

The Development of an Infrastructure for End-to-End Hybrid Rocket Flight Simulation, Motor and Aerodynamic Prediction and Testing, and Design Analysis at Utah State University

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The foundations for simulation and testing of hybrid rockets at Utah State University are presented. The testing and analysis was motivated by the participation of Utah State University in the 2007-2008 University Student Launch Initiative. Due to the requirements of the competition, a 6 degree of freedom flight simulator, a motor simulator, wind tunnel and rocket motor test facilities were developed to better characterize the rocket entered into the 2007-2008 USLI competition. This effort also improved the resources for rocket design, research and testing at Utah State University.

Nomenclature

A^*	= nozzle throat area	t	= time
A_{burn}	= total surface area	T_0	= stagnation temperature
$A_{c_{\text{chamber}}}$	= chamber cross sectional area	T_{fuel}	= fuel temperature
A_{ox}	= injector hole area	V_c	= combustion chamber volume
$C_{d_{ox}}$	= injector discharge coefficient	γ	= specific heat ratio
c_p	= solid fuel specific heat	μ_{ox}	= oxidizer viscosity
c_{p_e}	= specific heat of oxidizer at flame	ρ_{fuel}	= fuel density
h_v	= heat of vaporization	ρ_{ox}	= oxidizer density
L	= length of fuel grain	$(c_{\bar{\mu}})_{\text{blowing}}$	= skin friction coefficient with blowing
p_0	= stagnation pressure		adjustment
p_{ox}	= oxidizer pressure		
P_r	= Prandtl number		
\dot{r}	= instantaneous regression rate		
R_g	= gas constant		

I. Introduction

The Chimaera Project at Utah State University has a long history involving the design, construction and launch of experimental hybrid rockets. However, before this year, the framework for adequate simulation, testing, and analysis had not been developed. In previous years, the project revolved around legacy objectives which centered on the eventual construction of a hybrid rocket capable of flight over 100,000 feet AGL. Although these goals provided an incentive for a valuable educational experience for generations of the Chimaera project, insufficient resources were given to the development of instrumentation, simulation, and test hardware to ever make this goal achievable.

The 2007-2008 Chimaera Project shifted its sights off of legacy objectives and instead focused on the NASA University Student Launch Initiative (USLI) competition. The NASA USLI is a competition to design, build, and launch a sounding rocket with a scientific payload to exactly one mile altitude. USLI is sponsored by NASA and underwritten by the National Association of Rocketry (NAR). The Utah State University team chose to incorporate a ballistic control system as the payload. This system allows for high precision altitude targeting. This control system consisted of airbrakes, a navigation algorithm involving a Kalman filter, and an energy-based asymptotic targeting algorithm. Navigation sensors include an inertial measurement unit (IMU) and pressure-pressure based altimeter. The complexity of this design and the degree of characterization of the rocket system required to achieve success lead to the need for advanced simulation and a high degree of characterization of system aerodynamics as well as motor impulse.

II. Simulation Tools

A. Flight Simulation

The hobby-rocket community abounds in relatively low-fidelity simulation tools¹. These simulation tools are often tuned for the use of hobby-sized rockets, have had little technical review or documentation, and have no means to implement an active control feedback system like that used on the USU rocket. Hence, the development of a powerful simulation tool to gauge the robustness of targeting and navigation algorithms as well as rocket performance was warranted. The overall flow of the simulation program is shown in Fig. (1).

