Refined Hybrid Rocket Static Fire Testing with Increased Performance and Precision

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ABSTRACT

Hybrid rocket development relies on precise sensor data to evaluate key performance parameters such as thrust, temperature, and chamber pressure. The accuracy of this data is influenced not only by instrumentation noise but also by the design and efficiency of the test infrastructure. This study presents a comprehensive upgrade of a lab-scale hybrid rocket static fire test cart, focusing on improvements in oxidizer flow capacity, system wiring, data acquisition reliability, and load cell calibration. Key upgrades include implementation of larger-diameter piping for increased oxidizer flow, simplification of wiring to decrease instrument noise, installation of upgraded USB cables to increase data transfer bandwidth, and integration of a new load cell track to eliminate hysteresis. Comparative testing between the legacy and upgraded test carts assesses the impact of these design changes. The previous cart exhibited significant pressure data noise (standard deviation of 3.29 psi), while the upgraded system achieved improved signal clarity (standard deviation of 0.39 psi). Additional comparisons include oxidizer flow capacity, data transfer bandwidth performance, and load cell hysteresis quantification. Multiple test configurations and flow conditions are evaluated to quantify increases in performance and precision. Results demonstrate the effectiveness of these upgrades in improving calibration accuracy, test reliability, and providing insights into optimizing hybrid rocket test infrastructure for more precise and repeatable experimental data.

INTRODUCTION

Hybrid rockets have been in development since the early 1930s. A hybrid rocket is a blend between a solid and a liquid rocket containing a solid fuel cell and a liquid or gaseous oxidizer. The oxidizer is injected into the fuel and ignited to produce thrust.

At the Utah State University Propulsion Research Laboratory (USUPRL), the development and testing of hybrid rockets is the central focus. Founded by Dr. Stephen Whitmore in 2005, the USUPRL has brought in over 3 million dollars of funding and has successfully completed 100+ programs. In late 2024, NASA began testing a hybrid rocket motor developed at the USUPRL for characterizing how the plume interacts with moon soil. [1] This development will directly impact work on the NASA Artemis missions.[1] Initial test fires were done under vacuum and are shown in Fig. 1. [1]

In 2024, the USUPRL was awarded 2 grants to research the feasibility of scaling hybrid rocket thrust capabilities from 250 lbf to 1000 lbf and to develop a hybrid rocket motor with reignition capabilities that could burn for a total of 210 seconds. Limitations in testing capabilities necessitated the construction of a new test stand that could successfully scale the motor to 1000 lbf.

Figure 1: Hybrid Rocket Vacuum Testing[1]

METHODOLOGY

Hybrid rocket tests are done in the Utah State University Battery Limits and Survivability Test (BLAST) cell. The test stand is fit on a cart to allow easy transport to and from the test cell. The BLAST cell is shown in Fig. 2. USB extension cables are placed through the wall to connect laptops running LabVIEW to the test cart.

Experimental Setup

The test cart comprises of various instruments and sensors. These include four type T thermocouples, four type K thermocouples, three pressure transducers, one load cell, one scale, two webcams, and three NI DAQ cards connected in a four-slot myDAQ. Sensors are connected into the DAQ cards and fed via USB through the test cell wall to the laptops. The scale and webcams are also fed via USB to the laptops. The complete cart is shown in Fig. 3.

Figure 2: Utah State University BLAST Cell

Figure 3: Hybrid Rocket Test Cart

During setup, the oxidizer tanks are placed on the scale. The motor is mounted on the opposite end, and piping connections are tightened. Exterior thermocouples are mounted in various places on the motor. The system is pressurized to a set pressure via the in-line regulator. The laptop LabVIEW vi controls valves to inject the oxidizer and ignite the system.

Test Cart Upgrades

The test cart wiring was overhauled to improve reliability, reduce noise, and simplify troubleshooting. In the old setup, signal and power lines were often bundled together without clear organization, leading to interference and inconsistent sensor readings. The new layout separates high power and low voltage lines and routes everything through dedicated paths. A centralized power block and proper grounding points were added to ensure stable voltage and reduce the change of ground loops. High speed USB 3.2 cables were also installed, improving data transfer and reducing clutter. These changes made the system cleaner, more reliable, and easier to work with.

RESULTS

Results of upgrades are recorded in this section. The upgrades include increasing the piping diameter, simplifying the test stand wiring, exchanging USB cables, and removing load cell hysteresis.

