | 3 | 40 | 94 | 1.5 | Gas | Gas |
| 0.5 | 0.5 | 2 | 50% | 2 | 40 | 94 | 1.5 | Gas | Gas |
| 0.4 | 1.2 | 5 | 25% | 8 | 40 | 94 | 1.5 | Gas | Gas |
| 0.4 | 1.2 | 10 | 25% | 16 | 40 | 94 | 1.5 | Gas | Gas |

**Thruster Response**

Initial gas-gas ignition tests proved successful integration of all the subsystems. Ignition was achieved in all of the trials, and pulse configurations operated as expected. Most importantly, for the same conditions of thruster operation (test duration and MR) no noticeable “hot spots” or non-uniform heating were present during any of the tests. Figure 6.3 shows an ignition snapshot of one of the trials.

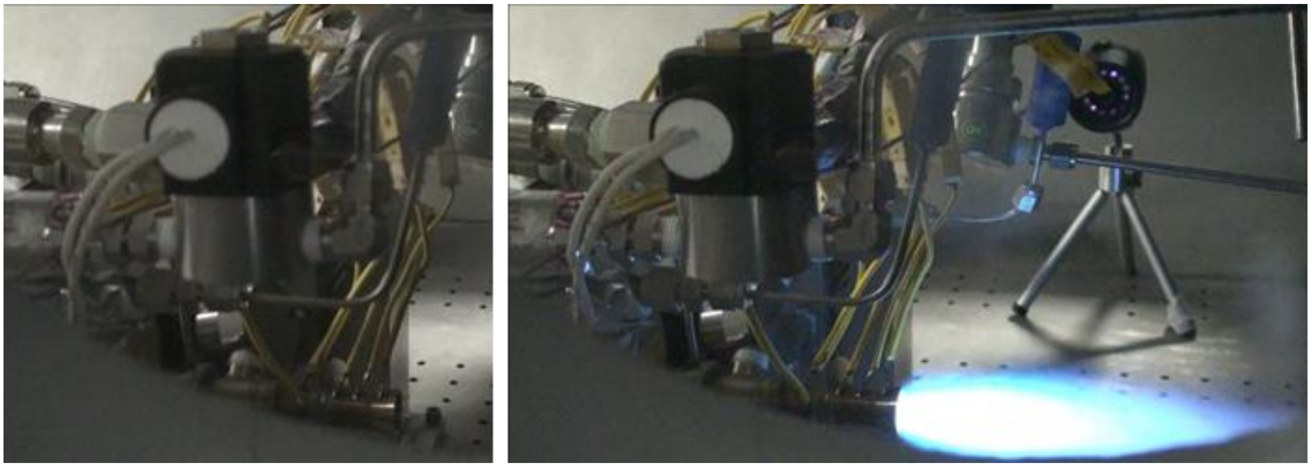

Figure 6.3: Gas-gas Ignition snapshot

Thruster temperature data was of particular interest for this test series. Thruster body temperature at the nozzle and combustion chamber reached a maximum value of 240 C (464 F) with experimental trials ran consecutively. Thermocouple positioning was shown in the experimental setup chapter; the temperature profile for the thruster is shown in Figure 6.4.

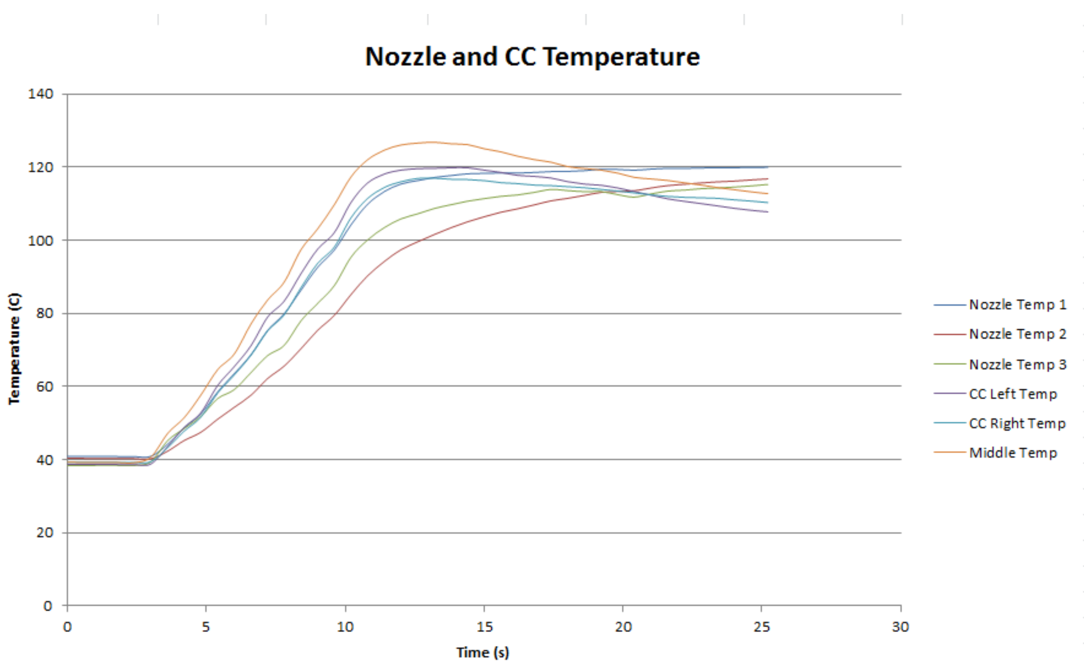


Figure 6.4: Gas-gas thruster body temperature profile

In order to see the heating distribution around the combustion chamber, thermocouples were placed where "hot spots" had been seen during the previous test series. Figure 6.5 shows a visual representation of the heating around the combustion chamber section before the nozzle at different times during the experimental sequence. The x-axis represents counter-clockwise degrees around the chamber; from this graph it may be seen that the sides of the chamber tend to heat more, which corresponds to the heating seen before, yet no "hot spots" were visible.

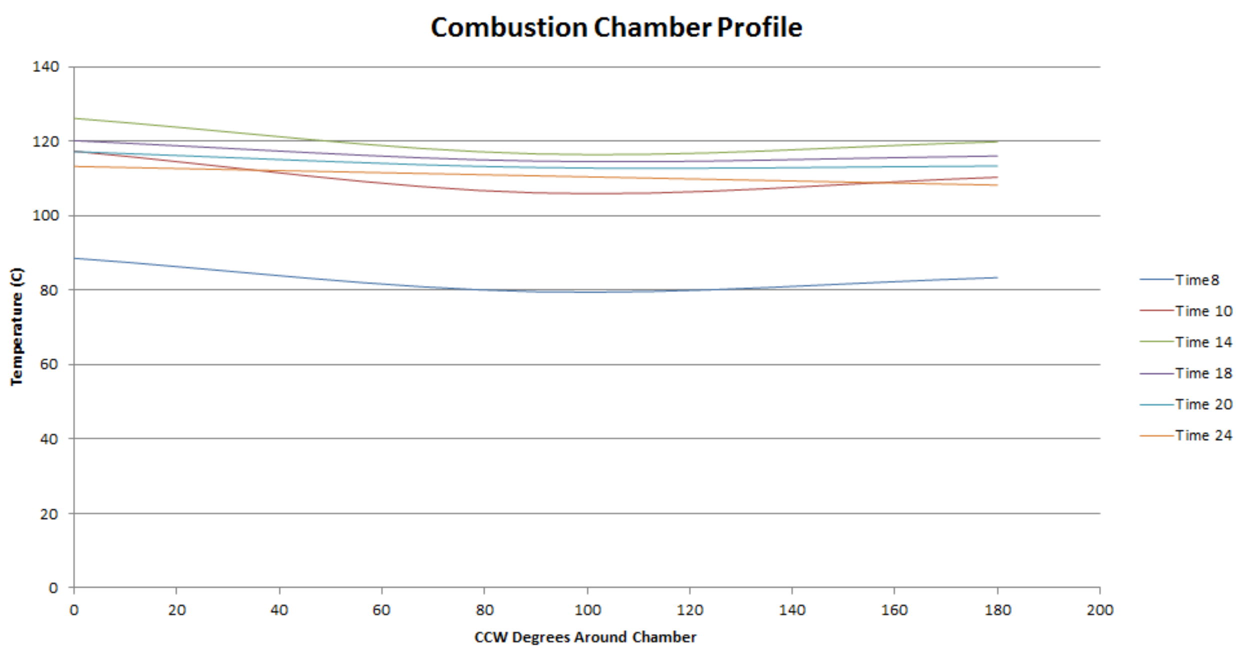


Figure 6.5: Combustion Chamber Temperature Profile

## Conclusions

Thruster modifications seemed to work for tests under the same conditions as the previous stage. No "hot-spots" or non-uniform heating was seen during any of the runs and thruster temperature never rose above 250 C. Automated control and ignition was validated, however thrust stand data recorded at 500 Hz proved yielded low resolution results, therefore data was used only for system integration validation purposes. A natural frequency of 7.2 Hz was obtained from the thrust stand data. The need for a chamber pressure measurement, in order to validate thrust measurements, was evident.

## 6.2 Second Stage Testing: Liquid-Liquid Propellant Combination

The second testing phase consisted in firing the thruster in a liquid-liquid propellant combination. The intent for this testing was to analyze automation control for the system, and overall system functionality under cryogenic operation; it is important to note this was the first time a cryogenic experimental setup was ignited in the Goddard laboratory. This required exact timing of the procedures for each subsystem and personnel coordination. Higher inlet pressures were tested this time given that a chamber pressure instrument was added to the thruster setup. Inlet propellant conditions were set to 75 psi and -158 C for LOX, while 70 psi and -165 C for the $LCH_4$. Steady state and pulsing conditions were tested; the test matrix followed is shown in Table 6.3.

Table 6.3 Liquid-Liquid Ignition Tests – Test Matrix

| Test Matrix: Thruster Ignition Tests | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Steady State Testing** | | | | | | | | | |
| On Time [s] | Off Time [s] | Pulses | Duty Cycle | Duration [s] | P Inlet - Ox [psig] | P Inlet - Fuel [psig] | MR | Ox Temp [°F] | Fu Temp [°F] |
| 0.5 | 0 | 1 | 100% | 0.5 | 75 | 70 | 1.5 | -158 | -165 |
| 0.5 | 0 | 1 | 100% | 0.5 | 75 | 70 | 1.5 | -158 | -165 |
| 1 | 0 | 1 | 100% | 1 | 75 | 70 | 1.5 | -158 | -165 |
| 3 | 0 | 1 | 100% | 3 | 75 | 70 | 1.5 | -158 | -165 |
| 5 | 0 | 1 | 100% | 5 | 75 | 70 | 1.5 | -158 | -165 |
| **Pulse Testing** | | | | | | | | | |
| On Time [s] | Off Time [s] | Pulses | Duty Cycle | Duration [s] | P Inlet - Ox [psig] | P Inlet - Fuel [psig] | MR | Ox Temp [°F] | Fu Temp [°F] |
| 0.5 | 1 | 2 | 33% | 3 | 75 | 70 | 1.5 | -158 | -165 |
| 0.5 | 0.5 | 2 | 50% | 2 | 75 | 70 | 1.5 | -158 | -165 |
| 0.4 | 1.2 | 5 | 25% | 8 | 75 | 70 | 1.5 | -158 | -165 |
| 0.4 | 1.2 | 10 | 25% | 16 | 75 | 70 | 1.5 | -158 | -165 |

### Thruster Response

The test objectives were to check if the thruster remained at acceptable temperatures (<700 C) during sustained steady and pulsed firings, as well as testing system and ignition reliability and repeatability. Different pulse widths and duty cycles were used to analyze response at different conditions. Figure 6.6 shows the thruster firing a 5 second steady state trial; the thruster body and propellant valves are seen frosted-up due to the line cooling. Every trial was successful in terms of

ignition and overall system response. For 5 second steady state runs, igniter on time was varied from 1s to 3s in one second increments; for the runs with 1s igniter on time, combustion stopped upon spark stoppage. This indicates sparking must be present for at least 2 seconds during the test.