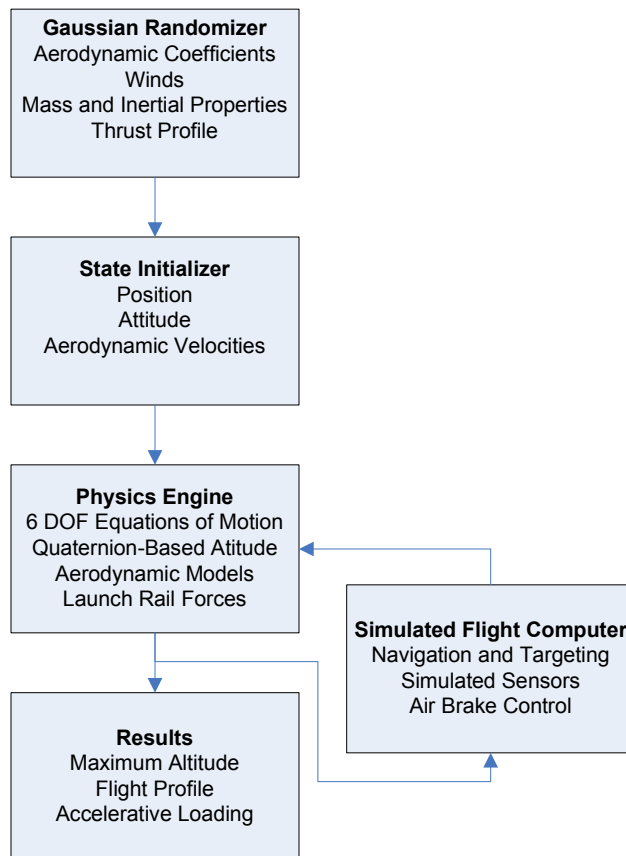


Figure 1. Simulator organization and data flow.

The core of the Chimaera Flight Simulator, (CFS), revolves around a 6 degree of freedom flight dynamics model. Aerodynamic coefficients were calculated using several different techniques including methods described in

Phillips², methods commonly used by the high-powered rocket community³, wind tunnel testing, and from empirical drag correlations long used by the aerospace community⁴.

The CFS also included code necessary to allow Monte Carlo simulations to determine the sensitivity of the rocket trajectory to initial conditions, sensor errors, and vehicle mass and aerodynamic properties. Aerodynamic coefficients, mass and inertial properties, the thrust profile, and winds were all varied to determine the total bounds of the flight profile. The results for a typical Monte Carlo run are shown in Fig. (2)

Also included in the simulator is a detailed flight computer that includes all of the navigation and targeting algorithms that were eventually flown at the USLI. The navigation algorithm consisted of both a simple inertial navigation routine for powered flight and a Kalman filter for the coasting portion of flight. The inertial navigation routine simply integrates acceleration to determine position and velocity. The Kalman filter, however, provides real time estimation of altitude, three components of velocity, and drag coefficient for both the brakes-on and brakes-off states of the rocket. This drag coefficient estimation allows for higher precision targeting and also enables the algorithm to adjust to unpredicted variances in winds and air density. The flight computer algorithm is also used to test the effects of sensor bias and scale factor errors on the overall performance of the algorithm.

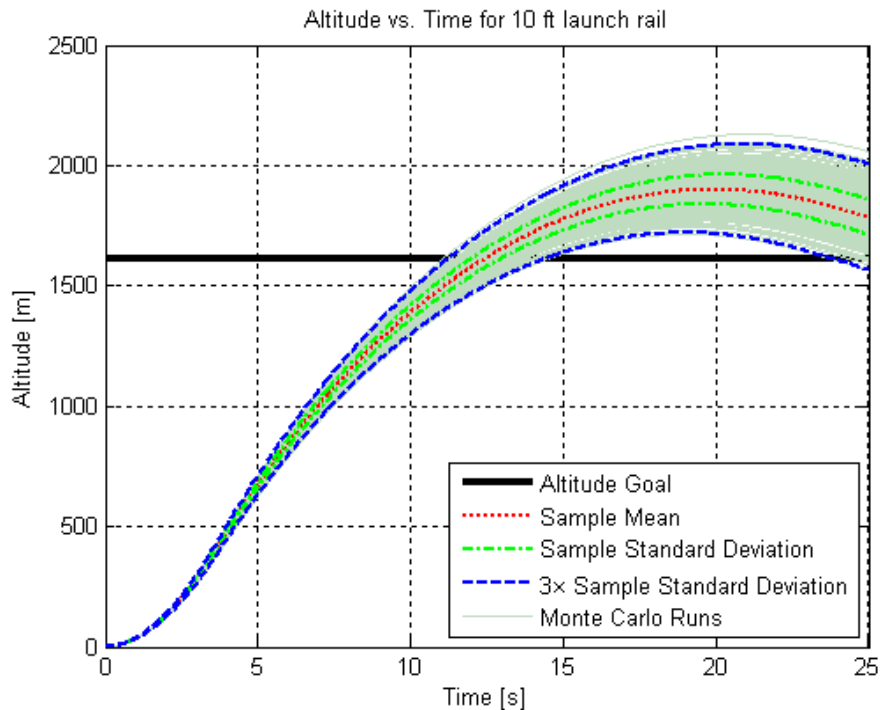


Figure 2. Typical Monte Carlo results for the Chimaera Flight Simulator.

