A Ground Test Rocket Thrust Measurement System

Mary Fran Desrochers, Gary W. Olsen, and M. K. Hudson

Department of Applied Science and The Graduate Institute of Technology
University of Arkansas at Little Rock, Little Rock, AR 72204 USA

ABSTRACT

A strain gauge thrust measurement system is described for rocket motor ground testing. The unit uses sigmoid beams to hold the rocket motor in place, with the strain gauges mounted on these beams. The theory and usage of strain gauges is briefly discussed, along with all circuit and other information necessary to build a similar system. The system was calibrated for the 50 lb thrust level and applied to the UALR Hybrid Rocket Facility. Its performance characteristics are discussed. The system was found suitable for continuous monitoring in such a ground testing environment, and indicated that the hybrid thruster utilized in the facility develops 41 lbf thrust at an oxidant mass flow of 0.125 lbm.

Keywords: rocket ground testing, thrust sensor, combustion diagnostics, strain gauge, hybrid rocket

Conversions from English to Metric Units:

1 lbm = 1 pound mass = 454 g
1 lbf = 1 pound force = 4.45 N (Newtons)
1 lb = 1 pound = 454 g
1 psia = 1 pound per square inch = 0.145 kPa

Introduction

One of the most important parameters of rocket design is the time-thrust profile that the rocket is capable of producing. It is important in the developmental testing of rockets to determine the effect of nozzle design, fuel/propellant mixtures, additives, and changing other parameters of the motor or engine system on performance. While regression rates are often measured and used to determine a rate of performance, thrust measurement during ground testing allows the direct comparison of various motor and fuel/propellant configurations.

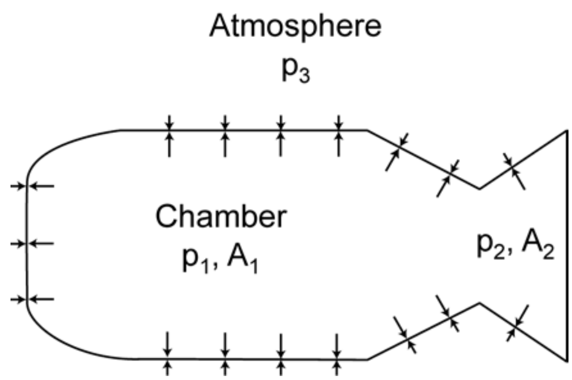


Figure 1. Simplified Schematic of a rocket motor.

Rocket propulsion is one type of jet propulsion. A rocket is propelled by the ejection of stored matter (propellant). The force produced by the ejection of the high-velocity matter is the thrust force (F). Thrust is defined as the sum of two terms, a momentum term and a pressure term. With reference to Figure 1, the equation for thrust is:

$$F = mv_2 + (p_2 - p_3)\, A_2 \qquad (1)$$

Momentum is the product of the mass and velocity of an object. For rockets, the momentum term is the product of the mass flow rate (m) and the exhaust velocity relative to the vehicle (v_2); it is the ejection of low mass gases at very high velocities. The pressure term is the product of the cross-sectional area of the nozzle exit (A_2)and the difference between the exhaust pressure (p_2) and the ambient fluid pressure (p_3).

The amount of thrust is determined, in part, by the amount of fuel and oxidizer in the combustion chamber. For a solid motor, neither the fuel nor oxidant can be varied during a burn, so the thrust is dependent on the original mixture and the grain physical configuration. In a liquid engine system, both oxidant and fuel can be varied to achieve start/stop and variations in thrust output. In a “normal” hybrid motor (as opposed to a reverse hybrid) as used here, the fuel is fixed, but the amount of oxidizer delivered to the chamber can be varied, thus varying the thrust.

The design of the nozzle is also critical to the thrust output. Briefly, if the nozzle is designed so that the exit pressure is greater or less than that of the surrounding medium, it will have a detrimental effect on the total thrust. The optimum expansion ratio will result when a nozzle is designed so that it expands the propellant products to the pressure that is exactly equal to the surrounding fluid pressure. While nozzles may be modeled analytically, each can be tested and fine-tuned for the desired performance through ground test thrust measurements.