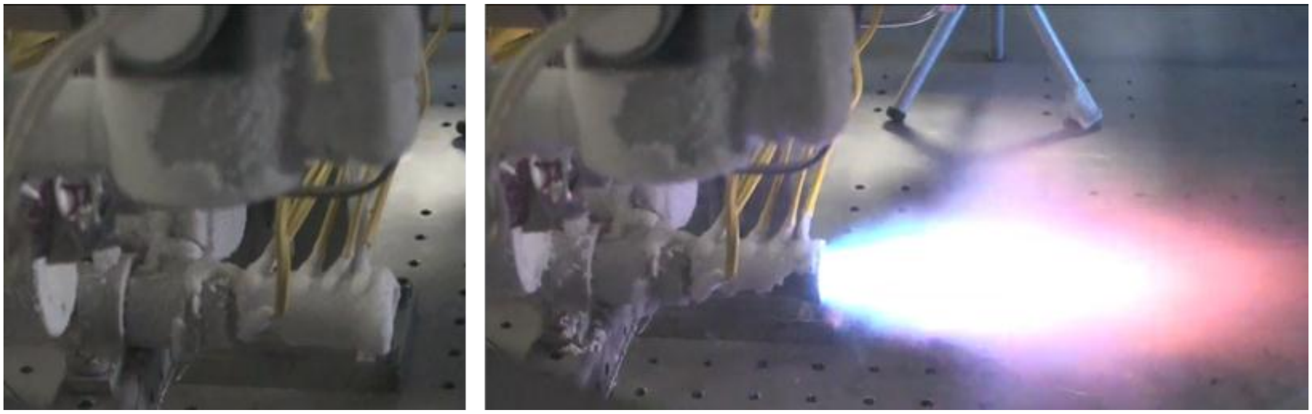

Figure 6.6: Liquid-liquid ignition snapshot

Figures 6.7 and 6.8 show the pressure and temperature data recorded during a 500 ms on/ 500 ms off, five pulse test. As it may be seen from the temperature graph, previous tests had been conducted before this one and still the thruster temperature reached a maximum value of 280 C (536 F). Also, pressure data indicates the time interval between tests caused a pressure increase in both the tank and consequently the line pressures. Therefore, inlet conditions were not the same values presented in the test matrix (Figure 6.3). Inlet conditions were higher in pressure and temperature 100 psi -238 F (-150 C) for oxygen, while 80 psi -148 F (-100 C) for methane, an indicative of the propellants being cold gases rather than liquid at these conditions.

For all the experimental trials, the chamber pressure measurement was not consistent in the sense that it was detected every so often; as it may be seen in Figure 6.7, only four chamber pressure rises are seen, even though there were five pulses. This was a consistent behavior throughout the test data, therefore this measurement was deemed unreliable. Given the fact that tests were conducted at ambient conditions, chamber pressure measurements are not reliable; transducer readings were not consistent and only reached a high level of 10 psi, therefore reliability on this measurement needs validation with future testing.

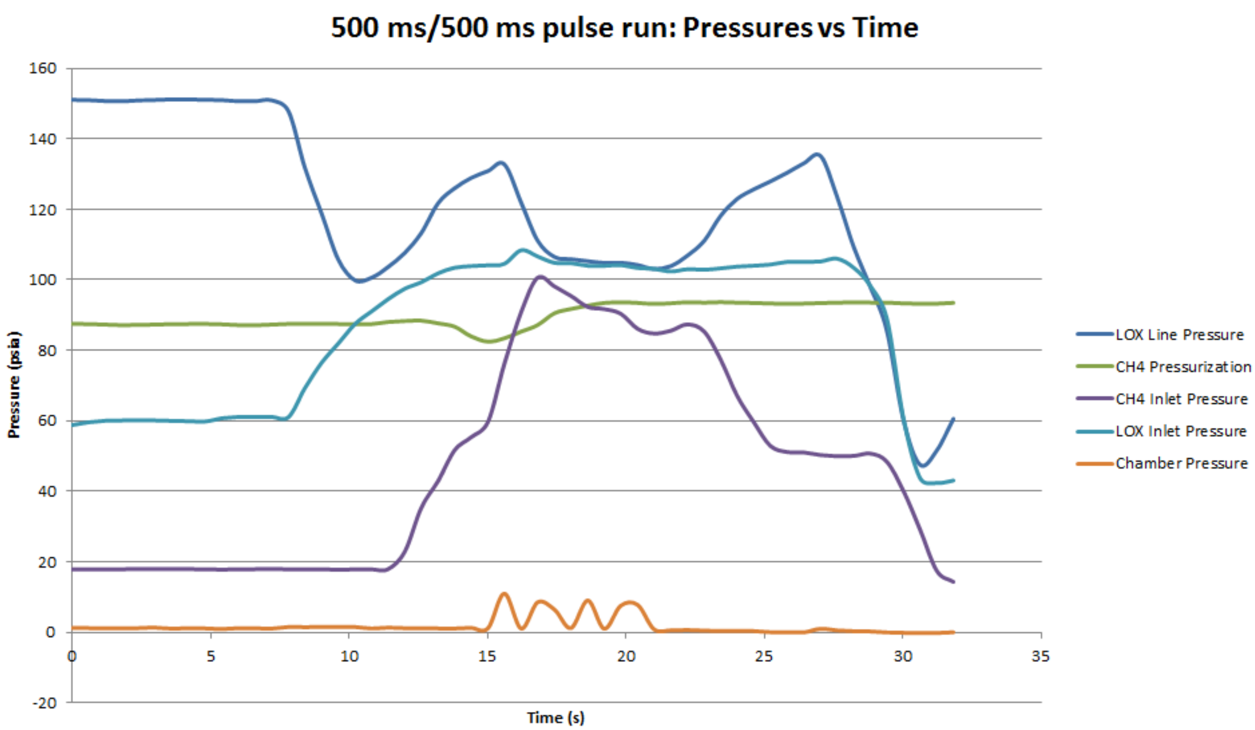


Figure 6.7: Liquid-liquid pressure data for 500 ms pulse operation

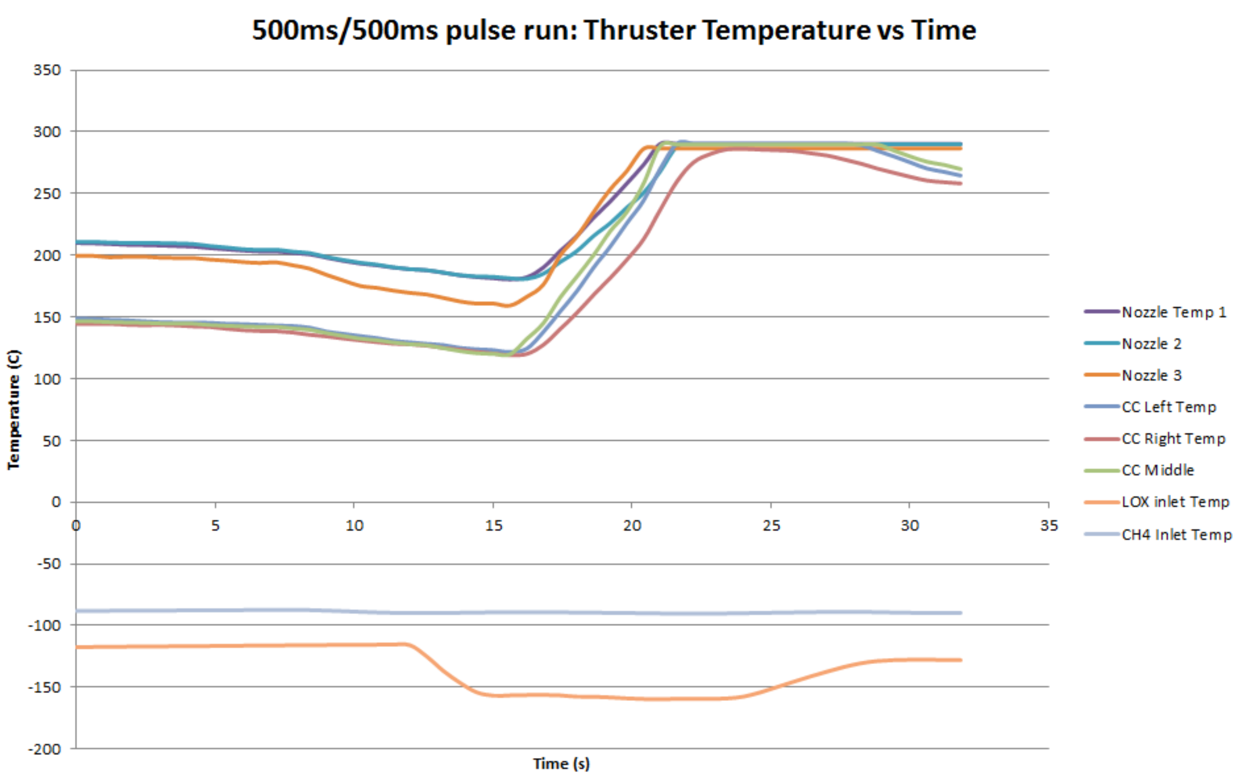


Figure 6.8: Liquid-liquid thruster body temperature data for 500 ms pulse operation

**Thrust Stand Response**

Thrust stand data was recorded at 1500 Hz this time to get higher resolution data. It is important to remember this measurement is not controlled by the main LabVIEW control interface, but rather factory software form the laser. Thrust measurement data provided clear displacement and hence, thrust profiles. A sample displacement profile during ignition of a 5 second experimental run is shown in Figure 6.9.

