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Structures And Daq System For The Lox/lch4 500 And 2000 Lbf. Rocket Engines

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STRUCTURES AND DAQ SYSTEM FOR THE LOX/LCH4 500 AND 2000 LBF. ROCKET ENGINES

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STRUCTURES AND DAQ SYSTEM FOR THE LOX/LCH4 500 AND 2000 LBF. ROCKET ENGINES

by

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THESIS

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ABSTRACT

With the progression of space exploration and research, new alternative fuels and fuel combinations have been discovered. The ability to produce methane from Mars’ atmosphere and oxygen from Mars’ regolith has led to the two becoming a great alternative propellant combination for rocket propulsion systems. To further advance LOX/LCH4 propulsion systems, a 500 and 2000 lbf rocket engine were designed and manufactured and are to be launched from the MIRO cSETR Technology Research and Innovation Acceleration Park (tRIAc) in Fabens, Texas for data collection and analysis. The objective of this thesis is to give a thorough overview of the static structures to be used in the launch of the 500 lbf and 2000 lbf LOX/LCH4 rocket engines, their design processes, finite element analysis and the various other methods used to validate their structural integrity. These static structures thus far include two static tank stands to support one cryogenic LOX tank, one CH4 tank, and a vertical thrust test stand.
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INTRODUCTION

With the 500 lbf rocket engine, and the cryogenic LOX and LCH4 fuel tanks ordered and manufactured, the need for some fundamental testing structure designs became a priority. Requirements were drawn up for the design of a vertical test stand to measure the true thrust value. To fuel said thrust test, the tanks would need tank stands that could support their weight along with any additional weight due to plumbing and protective Kevlar panels as well as resist any vibrational forces that might be transmitted through the plumbing lines. The hot fire test will be conducted with both manual and automated controls all configured with a c-RIO and c-DAQ inside a portable trailer. For future endeavors, expansions may be added to facilitate controlling larger systems or new instrumentation.
VERTICAL THRUST TEST STAND

The test stand for the 500 lbf rocket engine hot fire test, had various requirements based on the interfaces on the thrust module and the base at the launch site. There were also issues with vibrational forces causing the structure to fail, so natural frequencies were approximated using hand calculated analysis methods. For the purpose of simplifying ordering, manufacturing, and purchasing, standard beams were made a requirement unless absolutely necessary. Prior designs gave a starting base line; however, none met the requirements wholly.

TEST STAND REQUIREMENTS

- Maximum height of 5 feet
- Detachable/Non-permanent interface with thrust (load cell) module
- Detachable/Non-permanent interface with Fabens concrete secured steel I beam base
- Accessible interior and mounting points for provisional wiring plumbing and installation
- Use standard ASTM (A6) standards for steel beams
- Minimum natural frequency of 300 Hz
- Withstand a static weight load of 10,000 lbf with a safety factor of 2.0 to yield
- Maintain structural integrity when impacted by test mass with safety factor of 2.0 to yield
- Withstand both static and dynamic load caused by engine fire
- Both material and structure must withstand temperatures up to 2000° F
- Withstand transverse loads of 3000 lbf with safety factor of 2.0 to yield
TEST STAND DESIGN PROCESS

Initial designs preceding the finalization of the 500 lbf rocket consisted of a simple and accessible structure that used large 7” square tubes on each of the four outer corners as the main support to any vertical compressive stresses. Connecting I-beams reduced any buckling seen in the vertical tubes layered on top identical perpendicular I-beams to reduce any bending stresses caused by the weight of the engine and thrust modules. The overall mass of the structure and central position of the thrust module made all preceding designs fail in terms of maintaining their integrity up to 300 Hz. Various methods were made to raise the natural frequency however all designs maxed out at 85.1 Hz.
Subsequent designs used similar square tubes along the four corners as the main load bearing pillars, however their size and thickness were decreased based on an area calculated using simple cantilever beam stress equations and Euler’s buckling equation. Smaller angled square tubes were welded on to the sides to prevent any remaining buckling that might occur in the vertical beams and prevent certain reoccurring modes seen during the modal analysis. Figure 3.a shows one of the assorted designs using a thrust module loaded in tension, while figure 3.b shows another design with the load cell module loaded in compression.

![FIGURE 3: THRUST MODULE IN TENSION](image1)

![FIGURE 4: THRUST MODULE IN COMPRESSION](image2)

The model shown in figure 3.1 reaches a static safety factor of 2.0 to yield and a dynamic safety factor of 0.29 to yield with its first modal shape at a natural frequency of 88.8 Hz. Much lower than the 300 Hz requirement. The model shown in figure 3.2 reaches a static safety factor of 2.5 to yield and a dynamic safety factor of 0.21 to yield with its first applicable modal shape at a natural frequency of 85.1 Hz. The first three resultant modal shapes of all the designs, shown in Figure 3, were all almost exactly alike, the thrust module would show signs of vibrating and that vibration would spread throughout the beams directly supporting it, contorting the structure leaving the base structure almost completely untouched. Because the thrust module could not be further constrained due to its dynamic nature, the natural frequency requirement was re-evaluated.
and reduced to 80 Hz. The decision was also made to test the engine on a horizontal test stand primarily instead and leave the vertical stand for further testing.