This paper discusses a useful thrust sensor system of moderate cost that can be used with all types of rocket propulsion systems. In this case, the University of Arkansas at Little Rock (UALR) Hybrid Rocket Facility thruster, designed for 50-lbf thrust, is so instrumented. Solid propellant motors could easily be monitored using this type instrumentation, as can liquid engines with modifications to allow for the more complex fuel/oxidant feed system.

The Hybrid Rocket Facility

The Hybrid Rocket Facility has been described in detail elsewhere,[1] but is described briefly here for clarity. The facility utilizes a ground test 2×10-inch (51×254-mm) hybrid rocket thruster, designed to achieve approximately 50-lbf thrust. The unit uses a solid fuel grain of hydroxyl-terminated poly-butadiene (HTPB) and a gaseous oxidizer in the form of high pressure welding oxygen. The unit was designed to enable plume spectral studies,[2] fuel additive studies,[3] rocket materials research, and investigations of hybrid rocket instabilities.[4]

$$\Sigma F_H = F_B - F_A = 0$$
$$F_B = F_A$$
$$\Sigma M_B = -M_A - M_B + F_A L$$
$$M_A = M_B$$
$$M_A = \left(F_A L\right)/2$$

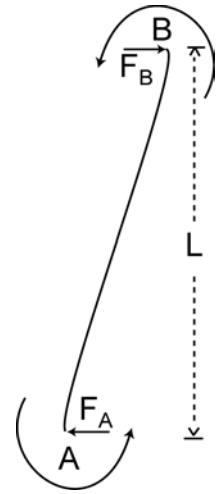
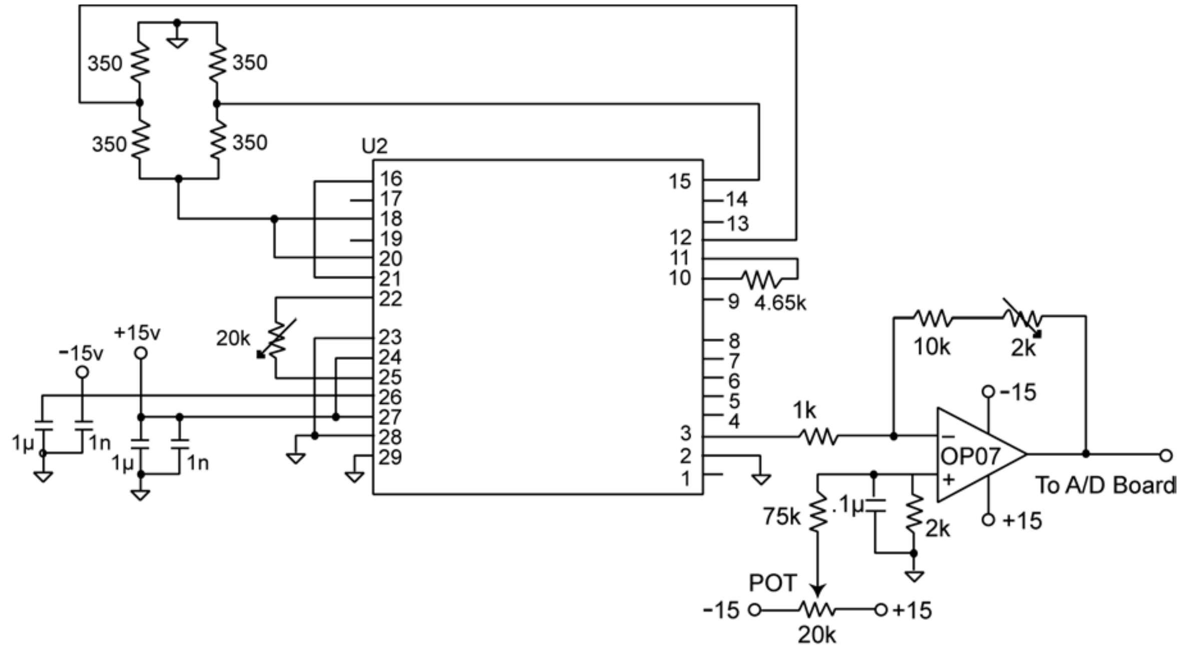


Figure 2. Diagram of a sigmoid beam.