B. Motor Simulation

In order to provide better characterization of the motor system used on the 2007-2008 USU entry into the USLI competition, modifications to USU developed regression rate and motor prediction tools⁵ were used to examine the effects of various parameters on the total motor performance. The basic outline of the motor prediction tool use for this end can be seen in Fig (3).

The first step in motor simulation is to calculate the motor fuel regression rate,

$$\dot{r} = \frac{.047}{P_r^{2/3} \rho_{\text{fuel}}} \left(\frac{c_p [T_0 - T_{\text{fuel}}]}{h_v} \right)^{.23} \left[\frac{A_{\text{ox}} C_{d_{\text{ox}}}}{A_{\text{chamber}}} \sqrt{2 \rho_{\text{ox}} (p_{\text{ox}} - p_0)} \right]^{4/5} \left(\frac{\mu_{\text{ox}}}{L} \right)^{1/5}. \quad (1)$$

This regression rate model is then used to predict motor combustion chamber properties using Chemical Equilibrium with Applications⁶, and basic nozzle analysis. This method was used to predict the time derivative of the combustion chamber pressure,

$$\frac{\partial p_0}{\partial t} = \frac{A_{\text{burn}} \dot{r}}{V_c} [\rho_{\text{fuel}} R_g T_0 - p_0] - p_0 \left[\frac{A^*}{V_c} \sqrt{\gamma R_g T_0 \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}} \right] + \frac{R_g T_0}{V_c} A_{\text{ox}} C_{d_{\text{ox}}} \sqrt{2 \rho_{\text{ox}} (p_{\text{ox}} - p_0)}. \quad (2)$$

Also included in the motor prediction tool, was an isentropic blow-down model used for nitrous oxide tank depletion. These models are then integrated in time to yield a complete thrust profile for a set of given initial motor parameters. These models were first verified using actual motor test data, and then were used to determine the effects of different initial oxidizer temperature on total motor performance. A comparison of simulator results for different oxidizer temperatures with actual motor test data can be seen in Fig (4).

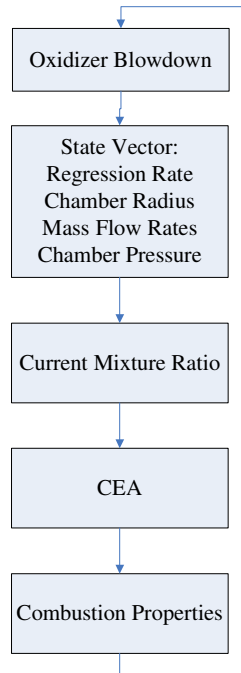


Figure 3. Motor simulation tool overview.