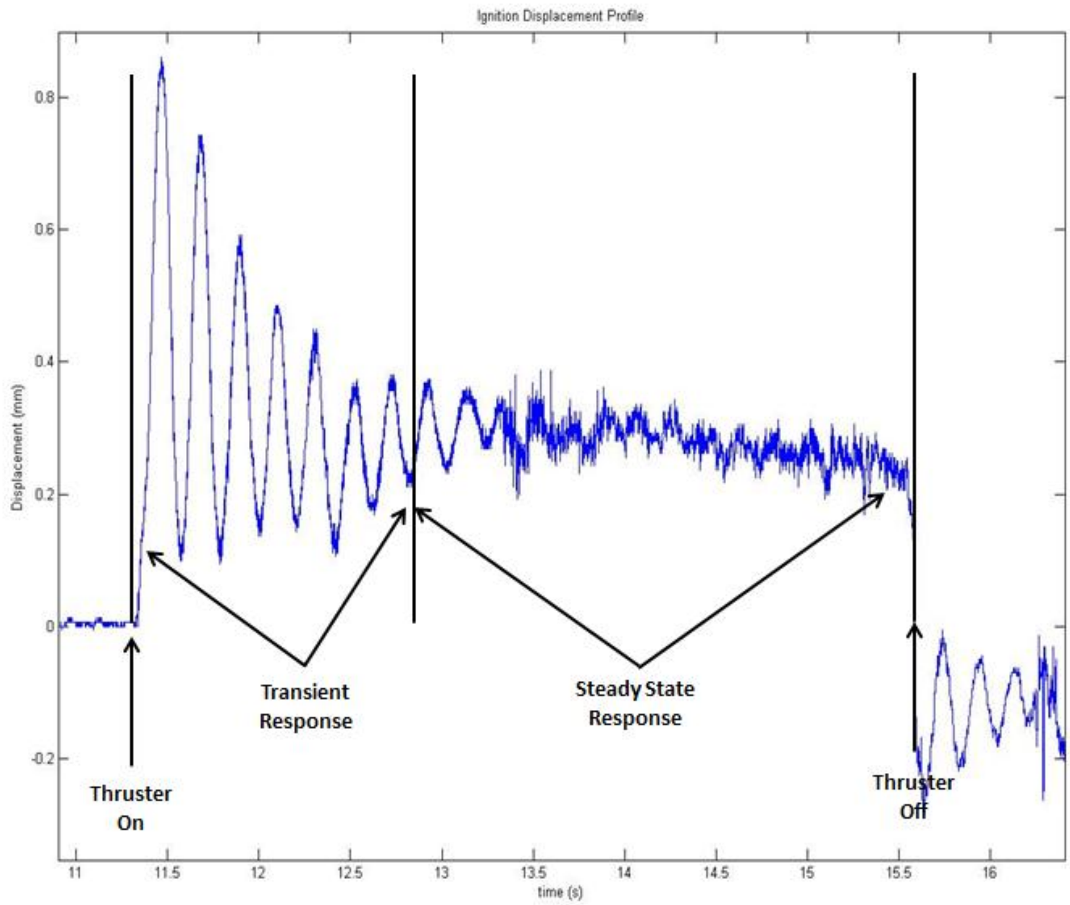


Figure 6.9: Displacement profile during ignition of 5s steady state run

This figure plots unfiltered but averaged data from the laser measurements, having displacement in the y-axis vs time on the x-axis. Displacement data is processed by averaging the data at user-selected time intervals, particularly during ignition. A typical thrust profile is seen from this data, an initial thrust spike followed by steady state response, and finalized by clear thrust decay. Starting from the "zero" or initial position of the stand, there is an initial overshoot, as expected, due to the pressure build-up in the line. A transient range of about 1s of total operation for this run may be noticed, after which steady state

is reached and thrust data is stable. For thrust conversion purposes, steady state displacement data is preferred, if initial transient data is included in the thrust conversion, the thrust average will be slightly higher as more displacement is generated initially. Upon thrust decay the structure is seen to adjust to a new equilibrium position, it is important to note that laser resolution makes this far more noticeable.

In order to determine frequencies contributing to the system's response, a Fast Fourier Transform (FFT) was conducted on the data. The results of this analysis for steady state runs show only one major frequency of 4.7 Hz affecting the system's dynamic response. This is the natural frequency of the system when the stand is holding 4.9 kg on both the moment arm and counterweight arm. It is important to note that the data must be set to a 0-average condition to meet FFT requirements. Figure 6.10 shows the displacement profile with its corresponding FFT analysis.

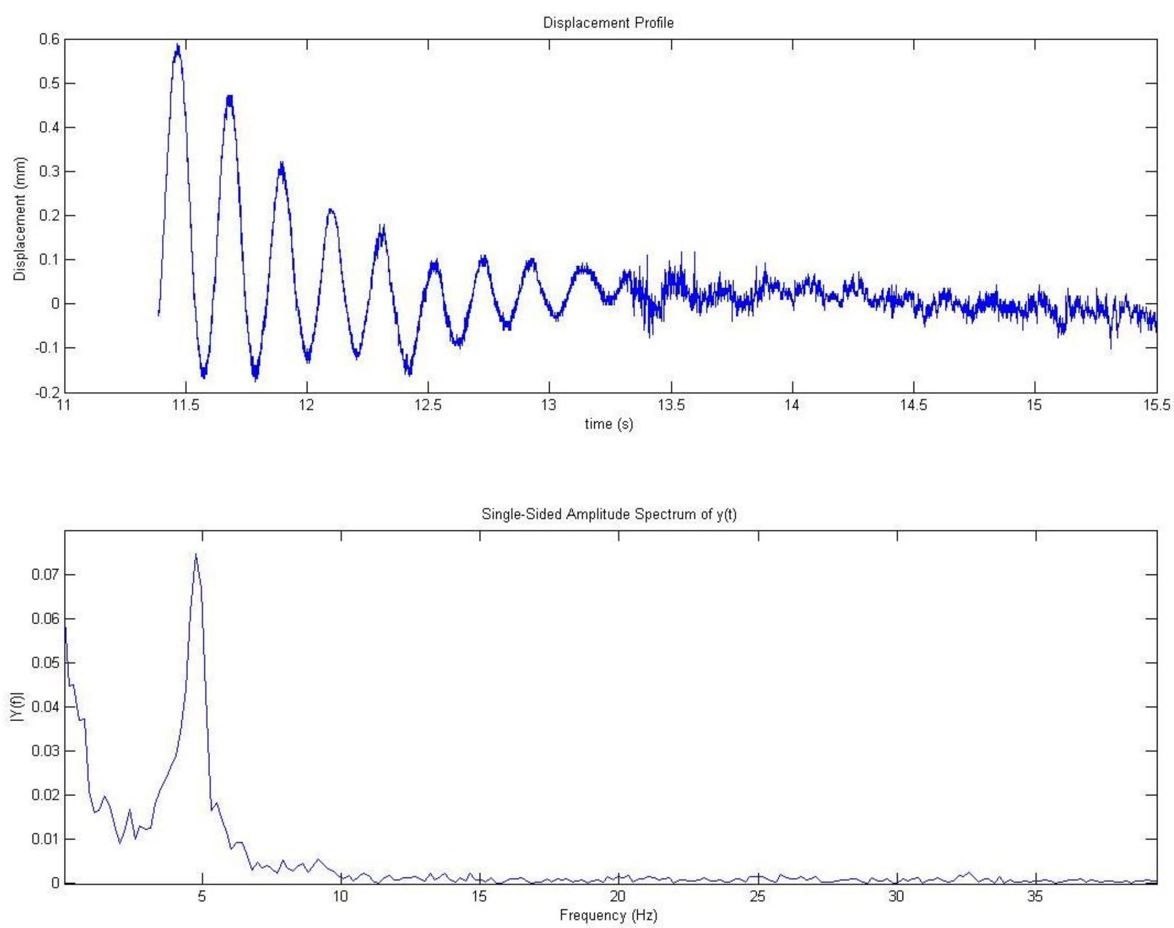


Figure 6.10: Fast Fourier Transform analysis on steady state thrust stand data

Similarly, a displacement profile for the thruster under pulsed operation is presented in Figure 6.11. A 400ms/1200ms on/off pulsing operation was selected for discussion. Under pulsed operation, there is a repeatable displacement profile induced by each ignited pulse. For all pulses there are two main displacement peaks which are consisted throughout all of the pulses induced on the stand. The repeatability of the measurements is clearly seen from this graph both during ignition and during valve closing.

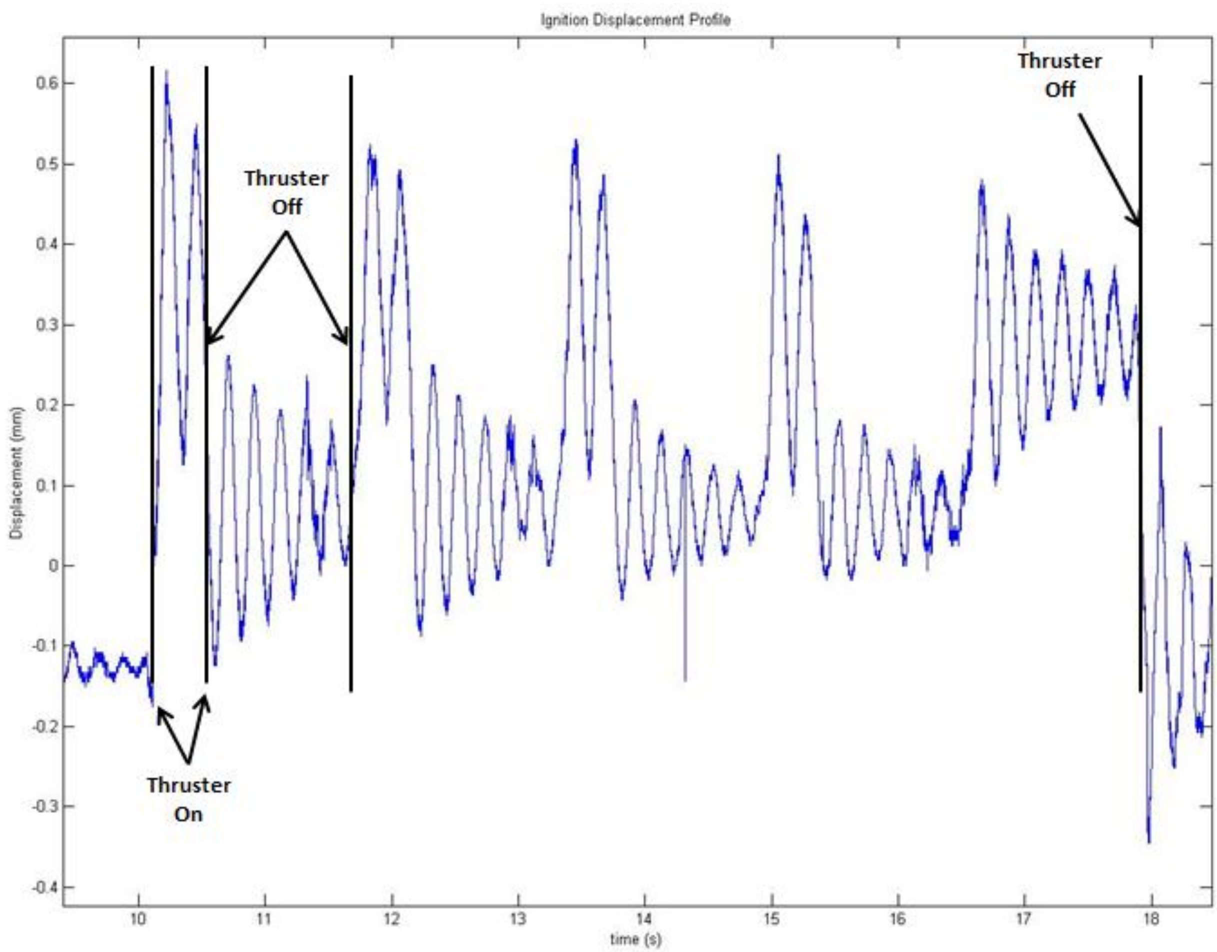


Figure 6.11: Displacement profile under pulsed operation (400 ms on/1200 ms off 5 pulses)

A Fast Fourier Transfer analysis was conducted as well in this data and is presented in Figure 6.12. The natural frequency of the system of 4.7 HZ is again visible during this trial; on/off pulsed frequencies are shown in the graph as well. However additional frequencies are visible; these may be attributed to thruster instrumentation oscillation (i.e. valves and chamber pressure measurement)

caused by the pulsed operation of the thruster. These instruments in the thruster system are not anchored to the stand itself, but rather to the thruster body and feed lines. Hence, pulsed thruster operation may have induced oscillatory movement of these instruments in particular.