With the decision to test horizontally as opposed to vertically, the thrust module’s design and functionality came into question. It was fully reviewed and underwent design modifications. Rather than four load cell modules, the new thrust module would only have three and would consist of 0.5” hexagonal plates and hollow cut out square tubes. The designs for the thrust module changing would mean that the entire vertical test stand would change as well.
LOX/LCH4 TANK STANDS

Two types of cryogenically stored fuels are being used in the launch of the 500 and 2000 lb. rocket engine. During the test fires, two 36” diameter cryogenic spherical tanks were special ordered. The design process began with determining the requirements for a tank stand design that would prove structurally sound. Primarily the weight of the tank was to weigh solely on the lower flange shown in Figure 5.1. However, analysis showed that the manufacturer neglected to create a flange capable of withstanding the tank’s own weight. Thus, a revised design with feet on the lower quarter was drawn up, this is shown in Figure 5.2.

![Figure 9: 36” Diameter Tank Design](image1)

![Figure 10: Revised Tank Design](image2)

The dry weight of the tank came to 1000 lbf, with a wet weight of 1600 lbf, both approximated using the density of A36 steel (0.28 lb/in\(^3\)), density of LOX (0.0412 lb/in\(^3\)) and volume of the 36” sphere. Kevlar panels, about 0.5” thick, needed to be added to the sides to prevent any high velocity projectiles from puncturing the pressurized tank. These panels supplied an extra 500 lbf bringing the total (wet) weight to 2000 lbf.
TANK STAND REQUIREMENTS

- 2” clearance for forklift installation
- Minimum natural frequency of 80 Hz
- Use standard ASTM (A6) standards for beams
- Accessible interior for plumbing and installation
- Non-permanent/Detachable interface with tank feet
- Non-permanent/Detachable interface with trailer bed
- Withstand static load of 2,000 lbf with safety factor of 2.0 to yield
- Withstand transverse loads of 1000 lbf with safety factor of 2.0 to yield
- Minimum 3’ clearance from lower flange to ground for adequate plumbing space
- Maintain Structural Integrity in case of impact by high velocity projectile using Kevlar

With an approximate wet tank weight of 2000+ lbs., including the Kevlar panels a quick compressive stress calculation leaves a minimum area of $27.5 \times 10^{-3}$, near negligible, using a force of 2000 lbs., a stress at yield of 36,300 Psi and a safety factor at minimum of 2 to support the entire weight.

$$\sigma = \frac{F}{A} \quad (1)$$

A basic bending stress formula is used to find the minimum dimensions for a tank stand leg that would produce a stress well within a safety factor of 2 to yield. Using equations (2) and (3) a square tube with sides [a] of 3” and a wall thickness [t] of 0.375, where [b]=[a-2*t] would withstand up to 4076 lbs. before bucking.

$$\sigma = \frac{\pi^2 EI}{(KL)^2} \quad (2)$$
\[ I = \frac{a^4}{12} - \frac{b^4}{12} \]  \hspace{1cm} (3)

Square tubing was deemed unnecessarily precautious and were replaced with C-Channels with a length of 4”, due to the thickness of the tank’s feet, an unchanged thickness of 0.375”, and a flange length of 2.5”. The tank legs would be 35” in length to allow adequate space from the ground to the lower flange. A bending stress equation (4) was used to determine an ideal thickness for the plates the tank feet would connect directly to. The c-channels would rest directly under each of the four feet so the tank itself would not contribute to any bending stress. A 0.5” plate with a length of 19.5” a dimension decided by a combination of the size of the tank, the clearance distance and the size of the 1.5” x 1.5” x 0.125” beams that would secure the Kevlar panels. Some 1.5” x 1.5” x 0.125” square tubes were also added beneath the Kevlar support tubes to further reduce any bending that would be seen in the connection plates. Thus, a finalized design as seen in figure 2 was submitted for analysis.

*FIGURE 2*: TANK STAND FOR LOX/CH4 CRYOGENIC FUEL TANKS
FINITE ELEMENT ANALYSIS

The finite element analysis (FEA) was conducted using Hypermesh. Each piece of the assembly was treated as a midplane and fitted with shell elements. The four bolt holes at the bottom of the tank stand feet were restrained using SPCs and a CBar element to represent a bolt. The same was done to represent the tank to tank stand interface. Preliminary modeling was done using the tank’s geometry and material properties to simulate dry weight.