Enhanced Oxidizer Flow Capacity with Larger Diameter Piping

To improve the performance of our hybrid rocket motors, we upgraded the oxidizer flow line by increasing the inner diameter of the piping from 0.277 inches to 0.620 inches. This modification significantly enhances the flow capacity, allowing for a greater supply of oxidizer propellant to the combustion chamber. Using the Darcy-Weisbach-derived equation for turbulent flow, the flow rate Q scales with the pipe diameter D as $Q \propto D^{(2.5)}$. [3] For our new piping, the flow rate ratio is calculated as:

$$\mathbf{(Q_{NEW} / Q_{OLD}) = (D_{NEW} / D_{OLD})^{(2.5)}}$$

$$\mathbf{(0.620 / 0.277)^{(2.5)} \approx 11.2}$$

This result indicates that the new piping, with an inner diameter of 0.620 inches, provides approximately 11.2 times the flow capacity of the previous 0.277-inch diameter pipe, assuming constant pressure drop and friction factors. The increased flow capacity ensures a more robust oxidizer supply, enhancing the thrust and efficiency of our hybrid rocket motors.

Instrument Noise Reduction

To address the noise issues observed in earlier testing, the new test cart implemented several improvements in sensor integration and electrical layout. In the original configuration, long analog signal paths between pressure transducers, thermocouples, and the DAQ system introduced the possibility of electromagnetic interference (EMI), particularly in regions near high-voltage relay boards and spark ignition circuitry. Additionally, inconsistent grounding and distributed power supplies contributed to unwanted signal variability.

The updated cart design consolidates data acquisition with a National Instruments cDAQ-9174 chassis. This modification significantly reduced wiring length and eliminated intermediate connections prone to noise pickup. Power distribution was restructured to establish clear separation between high-power and low-signal components, minimizing crosstalk and ground loop formation. Internal cable routing was optimized to shorten critical signal paths and reduce EMI exposure. These changes improved signal stability, allowing for higher-resolution data capture with reduced noise and more consistent sensor output across repeated tests.

Wiring simplification goes in this section and anything else that helped with noise reduction.

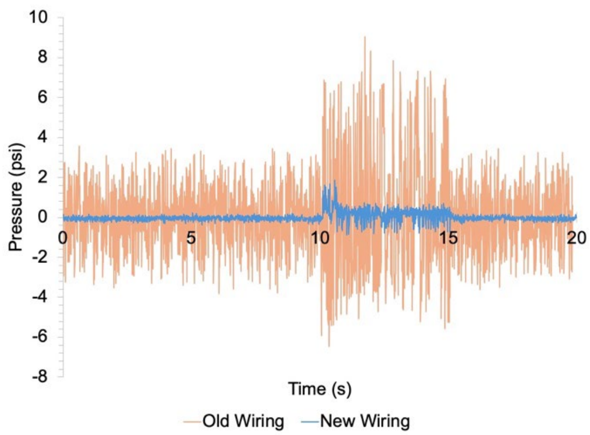

Figure 1: Pressure Transducer Noise Comparison

Information Bandwidth

A key aspect of the test setup is the data transfer from the cart to the lab laptop. To transfer data through the thick walls of the test cell, 10 m USB extension cables are passed through a small opening near the top of the bullet proof glass. The USB cables are connected to the instruments on one end and fed through a docking station into the laptop on the other end.

The previous setup included one USB 3.0 and two USB 2.0 cables. On the cart, two USB 3.2 buses connected data from the myDAQ, a scale, fiberoptic spectrometers, webcams, and a decibel reader. When all devices were plugged in, the laptop had issues acquiring data from the decibel reader. The video recording software would not record video with sound and decreased the resolution of the webcams from 4k to 720p. This presented a problem for accurate data recording and processing.

The first steps taken to solve this problem included plugging certain devices into a stand-alone extension cable depending on what devices needed to be used, eliminating the USB bus for that specific device. This solution temporarily solved the problem for tests where only some devices were needed. The problem still needed to be solved for situations where all devices are operational.

Four USB 3.2 cables with transfer speeds of up to 5 GB/s were purchased and fed through the test cell pass through. The previous cables were removed. After initial tests, all devices were able to function simultaneously, and webcam footage resolution was increased from 720p to 4k. No connectivity issues persisted.

Load Cell Calibration

The rocket test stand was designed to measure axial thrust forces generated by a rocket motor, utilizing a horizontal configuration constructed from aluminum extrusion T-slot rails. The setup consisted of a fixed bottom rail and a sliding top rail, with the rocket motor mounted on the top rail. A load cell was integrated to capture thrust forces, interfaced with a National Instruments NI-9205 DAQ card to acquire raw voltage data. Initially, polytetrafluoroethylene (PTFE) sliders facilitated smooth movement between the top and bottom rails, enabling low friction sliding during calibration without the rocket motor mounted. Calibration tests in this configuration showed consistent load cell responses, with the load returning to 0 lbf post-test, indicating negligible residual forces.