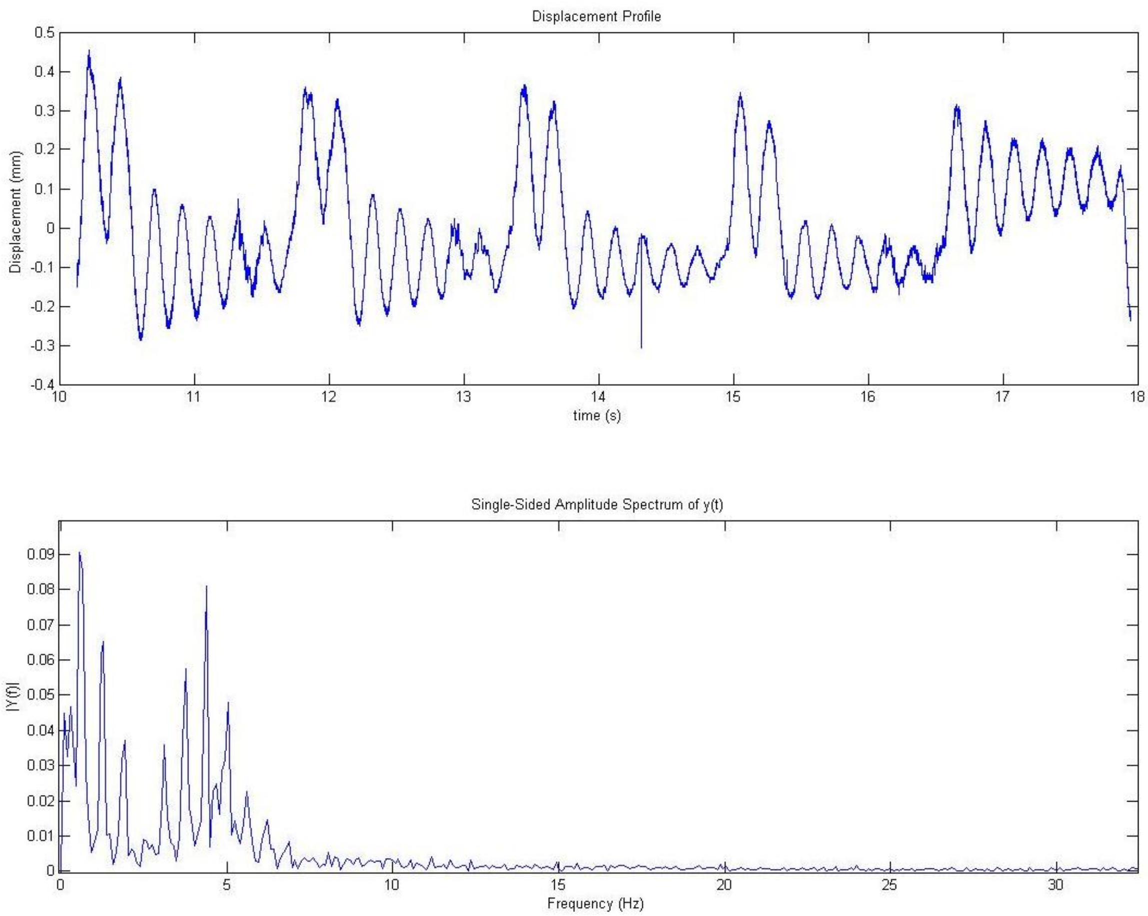


Figure 6.12: Fast Fourier Transform analysis on pulsed operation data

Table 6.4 summarizes the average thrust estimates for all the liquid-liquid runs. It can be seen, from the summarized data that the average was constant for the runs with the exception of a 5 second run, in which the combustion stopped yet average thrust was taken for the whole 5 second duration. There were three series of tests conducted, targeted to be at the same conditions, therefore they are separated by series. Data is processed via the use of MATLAB and an m-file; data is not filtered, but it is

averaged. For pulsed operation, average thrust is computed per pulse, and a final average is made for the whole test.

Table 6.4: Liquid-Liquid Thrust Results Summary

| Liquid Thrust: Round 1 | |
|---|---|
| **Thrust Description:** | **Average Thrust (lbf):** |
| *500 ms Steady State (1 pulse)* | 0.39 |
| *3000 ms Steady state (1 pulse)* | 0.44 |
| *400 ms on 1200 ms off (5 pulses)* | 0.46 |
| *5000 ms Steady State (1 pulse)* | 0.44 |
| **Liquid Thrust: Round 2** | |
| **Thrust Description:** | **Average Thrust (lbf):** |
| *5000 ms with 1000 ms Igniter (1 pulse )* | 0.26 |
| *400 ms on 1200 ms off (10 pulses)* | 0.40 |
| *5000 ms with 2000 ms Igniter (1 pulse)* | 0.38 |
| *500 ms on 500 ms off (5 pulses)* | 0.41 |
| *5000 ms with 3000 ms Igniter (1 pulse)* | 0.43 |
| **Liquid Thrust : Round 3** | |
| **Thrust Description:** | **Average Thrust (lbf):** |
| *10000 ms Steady State (1 pulse)* | 0.42 |

It was noted in previous results discussion, that igniter on time was varied for the 5s steady state runs and that combustion stopped for two of these runs. For comparison purposes, for the first one (4$^{th}$ test on Table 6.4), displacement data was only averaged for the time that ignition was visible; the second (5$^{th}$ test on Table 6.4) was averaged for the whole test duration even though ignition stopped. This is the reason why there is a 0.26 lb average for this particular run.

Displacement data for both of these runs shows repeatable behavior in terms of thrust stand response. Initial behavior similar to the one presented in Figure 6.9 is seen until combustion stopped, and a sudden drop in displacement generation is seen as it should have been expected. This is indicative of appropriate thrust stand functionality and response to combustion and cold gas flow through the thruster. Both of these cases are presented in Figures 6.13 and 6.14. The graphs for the rest of the runs are appended to this work.

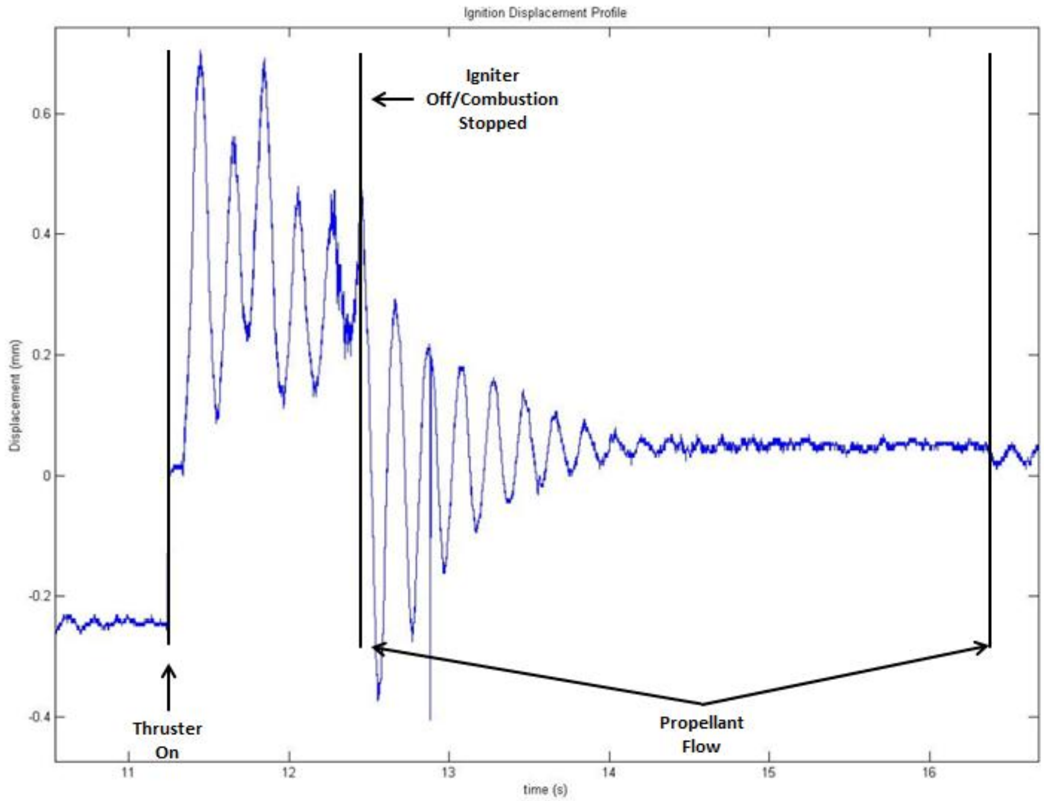


Figure 6.13: Thrust stand response during flame extinction (5s run with 1 s igniter)

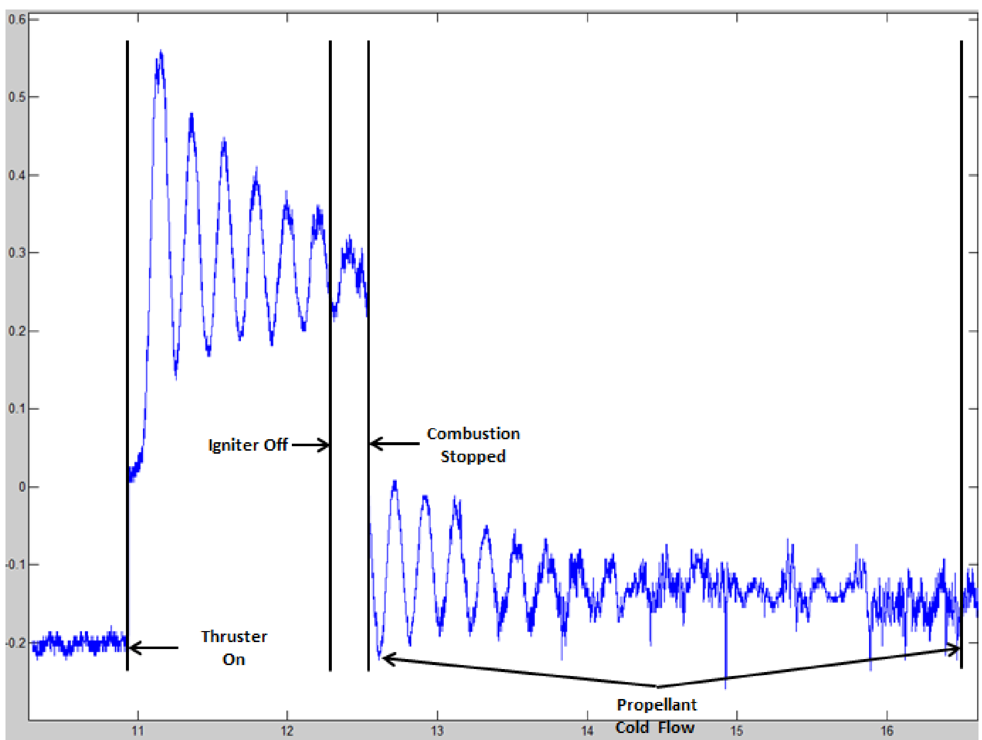


Figure 6.14: Thrust stand response during choked flow extinction (5s run 1s igniter)

**Valve Time Response**

Thruster performance is affected by valve characteristics. Cryogenic solenoid valves from GEMS Sensors & Control, the same valves used in the liquid methane production and delivery unit (Chapter 2). In order to characterize the delay in the system for control purposes, a small study was conducted to analyze the opening/closing time response of the thruster valves to compensate control pulse width to achieve desired thruster operation. Valve response was analyzed when the valves where at room temperature at testing pressures of 100 and 150 psig; the same test sequence was conducted at a point where the valves had been in cryogenic service with liquid nitrogen at -177 C flowing through. The reason behind test variation was to analyze temperature effects on valve response time, considering the valves are never in service at the same exact temperature.

For statistical and repeatability purposes, a total of four valves were tested, each of which was cycled (opened/closed) two times. A vibration sensor was taped onto the valves' surface to sense any vibration caused by the movement of the valve plunger; the voltage trace across a small resistor for each valve was recorded as well as the response from said sensor, the difference between the graphs gives an accurate estimation of the valve time response. This method also provided a way to record, for future tests, the time at which the valves open.