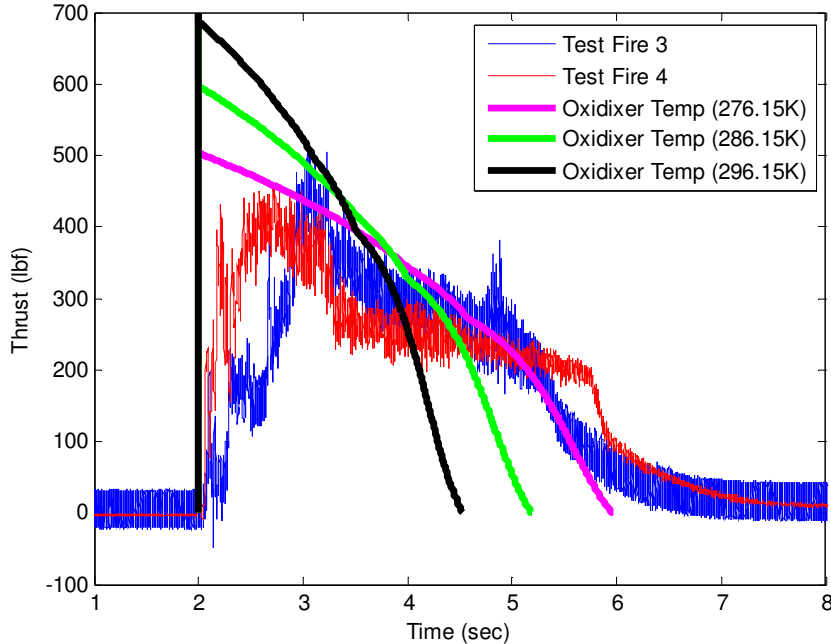


Figure 4. Effect of various oxidizer temperature loadings on motor thrust curve in comparison with actual motor test data. Actual oxidizer temperature was 276 K.

III. Wind Tunnel Development and Characterization

The airbrake payload involved in the USLI competition required a great deal of characterization. Because the airbrake system produces a highly separated, turbulent, unsteady wake, computation methods are of little use in predicting air brake performance. For this design, the air brake drag coefficient was measured using a wind tunnel wake survey in which the total momentum defect behind a rocket model was integrated to retrieve drag coefficient estimates.

A national instruments Compact Fieldpoint system was used for data collection of two separate manometers. A SETRA 2239 manometer was used for collecting dynamic pressure data while an MKS manometer was used to collect static pressure data. A general wiring schematic of the instrumentation system used for these tests is shown in Fig (5).

The physical hardware required to conduct the wind tunnel survey was constructed from scratch. A 1:3 scale model of the proposed rocket structure was printed out on a 3D printer owned by the mechanical engineering department at USU. The test model had interchangeable parts such that various airbrake and fin designs could be testing without replacing the entire aerodynamic model. This model was mounted on a vertical rod that could be moved up and down and tightened with a set screw. A pitot probe was mounted behind the wind tunnel model and could be moved into and could be moved about the horizontal axis by means of a simple rack and pinion gear. This arrangement can be seen in Fig (6) and the resulting momentum defects for brake-on and brake-off models is shown in Fig (7).

The rocket configuration shown yielded a drag coefficient of approximately 0.41 without airbrakes and 1.6 with airbrakes deployed. These results are very similar to those calculated from the first test launch of the 2008 Chimaera rocket. The first launch drag coefficient results were processed from acceleration data using the same Kalman filter equations designed for rocket navigation and yielded drag coefficients of 0.32 and 1.55 for brakes-on and brakes-off drag coefficients, respectively. Although the brakes-off drag coefficient is lower than measured in the wind tunnel, a drag-reducing boat tail was added to the rocket design after wind tunnel testing. The acceleration data collected from the first test launch is shown in Fig (8).