FIGURE 12: TANK TO TANK STAND FEA MODELING INTERFACE

FIGURE 13: TANK STAND DESIGN FEA MESH

FIGURE 14: CLOSE UP TANK STAND HOLE MESH
The tank and Kevlar weights were modeled as concentrated mass points distributed amongst RBE3s and RBE2s that connected to the bolt holes found in the top and bottom of each of the four upright support beams.

A force of several thousand pounds; to represent the wet weight of the fuel; was applied and the stresses found throughout the structure were minimal. Stresses only displayed around the legs of the tank stand with no stresses venturing any higher than a few thousand Psi. The approved design was broken down into blueprints to be manufactured with a powdered black paint coating and limited specialized manufacturing.
**FIGURE 17: MATERIAL PROPERTIES REFERENCED FOR CALCULATION PURPOSES**

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Metric</th>
<th>English</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7.85 g/cm³</td>
<td>0.284 lb/in³</td>
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</table>

<table>
<thead>
<tr>
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<th>Metric</th>
<th>English</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, Ultimate</td>
<td>400 - 550 MPa</td>
<td>58000 - 79800 psi</td>
<td></td>
</tr>
<tr>
<td>Tensile Strength, Yield</td>
<td>250 MPa</td>
<td>36300 psi</td>
<td></td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>20 %</td>
<td>20 %</td>
<td>in 200 mm</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>290 GPa</td>
<td>29000 ksi</td>
<td></td>
</tr>
<tr>
<td>Compression Yield Strength</td>
<td>152 MPa</td>
<td>22000 psi</td>
<td>Allowable compressive strength</td>
</tr>
<tr>
<td>Bulk Modulus</td>
<td>180 GPa</td>
<td>23200 ksi</td>
<td>Typical for steel</td>
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<tr>
<td>Potassium Ratio</td>
<td>0.26</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>79.3 GPa</td>
<td>11500 ksi</td>
<td></td>
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</table>

<table>
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<th>Component Elements Properties</th>
<th>Metric</th>
<th>English</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon, C</td>
<td>0.29 %</td>
<td>0.29 %</td>
<td></td>
</tr>
<tr>
<td>Copper, Cu</td>
<td>&gt;= 0.25 %</td>
<td>&gt;= 0.25 %</td>
<td>only if copper steel is specified</td>
</tr>
<tr>
<td>Iron, Fe</td>
<td>98 %</td>
<td>98 %</td>
<td></td>
</tr>
<tr>
<td>Manganese, Mn</td>
<td>0.80 - 1.2 %</td>
<td>0.80 - 1.2 %</td>
<td></td>
</tr>
<tr>
<td>Phosphorus, P</td>
<td>0.040 %</td>
<td>0.040 %</td>
<td></td>
</tr>
<tr>
<td>Silicon, Si</td>
<td>0.15 - 0.40 %</td>
<td>0.15 - 0.40 %</td>
<td></td>
</tr>
<tr>
<td>Sulfur, S</td>
<td>0.050 %</td>
<td>0.050 %</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 18: ONE PAGE OF FINALIZED BLUEPRINTS SENT OUT FOR FABRICATION**
DATA ACQUISITION TRAILER SYSTEM

LABVIEW SOFTWARE

Data acquisition for any hot fire testing of the 500 lb. engine, RCE, HPC or any other future c-SETR system is expected to be controlled manually using the hardware configuration in the DAQ trailer. The trailer is comprised of a c-RIO and a c-DAQ device which each have individual modules that correspond to specific instrumentation.

FIGURE 19: PROJECT EXPLORER PANEL FOR DAQ SYSTEM

The c-RIO is a system used to control any autonomous processes using a field programmable gate array (FPGA) programmed and stored within the processor of the c-RIO. In any case of lost power, lost connection, or dangerous levels recorded from the instrumentation, the c-RIO will switch to an emergency autonomous mode that will override any manual controls.
and begin activating any emergency protocols, and autonomous valve sequences to shut down the system and maintain the facility and staff safety. The c-DAQ is a much simpler device as it is tasked only with recording any applicable data and saving it. All Software needed for RCE or 500 lb. testing will be found in the Test Stand 3.0 project file. The VIs highlighted in the image are the most frequently opened.

FPGA GUI

![FPGA GUI](image)

**FIGURE 20: MAIN CONTROL GUI FOR DIAGNOSTICS AND TROUBLESHOOTING ONLY**

The code stored on the c-RIO has a graphical user interface (GUI) that does not need to be modified unless new or different autonomous functionality is needed on the c-RIO’s part. The GUI is shown in the figure below. This GI is not to be controlled manually during testing. This
is a fully automated built in GUI that is loaded onto the c-RIO to autonomously control the system during regular testing and emergency sequences.