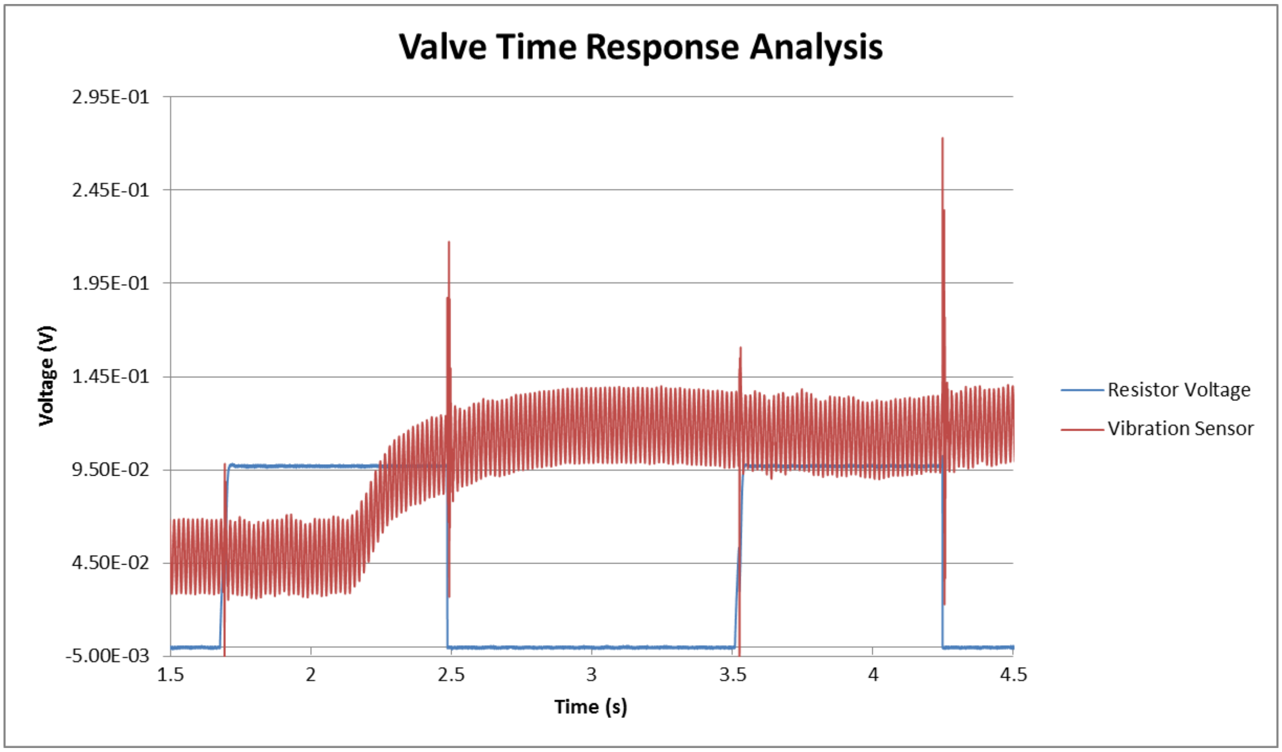


Figure 6.15: Thruster Valve Time Response Analysis

Figure 6.15 shows the graphs obtained during two cycles (open/close) of valve operation with 12V power supplied and pressurization of up to 150 psig. Vibration sensor response and voltage across a known resistance are measured and recorded. Once this graph is obtained, a closer look is taken at both the opening and closing cycles; this allows the user to see the difference between voltage activation and vibration sensor activation. The difference between these two yields a time response for the valve. Figures 6.16 and 6.17 show logic followed for analyzing the open and close time response analyses respectively.

The final average open/close responses are presented in Table 6.5; manufacturer specifications stated a time response of 4-20 ms should be expected depending on operating conditions. These values presented in the following table need to be taken into account when creating the control script in order to achieve more precise thruster operation time. For any given pulse width applied by the control system, valve operation will take away 15 ms during opening operation and add 7 ms for closing.

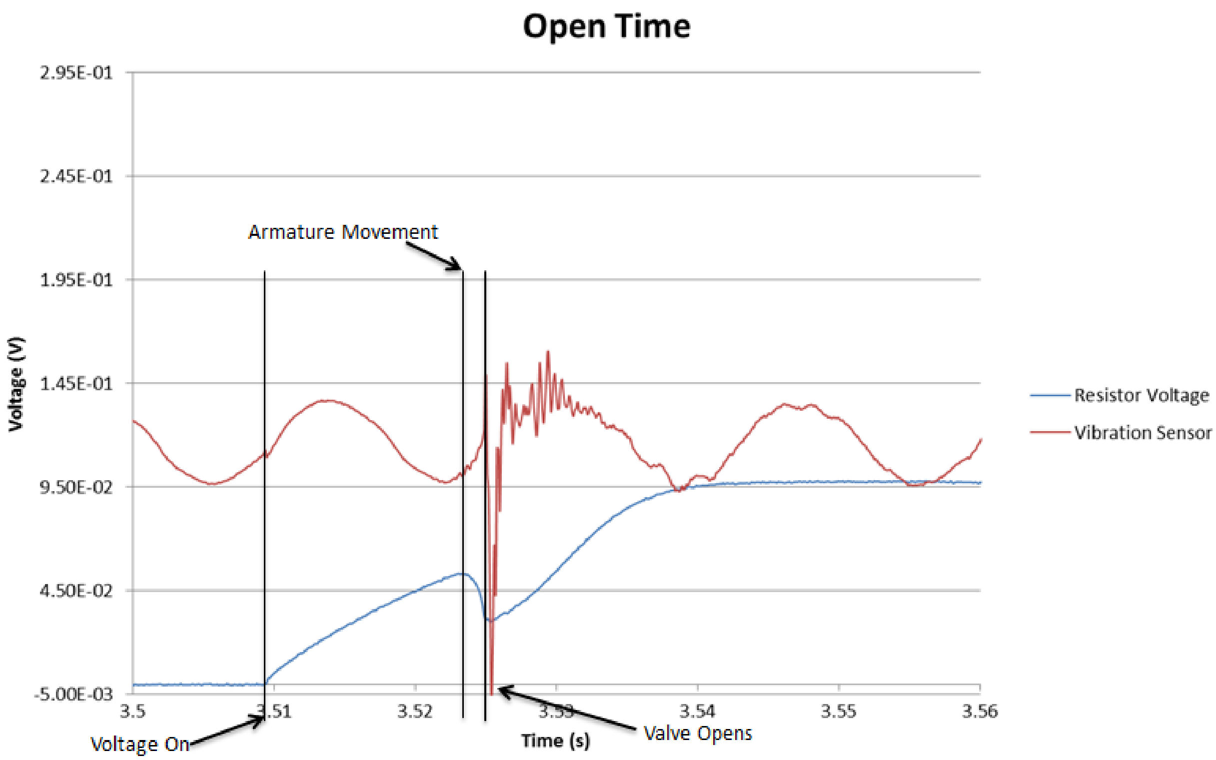


Figure 6.16: Valve Open Time Response Analysis

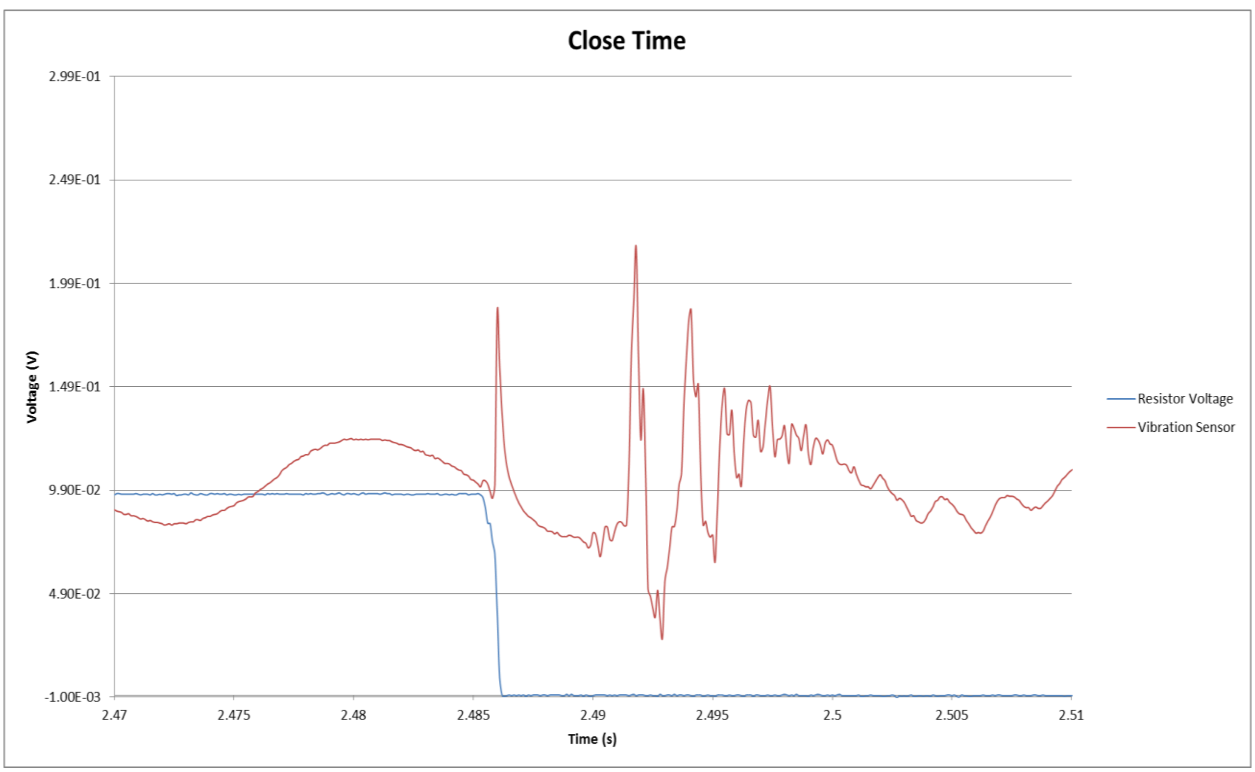


Figure 6.17: Valve Close Time Response Analysis

| Temperature | Valve Action | Time response (ms) |
|---|---|---|
| Room | Open | 15.6 |
| | Close | 7.7 |
| Cryogenic | Open | 14.1 |
| | Close | 7.6 |

Table 6.4: Valve Time Response Analysis Results Summary

This study also demonstrated that a vibration sensor alone may be used to record the exact time at which any valve in the system has opened, as is crucial to correlate thrust, pressure, and temperature data to valve operation during future testing.

**Issues**

Flow meters in the line proved to be a major obstruction for line cooling, thus, they were removed and flow rate estimation for given tank pressures were estimated. Theoretical flow rate estimations were conducted, using Bernoulli's flow relationships, to determine required propellant injection pressures. Thrust data results showed no more than 0.5 $lb_f$ thrust was produced at these conditions. Thrust measurement is considered to be the most reliable measurement, when compared to the theoretical flow estimations or the already described erratic chamber pressure measurement. Hence, performance parameters for the thruster at the conditions tested are not presented in this work. Instead, further improvement in flow rate measurement techniques and chamber pressure transducer troubleshooting were begun for the future testing.

Laser compatibility issues with LabVIEW prevented the inclusion of this measurement within the automation controls system. This makes an exact time correlation with pressure data not possible at this point.