The Thrust Sensor

Strain gauges basically consist of thin film resistors that are affixed to a surface of an object in which we wish to measure the strain caused by an event. For example, a simple wrench might have a strain gauge mounted to one of its surfaces. When the wrench is used, the deformation of the wrench material (strain) is measured by the change in resistance in the gauge that occurs upon tightening a nut or bolt. By accurately calibrating the wrench, and then monitoring its output upon tightening actual fasteners, one has a very accurate torque wrench. For our purposes in this study, the motor system could be mounted using four beams. These beams gave a surface that one could easily affix the strain gauges of the proper type for our thrust measurement.

The thrust sensor was designed and constructed so that the motor was supported on these four beams. Each of the beams were fixed on both ends, one end to the motor, one end to the ground-test frame, which forced them to deflect in the shape of a sigmoid curve (Figure 2) during a firing. The flexing beams were made from 2024-T81 aluminum with a yield strength of 65 kpsi. Strain gages were placed on the beams to convert strain to a voltage proportional to the thrust force. The sigmoid beam is often used in the design of transducers because of its predictable nature and known shapes of deflection. This makes the solution to the problem of how to



1	Output – 1	11	R-gain	21	Exc-sel-2
2	Fine-gain	12	– input	22	Ref-out
3	Fine-gain	13	Input-trim	23	Sense-low
4	Filter-trim	14	Input-trim	24	Regulator
5	Filter-trim	15	+ input	25	Ref-in
6	Bandwidth-3	16	Exc-sel-1	26	–vs
7	Output – 2	17	I-sel	27	+vs
8	Bandwidth-1	18	V-exc-out	28	Common
9	Bandwidth-1	19	I-exc-out	29	Out-trim
10	R-gain	20	Sense-high		

Figure 3. Circuit diagram of the thrust transducer.

calculate the stress and strain simple. To perform the calculations, the beam is split into two equal length beams in simple deflection. Using one of the beams, the stress on the beam and the maximum deflection are determined. The rocket design thrust was 50 lbf maximum, but the transducer system was initially designed for a 30 lbf maximum due to the less than optimal nozzle design that could cause a decrease in thrust output.[5] A computer program was written to perform the iterative calculations to determine the dimensions of the support beams to give approximately 1 mV/V sensitivity for the bridge circuit.[6] Total load, overall beam length, gage to gage distance, width of the beam, modulus of elasticity, and gage factor were input into the program along with a starting and ending thickness and an increment for the thickness. The beams of the transducer were designed such that even with overload, the beams would not plastically deform. At 100-lbf load, the maximum stress in the beams would be 19.2 kpsi, which is much less than the yield strength of the material. Calculations were performed to determine if the beams would deform under the load of the rocket itself. However, the weight of the rocket is well below the weight at which measurable deformation would occur.

Two fully active Wheatstone bridge circuits were used to measure the strain. Full bridges were used because they provide temperature compensation and are more sensitive than other bridge arrangements. A general-purpose strain gage from Measurements Group (CEA-13-125UW-350) was used in the bridges. Using M-