![FPGA GUI Module in Project Explorer](image)

**FIGURE 21: LOCATION OF THE FPGA GUI MODULE IN PROJECT EXPLORER**

This VI can be opened by selecting it off the project explorer window under the C-RIO chassis tab. The interface that displays is just a byproduct of the LabVIEW coding format. It can be used to ensure that all switches are actuating properly, autonomous sequences are running as expected, and relays are receiving signals correctly. However, the system is not to be run using this GUI. Attempting to run the automatic sequence from both the FGPA VI and the RCE or 500 lb. VI, will result in garbled signals and inaccurate data readings. This is an easy mistake to make if one GUI is left running and an attempt is made to run diagnostics on the solenoid valves. The FPGA VI must be stopped manually, if activated, before running either of the two manual control VIs. The same switches you manually activate on the FPGA GUI during DAQ testing will be what the RIO will switch autonomously during hot fire testing but from its own FPGA GUI.
The FPGA is broken into the 9 while loop blocks shown above. The modules shown in red are the only two that should need any modification in the future. The Igniter Control, Buzzer & Light Logic, Redline Acquisition, Valve Control Loop, Vale Emergency Sequence, Valve Autonomous Sequence, Valve State Control, SOV State Check while loops, block manual controls and monitors the status of redline instrumentation throughout testing and implement any safety protocols for emergency situations.
For future testing the only sections that should be changed within the FPGA VI are the Valve Automatic Sequences; and the Redline Acquisition case switch since the c-RIO instrumentation connections and autonomous sequences will differ from system to system and valve sequencing is still in the works. These sections are shown in red above in figure 23. An excel conversion sheet was created so that the on and off sequences can quickly and easily be converted to base 10 to be inserted into the SOV valve timing loop and SOV emergency Control loop panels. Both of those entry locations are shown below.

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<tr>
<th>Nitrogen</th>
<th>Oxygen</th>
<th>Methane</th>
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</thead>
<tbody>
<tr>
<td>Time step</td>
<td>CH4 tank</td>
<td>CH4 vent</td>
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<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
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<tr>
<td>35</td>
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</tbody>
</table>

**FIGURE 25: AUTOMATIC BASE 10 CODE GENERATING EXCEL SHEET**

Two systems have been worked on and the project explorer contains a main GUI that can be used for each test system. The case switch, shown on the left in figure 23, can be set to “RCE” and the total time for the rest run or “500 lb” and the necessary time period for that test run.
REMOTE CONTROLLED ENGINE (RCE)

**FIGURE 26:** SECOND DISPLAY SCREEN OF MAIN GUI

**FIGURE 27:** MAIN PANEL OF MAIN GUI
TESTING PROCEDURE

It is imperative that certain steps be taken before any hot fire testing. The FPGA VI must be compiled to send any new updates to the C-RIO to implement. The FPGA VI needs to be run, and the program must be compiled using the local compile server.

These steps are time consuming regardless of the scope of the changes and should be done ahead of time to prevent delays in testing. If no changes were made since the last compilation, then the process will proceed immediately. With the C-RIO properly compiled the system should be ready for hot fire testing. The log file path under acquisition set up must be correct as shown below for project to run as expected.
If the system is running this VI can be accessed using the settings button that will display, showed down below boxed in green, otherwise it can be accessed using the Settings Dialog button found on the Settings panel in the Project Explorer as shown in figure 21.

![GUI PANEL SETTINGS AND AUTOMATIC SEQUENCE ACCESS](image1)

To begin a test, open the VI for the RCE system if not already opened. Choose the correct settings for the run using the drop-down box circled in yellow in figure 30 and 31. This option
sets the automatic sequencing and any other important variables for the test. The system can then be run the system using the white arrow at the top left corner of the window. The Valve state should change from “Not Enabled” to “Wait” this signals that the system is ready to be activated. The system must be unlocked using the gray flip switch and the sequencing started using the “Start Automatic Sequence” button. An emergency shut down button, labeled “Emergency Stop” is programmed to manually cease testing if anything dangerous is noticed during testing that does not automatically trigger red lines within program.
TITLE OF APPENDIX

LOX – Liquid Oxygen

CH4 – Liquid Methane
CURRICULUM VITA

Rachel Pilgrim graduated with her bachelors of science in mechanical engineering in the spring of 2017. She continued at UT El Paso to pursue a master’s in mechanical engineering. Throughout her graduate career at UTEP, she worked with the LOX/CH4 team at the c-SETR designing various supporting propulsion system test structures for the launch of their 500 lb. and 2000 lb. rocket engines. In the summer of 2018 and the spring of 2019, she traveled to NASA; JSC and MSFC respectively, for internships. She will attend another internship in the Fall of 2019 back in Huntsville at the start of her Ph.D.