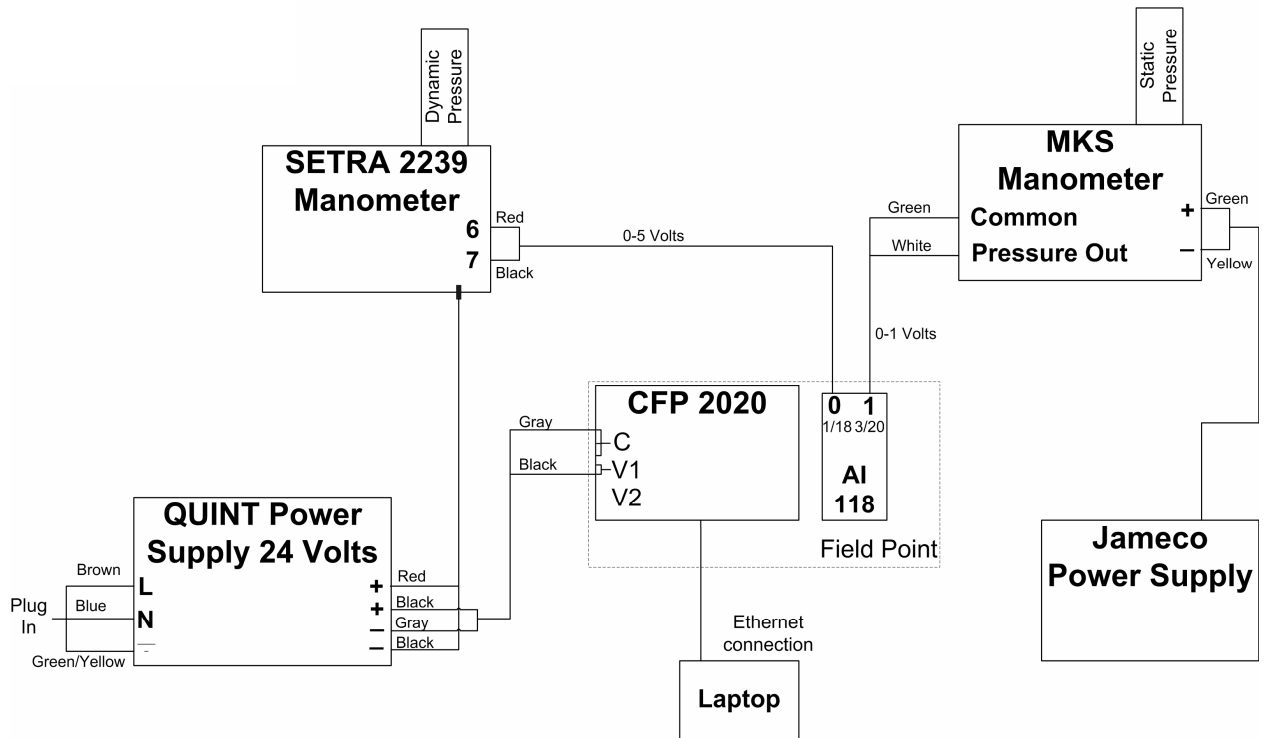


Figure 5. Instrumentation system for wake survey analysis in USU wind tunnel.

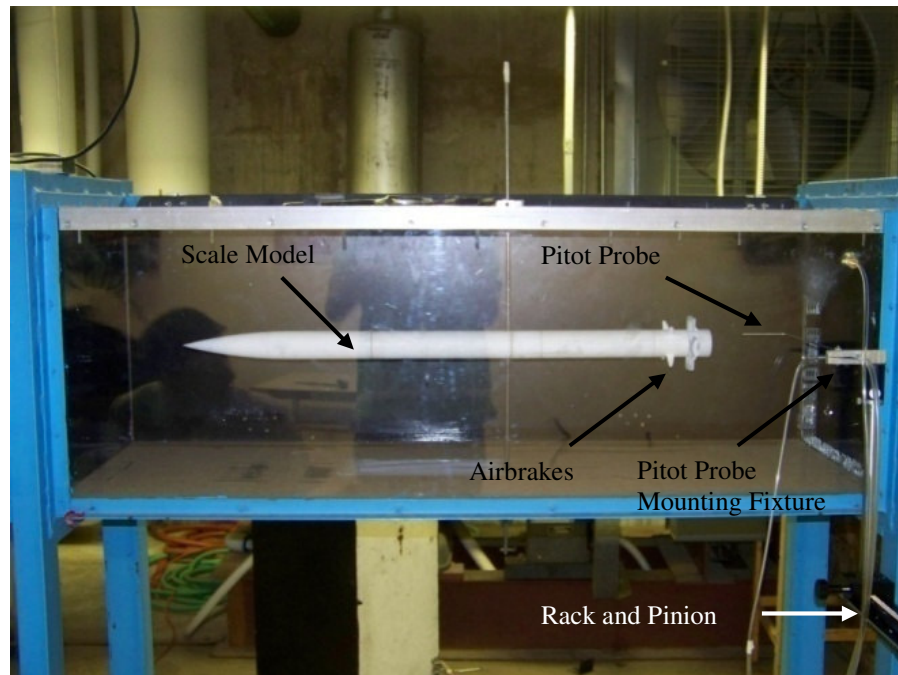


Figure 6. Wind tunnel wake survey arrangement.