# Chapter 7: Summary and Conclusions

The design, development, integration, and preliminary testing of a thruster performance analysis system were completed. A liquid methane production and delivery unit as well as a torsional-type thrust stand were designed and developed to meet specific thrust and flow rate requirements for testing the Pencil Thruster. This test article is part of a collaborative NASA-UTEP project to develop reliable LOX-$LCH_4$ thruster technologies.

The liquid methane production and delivery unit uses an in-house condenser with $LN_2$ flowing through coils to condense methane. A secondary tank is used to pressurize the liquid to the desired pressure, depending on flow rate required. A capacity of 2.2 L of liquid methane allows testing at different duty cycles and pulse configurations.

The torsional-type thrust stand was designed, developed, and underwent preliminary testing under thruster operation; yielding repeatable results under both pulsed and steady state thruster operations. Test article weight has a significant effect on system dynamic response, by decreasing considerably the natural frequency of the system. Two different natural frequencies at different thruster weights were recorded: 7 Hz for the thrust stand with a 2.5 kg system; and 4.8 Hz for a 4.9 kg system.

A fully-automated LABVIEW-based controls system was developed to integrate the systems mentioned before, as well as the LOX and thruster ignition subsystems. The control system allows the user to create an experimental sequence of valve opening/closing times in a text file; this file is read and executed by the software. Built-in emergency activation is programmed in the structure if thruster instrumentation surpassed pre-set values that the user defines.

Preliminary system integration was tested by firing the Pencil Thruster at ambient conditions. This first stage testing was done in both gas-gas and liquid-liquid propellant state combinations. Flow meters in the system did not allow system cooling for cryogenic liquid-liquid testing, therefore they were removed. Theoretical flow rate estimations were conducted using Bernoulli's equation to determine injection pressures. Ignition was achieved in all of the runs; an average thrust of 0.45 $lb_f$ was determined from the thrust stand response data. Due to the lack of flow rate and reliable chamber pressure measurements, thruster performance parameters were not presented in this work. Further

validation of flow rate and chamber pressure is required. Cavitating venturis are currently being explored as the main alternative for future flow rate control. These are currently under testing phase to determine applicability in the system.

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# Appendix

## Hazards Analysis for "Pencil Thruster" Experimental Setup

Center for Space Exploration and Technology Research (cSETR)

The University of Texas at El Paso
College of Engineering, M-305
El Paso, Texas79968-0717
Phone: (915) 747-7398

Hazard Analysis Descriptions of Fields:

System: Description of the system where the hazard may reside.

Hazard: Description of the specific hazard that could occur.

Severity: measure of the severity of the Hazard as listed below (in Excel, menu options exist):

1 - Minor
2 - Moderate
3 - Significant
4 - Catastrophic

Likelihood: measure of the probability or likelihood of occurrence according to the below listed options (in Excel, menu options exist):

1 - Unlikely
2 - Infrequent
3 - Frequent
4 - Imminent

HA Index: measure of the degree of consideration needed as follows (calculated automatically in Excel):

1 - Minimal Risk: Proceed with Mitigation in mind
2 - Moderate Risk: Proceed with Mitigation in mind
3 - High Risk: Proceed with PI Concurrence and Mitigation in mind
4 - Severe Risk: Proceed only with PI Approval and Review of all means of mitigation

Hazards Analysis for Pencil Thruster

| H# | System | Hazard | Severity | Likelihood | HA Index | Mitigation |
|---|---|---|---|---|---|---|
| 1 | Propellant Lines | Pressure build-up | 2 - Moderate | 1 - Unlikely | 1 | Install relief valves in adequate sections of line, facing safe location |
| 2 | Propellant Lines | LN2 spill | 2 - Moderate | 2 - Infrequent | 2 | Proper ventilation, containment areas, usage of appropriate PPE (gloves, glasses, apron, mask) |
| 3 | Propellant Lines | LCH4 spill | 2 - Moderate | 2 - Infrequent | 2 | Proper ventilation, containment areas, usage of appropriate PPE (gloves, glasses, apron, mask) |
| 4 | Propellant Lines | LOX spill | 2 - Moderate | 1 - Unlikely | 1 | Proper ventilation, containment areas, usage of appropriate PPE (gloves, glasses, apron, mask) |
| 5 | Propellant Lines | LOX combustion | 3 - Significant | 1 - Unlikely | 2 | Proper maintenance of delivery system (cleaning, filtering), isolation of propellant. Remote operation of LOX system and personnel clearance from affected area |
| 6 | Propellant Lines | Explosion | 4 - Catastrophic | 1 - Unlikely | 3 | Proper ventilation system, close propellant valves, run purge |
| 7 | Propellant Lines | Fire | 3 - Significant | 1 - Unlikely | 2 | Usage of propellant-compatible materials, suppression system on-hand at time of experimentation, stop experimental sequence, emergency stop if necessary |
| 8 | Propellant Lines | Valve Failure | 2 - Moderate | 1 - Unlikely | 1 | Stop experimental procedures, check valve connections, troubleshoot |
| 9 | Control | LabVIEW failure | 3 - Significant | 2 - Infrequent | 2 | Press Emergency Stop button |
| 10 | Power lines | Short-circuit | 2 - Moderate | 2 - Infrequent | 2 | Stop experimental procedures, check electrical connections |
| 11 | Cryogenics | Skin burn | 2 - Moderate | 1 - Unlikely | 1 | Usage of appropriate PPE and remote operation of system |
| 12 | Ignition | Ignition failure | 3 - Significant | 2 - Infrequent | 2 | Stop propellant delivery, turn ignition system off, run purge on system |
| 13 | Power | Power outage | 2 - Moderate | 1 - Unlikely | 1 | Isolate test area, stop experimental procedures |
| 14 | Propellant Lines | Gaseous CH4 leak | 2 - Moderate | 1 - Unlikely | 2 | Use of methane detector on test area, stop experimental sequence, troubleshoot. Bunker back door open fr proper ventilation |
| 15 | Propellant Lines | Oxygen leak | 2 - Moderate | 2 - Infrequent | 2 | Monitor oxygen level in test area, stop eperimental procedure, troubleshoot. Bunker back door open for proper ventilation |

## Pencil Thruster Experimental Procedure

| | |
|---|---|
| Project: | LOX/LCH4 RCSSystem |
| Test/Experiment: | PencilThrusterTesting |
| Experimenter: | |
| Reviewer: | |
| Version/Control Num. | |

**Experiment/Test Operating Procedure**

Equipment Specifications:

- 12 VDC valves
- 120 VAC valves
- 12V car battery
- 44kV ignition coil transformer
- Signal generator 20Vp-p max
- Pressure transducers 2x (0-200 psi, 0-500 psi)
- Type K and E thermocouples

Safety Requirements:

- Personal protective equipment required; closed toe shoes, safety glasses, no loose articles, leather gloves
- Clear test area with exception of test personnel
- Close off test area; when test is in progress, no one is allowed in test area or its surroundings
- Ensure remotely controlled systems function properly
- Ensure safety monitor is present during experimental procedures
- Ensure at least one team member is outside laboratory surroundings to keep away people during experimental sequences

Calibration Record:

Procedural Actions: QC

| # | Required Actions | Expected Results | Action Upon Adverse Result | ☒ |
|---|---|---|---|---|
| 1 | Complete pre assembly of pencil thruster. | Pencil thruster is assembled with all components. All components in place. | Postpone test until completed | ❑ |
| 2 | Ensure pencil thruster is secured to thrust stand inside vacuum chamber. Pencil thruster c-clamp must be flush to thrust stand moment arm; secure through nut and bolt | Pencil Thruster is installed and secured on thrust stand. All components are tightened. | Postpone test until completed | ❑ |
| 3 | Ensure bunker is free from foreign objects that pose a fire hazard. | No lose parts in area. Area cleaned. No foreign flammable objects | Postpone test until completed | ❑ |
| 4 | Ensure all instrumentation (valves, spark plug, spark plug wire, ignition coil wiring, flexible hose connections) are connected to pencil thruster components and igniter | All Wires and and igniter battery are properly connected | Postpone test until completed | ❑ |
| 5 | Ensure exhaust fans are on | Fans working and pulling air from vents | Postpone test until completed | ❑ |
| 6 | Ensure Kevlar barriers are in place | Barriers should be placed in front of test section and in between fuels and oxidizers | Postpone test until completed | ❑ |
| 7 | Check all thruster wiring is securely connected and out of flame direction | Wiring is correctly installed and safe from thruster flame direction | Postpone test until completed | ❑ |
| 8 | Via lab view, assure that all data transmissions is working properly | Labview monitors show proper data | Postpone test until completed | ❑ |
| 9 | Clean vacuum chamber windows for appropriate camera recording | Vacuum chamber window is clean allowing for appropriate | Postpone test until completed | ❑ |
| 10 | Pre check to ensure proper igniter functionality | Igniter works correctly producing sparks to thruster walls | Postpone test until completed | ❑ |
| 11 | Pre check to see all fluid connections are connected and tight | Connections should be tight to hand torque | Postpone test until completed | ❑ |
| 12 | Turn bunker light from green to yellow | light should show yellow | Postpone test until completed | ❑ |
|  | Begin $CH_4$ Condensation Process (Process duration varies upon environmental conditions, $LN_2$ availability. | $CH_4$ condensation is carried out | Postpone test until completed | ❑ |

| | | | | |
|---|---|---|---|---|
| | Upon desired amount of LCH4 is condensed, begin transfer to run tank | LCH4 is transferred to run tank | Postpone test until completed | ❑ |
| | During LCH4 transfer, begin LOX line and CH4 line cool-down. Open LN2 tanks for both lines as well as LOX cooling, bleed, thruster and LN2 cooling, CH4 bleed and thruster valves | Cool-down of LOX and CH4 lines begins | Postpone test until completed | ❑ |
| 13 | Verify CCTV cameras are situated correctly | cameras should show proper viewing angles and be secure | Postpone test until completed | ❑ |
| 14 | Verify cameras are working correctly | Optical equipment should work correctly and transmit remotely to computer | Postpone test until completed | ❑ |
| | Close LOX line LN2 tank, open LOX tank and continue line chill with LOX | LOX starts to cool in the line | Postpone test until completed | ☐ |
| 15 | Prepare cameras for recording of test | instrumentation should be ready to record with one click on computer | Postpone test until completed | ❑ |
| 16 | Ensure ignition coil is connected properly. Securely connect alligator clips to battery ends for igniter power supply | Ignition coil is connected to power supply | Postpone test until completed | ❑ |
| | Upon LCH4 transfer completion, check LOX and CH4 line temperatures to be -164 C | Lines are chilled and LCH4 is ready to be pressurized | Postpone test until completed | ❑ |
| | Pressurize LCH4 to desired pressure. Open Helium tank and valve on methane system | LCH4 is pressurized | Postpone test until completed | ❑ |
| 17 | Turn on signal generator and set for 100Hz square wave input, anda turn manual switch to on position | Signal generator ready for igniter input signal requirements | Postpone test until completed | ❑ |
| 18 | Ensure Killswitch is disengaged | Switch should be pulled out and ready to use in the event of abort | Postpone test until completed | ❑ |
| 19 | Verify test pressures for all tanks and bottles | Pre-test preparedness should declare what pressures the system should be at | Postpone test until completed | ❑ |
| | Stop LOX and LN2 flow. Close LOX tank valve, LN2 cooling valve on LabVIEW | | | ☐ |
| 24 | Press record on HD camera | Camera should start recording | Postpone test until completed | ☐ |
| 25 | Evacuate bunker and ensure that Doors are closed and latched | No personnel in bunker and doors do not open unless handle is activated | Postpone test until completed | ❑ |
| 26 | Turn bunker light from yellow to red | light should show red | Postpone test until completed | ❑ |