However, when the rocket motor and associated tubing were mounted on the top rail, test results revealed significant hysteresis in the load cell data. Thrust measurements began at 0 lbf, peaked at approximately 25 lbf during motor firing, but settled between 3-5 lbf at rest, rather than returning to 0 lbf. This discrepancy was attributed to excessive friction in the PTFE sliders under the added weight of the rocket motor and tubing. The frictional forces prevented the top rail from returning to its neutral position, introducing a residual load on the load cell and skewing the measurements. The issue was not evident during initial calibrations without the motor, underscoring a critical oversight in replicating real-world conditions.

To address hysteresis, a new mounting system was developed using a 3D-printed enclosure-style mount. This design fully captivated the top rail with small bearings on all sides, effectively transferring the motor's weight to the fixed bottom rail while minimizing frictional resistance in the axial direction. The bearings ensured smooth, low-friction movement, allowing the load cell to measure thrust forces accurately. Subsequent tests with the rocket motor mounted confirmed the efficacy of this solution, as no hysteresis was observed, and the load returned to 0 lbf at rest, even under the motor's full weight.

This experience highlighted the critical importance of calibrating load cells under conditions as close as possible to the actual test scenario. Had the initial calibration included the rocket motor and tubing, the frictional limitations of the PTFE sliders would have been identified earlier, saving significant development time and resources. Calibration in idealized conditions may yield misleading results, as real-world factors such as additional weight, dynamic forces, or environmental influences can significantly affect measurement accuracy. This lesson has informed our approach to future test stand designs, prioritizing comprehensive calibration protocols that account for all operational variables.

The calibration process involved generating a linear fit equation to convert raw voltage data from the NI-9205 DAQ card into force measurements in pounds-force (lbf). Known weights were applied to the load cell, and corresponding voltage outputs were recorded. These data points were used to determine a line-of-best-fit equation of the form:

$$\textbf{Force} = \textbf{Voltage} \times \textbf{Slope} + \textbf{Offset}$$

where the slope and offset were derived using linear regression.[2] This calibration curve ensured accurate conversion of voltage signals to force measurements, validated through repeated tests with and without the rocket motor. The bearing-based mount further enhanced the reliability of these measurements by eliminating frictional interference, resulting in a robust and repeatable calibration process.

The transition from PTFE sliders to a bearing-based mount resolved the hysteresis issue and underscored the necessity of realistic calibration conditions. By integrating real-world factors into the calibration process and optimizing the mechanical design, we achieved accurate and reliable thrust measurements, enhancing the overall performance of the rocket test stand.

DISCUSSION

The upgrades to the hybrid rocket test cart significantly improved data accuracy, system reliability, and overall testing capability. Increasing the oxidizer line diameter by more than double resulted in an estimated 11.2 increase in flow capacity, enabling support for higher-thrust motors aligned with current scaling objectives.

Signal noise was greatly reduced from a standard deviation of 3.29 psi to 0.39 psi due to improved cable routing, better separation of power and signal lines, and more effective grounding. This enhanced signal clarity is critical for capturing reliable combustion and performance data.

The addition of high-speed USB 3.2 cables resolved bandwidth limitations, allowing all devices to operate simultaneously without loss of resolution or functionality.

The redesign of the load cell mount was particularly impactful. Replacing PTFE sliders with a bearing-based system eliminated hysteresis caused by friction under the motor's weight. Calibrating under actual load conditions ensured accurate, repeatable thrust measurements and highlighted the need for realistic test setups.

Together, these upgrades enhance the precision and reliability of hybrid rocket testing at USUPRL. The improved infrastructure supports more advanced research, better data quality, and lays the groundwork for continued development of scalable hybrid propulsion systems.

CONCLUSION

This study presented a comprehensive upgrade to a hybrid rocket test cart with the goal of improving data accuracy, test reliability, and system scalability. Key findings include a dramatic reduction in pressure signal noise thanks to an improved wiring layout, grounding, and USB cable upgrades. The oxidizer flow capacity was enhanced by over eleven times using larger-diameter piping, allowing for higher-thrust motor testing. Additionally, the replacement of PTFE sliders with a bearing-based load cell mount eliminated hysteresis, ensuring accurate and repeatable thrust measurements under real world loading conditions.

These contributions significantly strengthen the quality of hybrid rocket test data, which is essential for validating motor performance and guiding design decisions. The upgraded test infrastructure supports more advanced propulsion research and aligns with long-term goals such as scaling to 1,000 lbf thrust levels and developing motors with reignition capabilities.

Future work will focus on further improving sensor integration, automating calibration procedures, and expanding test stand functionality to support longer duration burns. The improvements made in this project establish a strong foundation for continued innovation in hybrid rocket development, both at USUPRL and within the broader aerospace research community.

Acknowledgments

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References

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