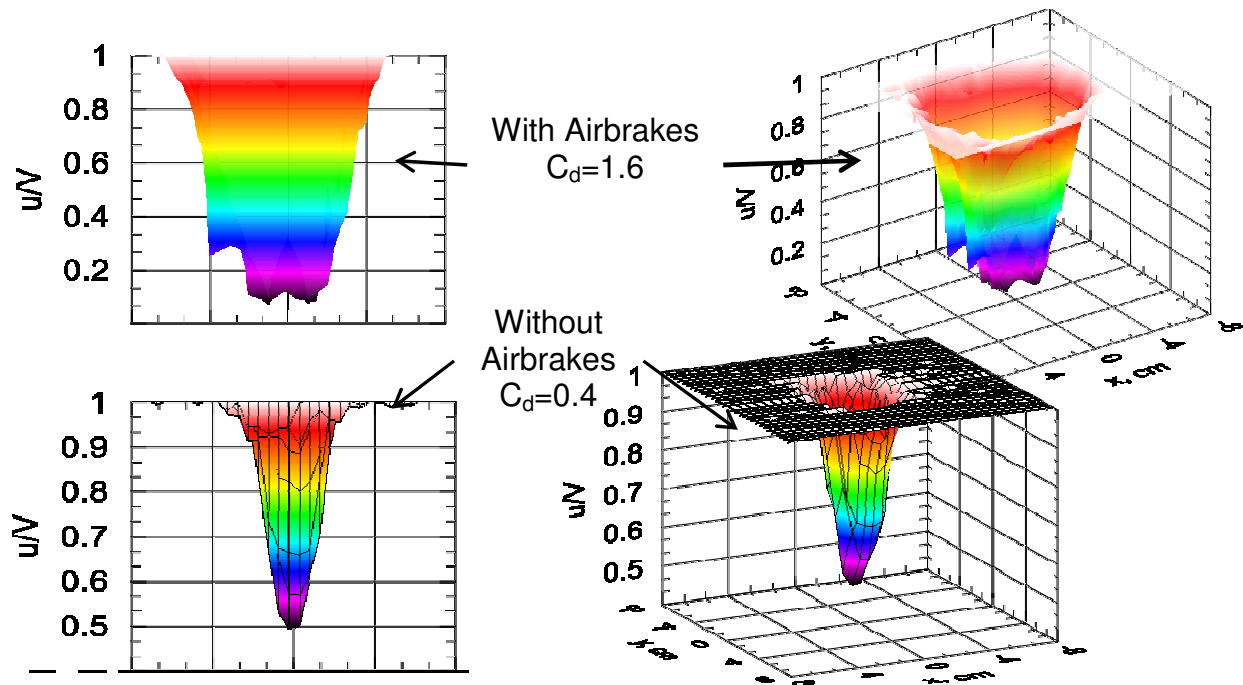


Figure 7. Wind tunnel wake survey results.