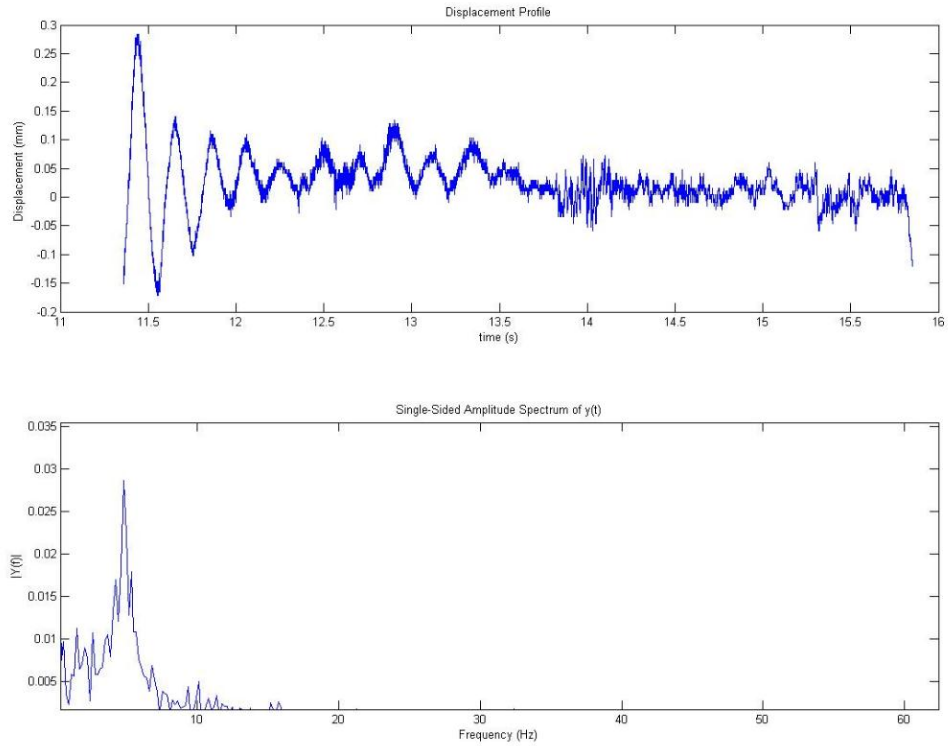
| | | | | |
|---|---|---|---|---|
| 27 | Personnel should be situated at testing stations (laboratory surroundings, LabVIEW controller, and safety monitor) | Testing teams should be situated at control, and video and data stations for test monitoring | Postpone test until completed | ❑ |
| | Close "Cart" LabVIEW program, open "Automation_Thruster" LabVIEW program | Automation program is started | Postpone test until completed | ☐ |
| 28 | Begin lab view recording | LabVIEW should begin recording data | Postpone test until completed | ❑ |
| 29 | Begin Countdown process | Count down leader will start countdown | Postpone test until completed | ❑ |
| 30 | Begin reading of experimental sequence in LabVIEW | Previously recorded script is read and sequence us run through | Stop test, trouble shoot | ❑ |
| 31 | Monitor temperature measurements of thruster instrumentation | Temperature rises as test goes on | Postpone test until completed | ❑ |
| 32 | Confirm combustion via CCTV imagery | Combustion flame should be visible through camera imagery | Stop test, Trouble shoot | ☐ |
| 33 | Monitor test carefully for test interval. | observe to see if no anomalies occur | Stop test, Trouble shoot once safe | ❑ |
| 34 | Ensure via CCTV or windows that no anomalies have occurred | All hardware should be normal | Trouble shoot once safe to enter | ❑ |
| 35 | Ensure bunker is safe to enter and switch light from red to yellow | no hazards pose risk, light to show yellow | Stop test, Trouble shoot once safe | ❑ |
| 36 | Close all fuel and oxidizer gas bottles from tank valve | valves should be fully closed | Stop test, Trouble shoot once safe | ❑ |
| 37 | Close regulators on fuel and oxidizer lines | regulators should be set to zero | Stop test, Trouble shoot once safe | ❑ |
| 38 | Exit bunker | No personnel in bunker and doors do not open unless handle is activated | Stop test, Trouble shoot once safe | ❑ |
| 39 | Run purge system | Nitrogen purge should occur | Stop test, Trouble shoot once safe | ❑ |
| 40 | Close all nitrogen gas bottles from tank valve | valves should be fully closed | Stop test, Trouble shoot once safe | ❑ |
| 41 | Close regulators on nitrogen lines | regulators should be set to zero | Stop test, Trouble shoot once safe | ❑ |

| | | | | |
|---|---|---|---|---|
| 42 | Open valves to ensure no gas is trapped | valves should open | Stop test, Trouble shoot once safe | ❑ |
| 43 | Inspect hardware for damage | no damage should occur | investigate and repair | ❑ |
| 44 | Turn off signal generator and manual switch for igniter. Remove clips from car battery | Ignition coil power is cut | Disconnect power cord from signal generator | ❑ |
| 45 | Save data and video recording | data should be stored and immediately backed up | Do not proceed until completed | ❑ |
| 46 | Turn light from yellow to green | light should show green | Trouble shoot | ❑ |
| 47 | Begin post test maintenance | cleaning assemblies and rechecking for damage | N/A | ❑ |
| 48 | Record events in test log | Log to be completed for testing | N/A | ❑ |
| 49 | Turn off Vent fans | Fans to be shut down by audio inspection | N/A | ❑ |
| 50 | | | | ❑ |

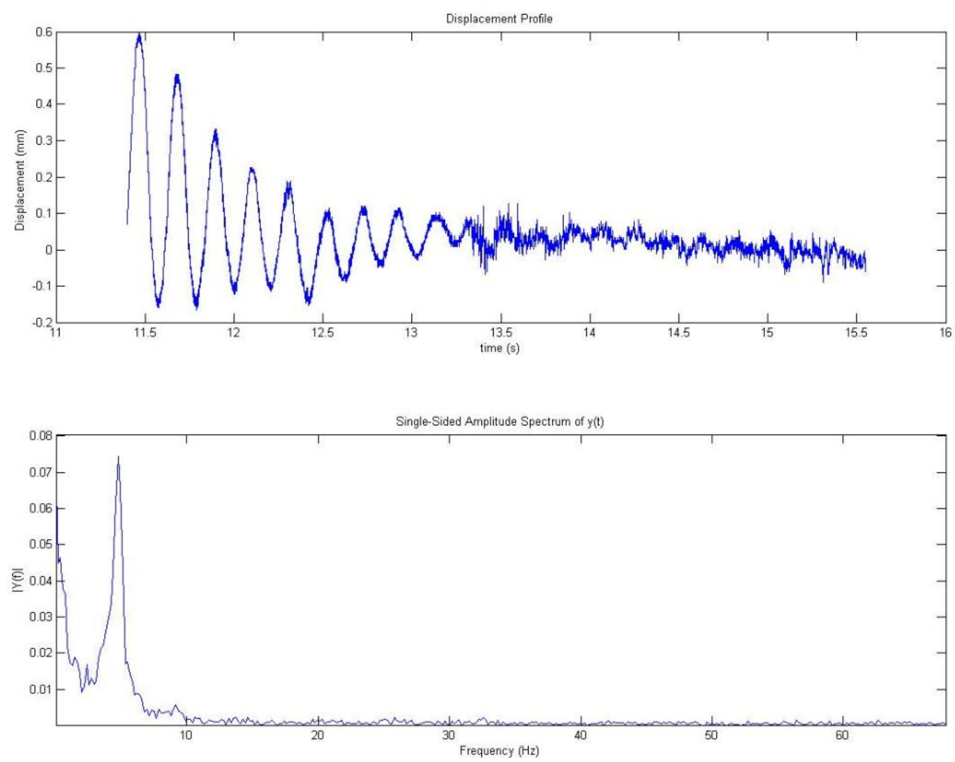
Project: LOX/LCH4 RCS System

Test/Experiment: Pencil Thruster Testing

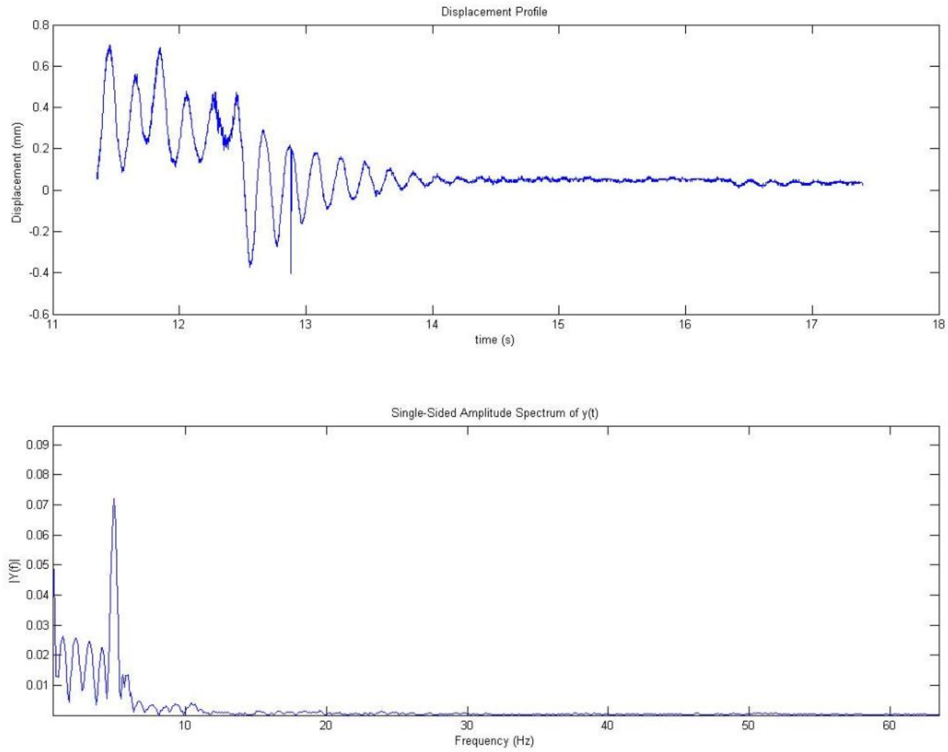
## Thrust Stand Response and FFT for Test Trials