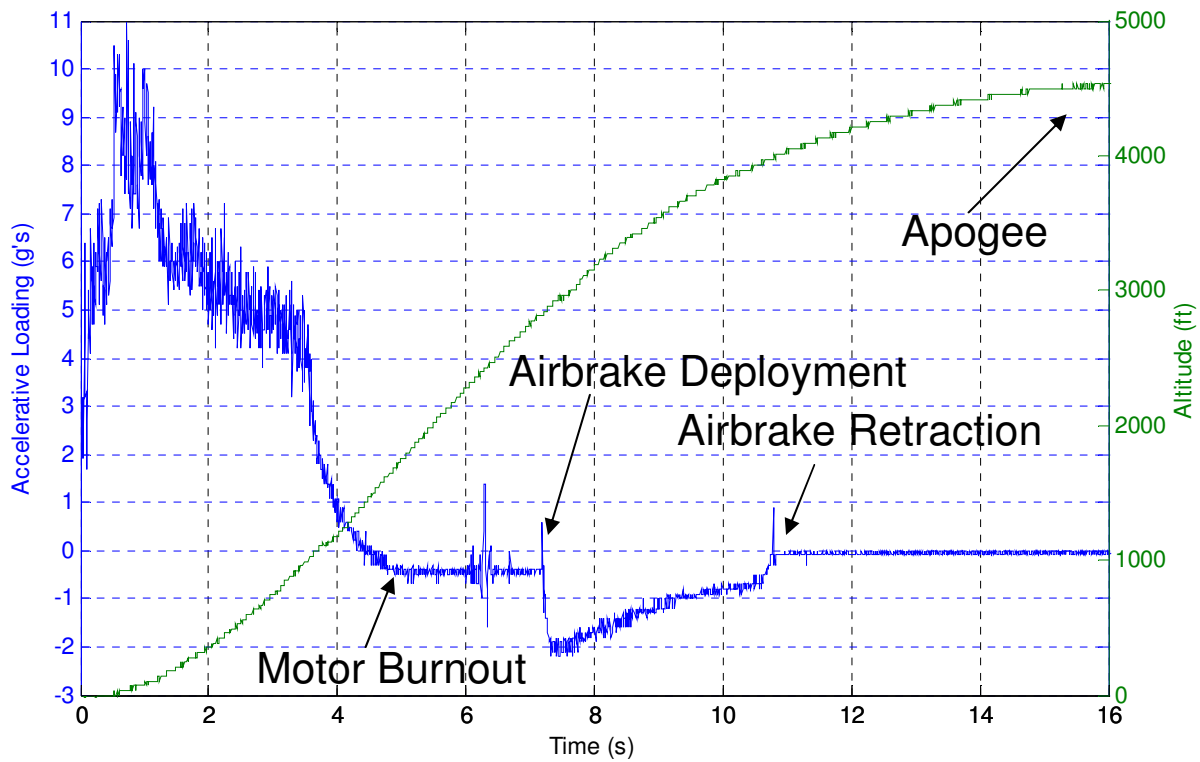


Figure 8. Axial acceleration and altimeter data from the first test flight of the USU rocket.

IV. Hybrid Motor Testing

For NAR certification, rocket motors are allowed to have 20 percent variability from published thrust data. Hence, rocket motor characterization far beyond that given by the manufacturer was warranted. Although some rocket motor testing has been done in the past by the Chimaera project, the majority of this testing has either been completed without significant instrumentation or on a test stand not owned by the Chimaera project. For these reasons, the assembly of a new test stand and an instrumentation system was required.

As the NASA USLI competition requires the use of commercial motors, and commercial hybrid motors have an oxidizer tank in-line with the motor, an angled thrust stand had to be fabricated to facilitate testing. This thrust stand was bolted to a movable fixture, which, in turn, was connected to the floor of the USU jet engine test cell. In addition to motor thrust, oxidizer tank and motor temperature were also recorded. The general test arrangement can be seen in Fig (9). Thrust profiles can be seen in Fig (4).

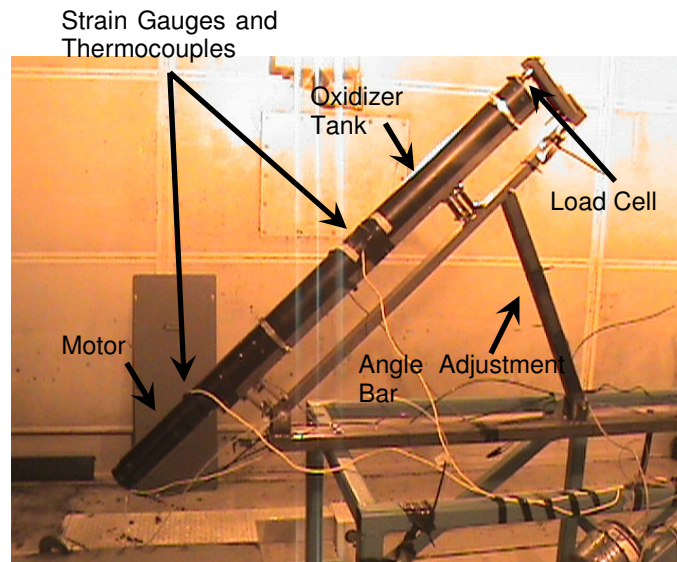


Figure 9. Rocket motor test assembly.

V. Conclusions.

The testing, analysis and simulation performed by Utah State University has given the Chimaera team an edge in the NASA USLI competition. Thus far, USU has received both the best report and presentations award and the award for best payload design. The USU rocket has thus far been launched twice and successfully recovered both times, the second time at the actual NASA competition in Huntsville Alabama. Although the on-board serial communication for the flight computer experienced a failure during launch, causing a subsequent failure of the operation of the navigation and targeting algorithm, all other hardware systems performed as expected, and the USU team still has a significant chance to win the 2007 competition. The analysis and testing at USU has also provided significant infrastructure for future Chimaera teams and other research projects in the areas of propulsion, aerodynamics, and flight simulation.

References

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