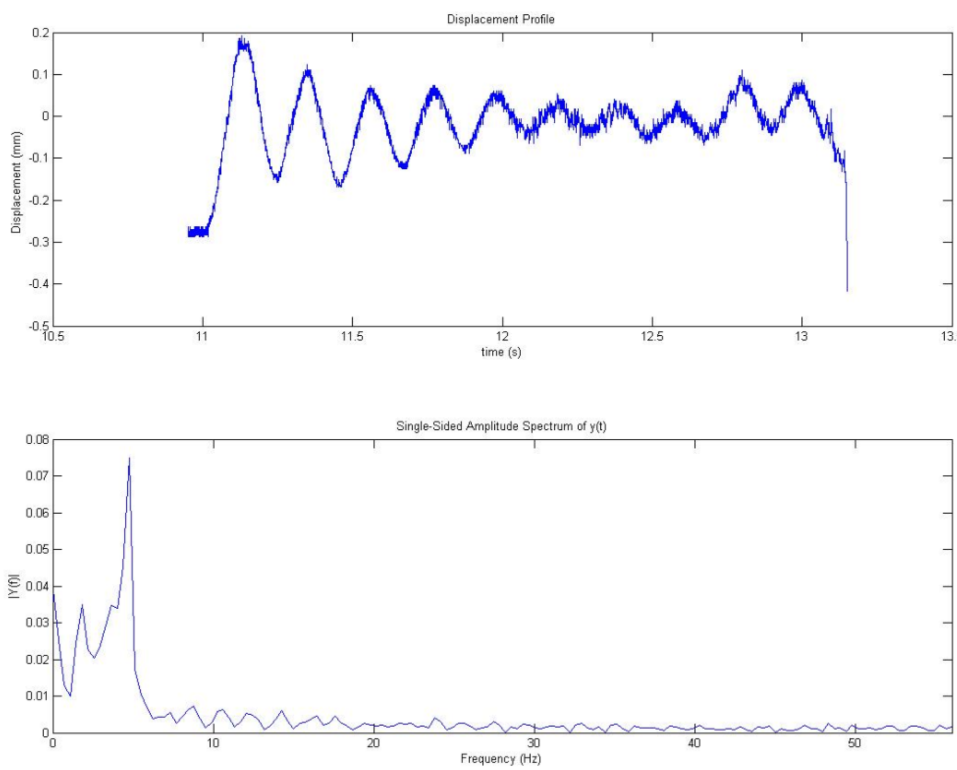

**5s Steady State Operation Response and FFT (3s igniter on time)**



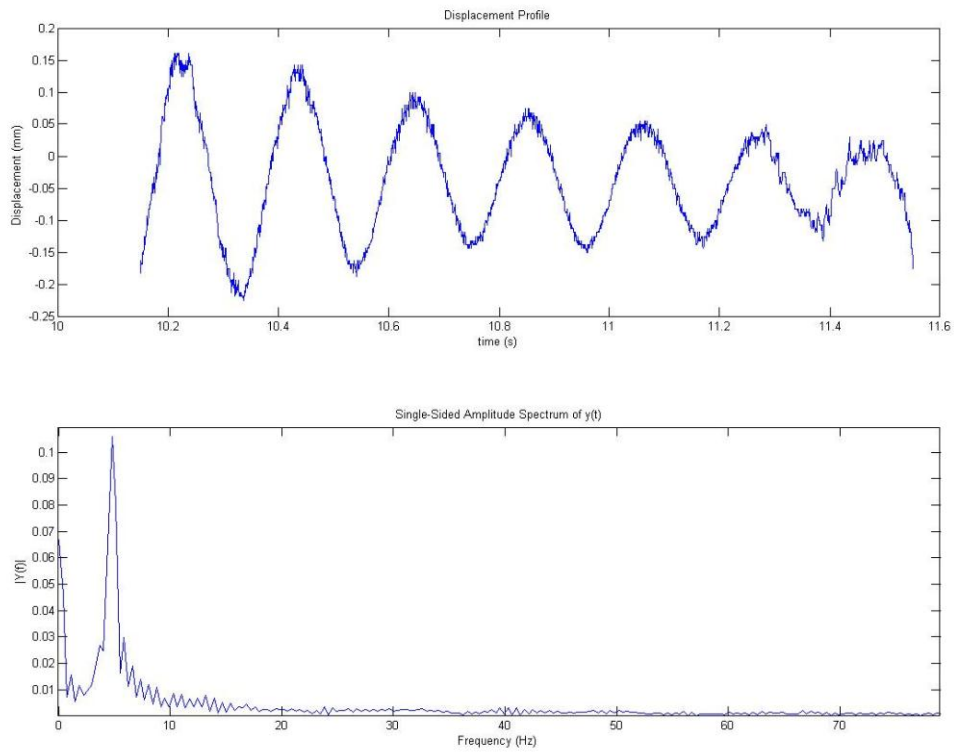

**5s Steady State Operation Response (2s igniter on time)**



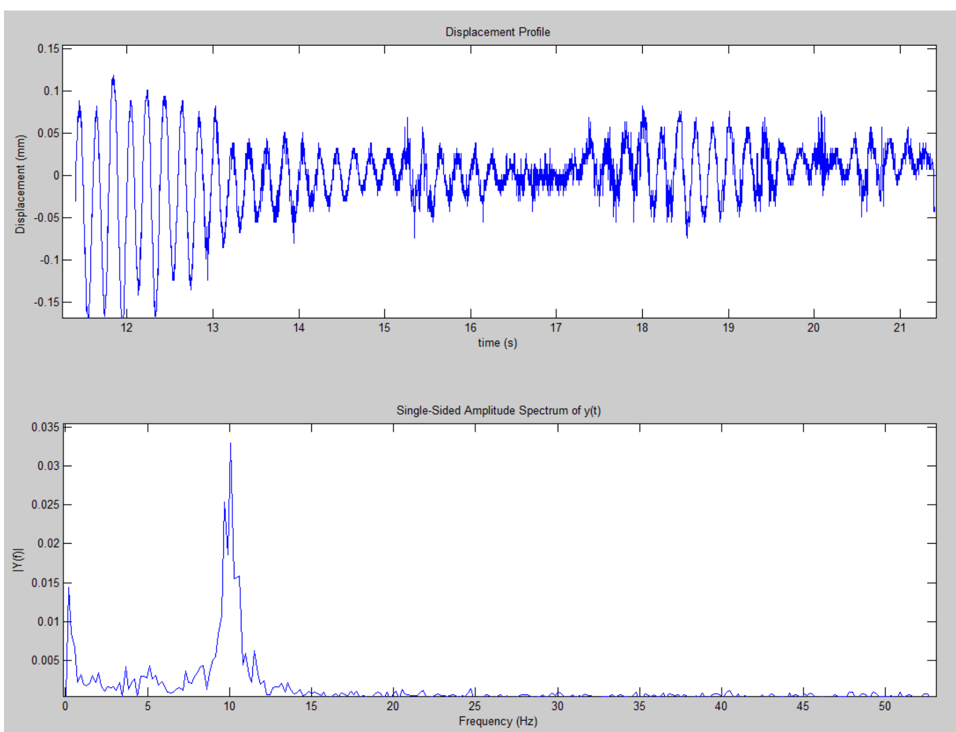

**5s Steady State Operation Response (Stopped Ignition)**



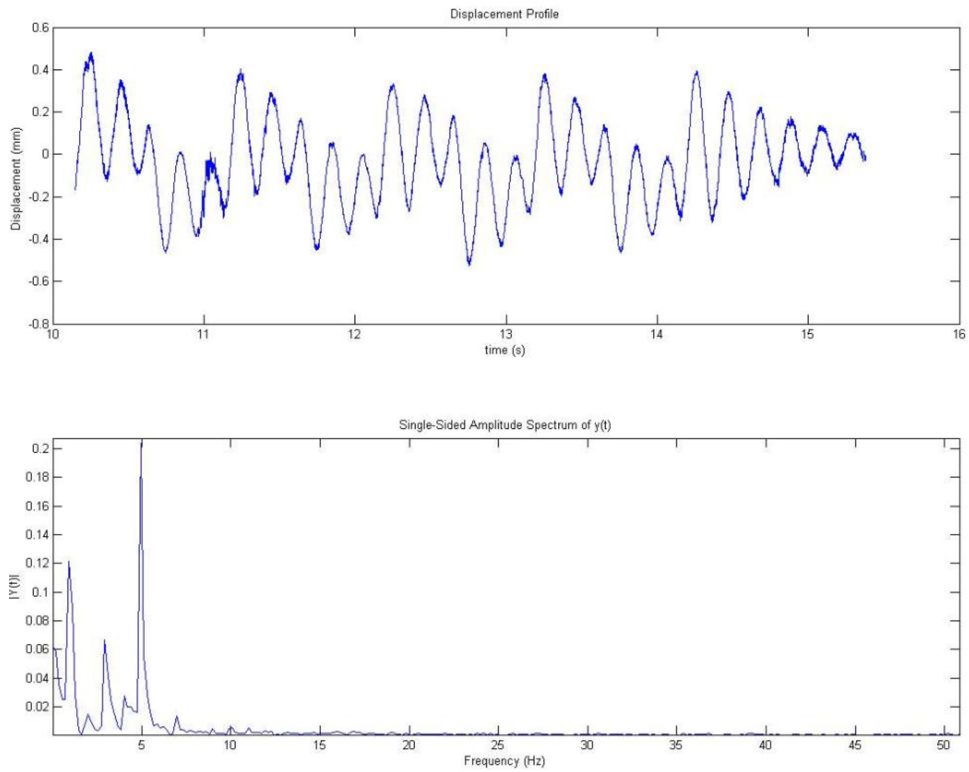

**3s Steady State Operation Response**



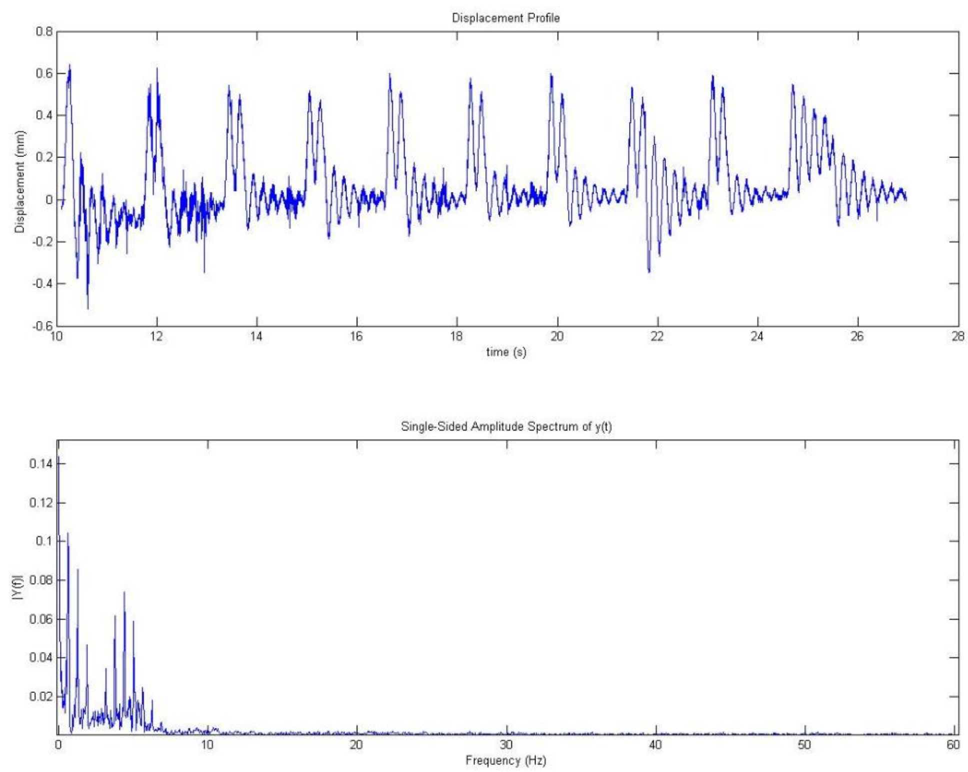

**1s Steady State Operation Response**




**10s Steady State Operation Response**




**500ms on/500 ms off Pulsed Operation Response (5 pulses)**




**400ms on/1200 ms off Pulsed Operation Response (10 pulses)**

# Vita

Arturo Acosta-Zamora was born and raised in El Paso, Texas. He attended the University of Texas at El Paso starting the Fall 2008 semester and graduated with a Bachelor's of Science degree in Mechanical Engineering in May 2011. Upon completion of this degree, he worked as an intern at NASA's Johnson Space Center performing structural analysis. He started working at the Center for Space Exploration Technology Research (cSETR) as an undergraduate and continued to work here while pursuing his Master's Degree in Mechanical Engineering in the Fall of 2011. His research focus is propulsion technologies, specifically LOX/$LCH_4$ thrusters.

Permanent address: 1439 Jim Larabel Dr

El Paso, TX, 79936

This thesis/dissertation was typed by Arturo Acosta-Zamora