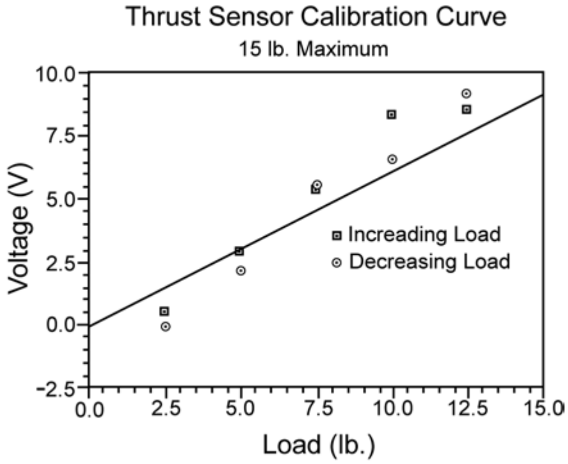


Figure 4. Plot of the hysteresis and linearity for the thrust sensor [V = 0.6144 × (Load) – 0.0482] 20 times the error is plotted.

Bond AE15, the gages were applied to the beams according to the manufacturers specifications.[7] A fixture was built to clamp the gages with the specified pressure to the beam during the curing process. The power density was calculated to be 3.17 W/in.^{2} which is considered to allow high accuracy when used on aluminum.[8]

To accommodate the frequency and gain requirements, a two-stage amplification circuit was built (Figure 3). The first stage consisted of a 2B31J Strain Gage Conditioner and the second stage was an OP07 Op-Amp, both from Analog Devices. After construction of the circuit, it was tested to determine its linearity using a DATEL voltage standard for input and measuring the output with a digital voltmeter. Next, the linearity of the entire system was determined by hanging weights off the end of the rocket and stand and recording the amplifier output voltage with the A/D converter (Computer Boards CIO-AD16F into a 486 DOS PC). The system produced 0.33 V/lb. The linearity of the transducer was determined to be +1.15% and –0.80% (Figure 4).

The original design called for measuring the thrust using two bridge circuits. This proved to be difficult in practice, due to the way the rocket was mounted. Both bridge circuits behaved linearly with respect to load, but the nozzle end bridge was highly influenced by pre-loading, depending on how the motor rear clamp was secured. The bridge on the injector head end

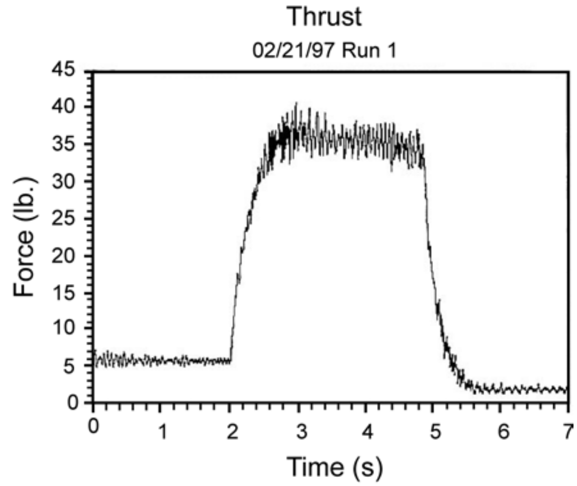


Figure 5. Plot of typical thrust data.

was not influenced to any great extent by pre-loading, so it was decided to use only the head end circuit to record the thrust measurements. The clamp position on the chamber's nozzle end was not changed during all experiments, following system calibration, further minimizing offsets and error. This clamp was not tightened, allowing that portion of the mount to simply ensure that the motor could not come loose during firing. This placed all strain in the forward, injector head beams. The experimental protocol was changed to result in the forward, head end sensors measuring a maximum of 60 lbf, since the nozzle end beams were not taking any load. This was accomplished by changing the gain resistor in the circuit, and the system was recalibrated.

Experimental Matrix

A sequence of firings was designed to measure the thrust output of the rocket using the sensor system. HTPB cured with N100, the most well characterized fuel/curative formulation, was used in the fuel grains to produce a thrust vs. oxidizer flow curve. The fuel grains were made according to the methods already developed.[1,3,5] Oxidizer flow rate was varied from 0.04 to 0.12 lbm/s, in increments of 0.02 lbm/s. Two firings were performed at each flow rate. At 0.06 lbm/s there were four firings to test the repeatability of the sensor.

Thrust Measurements

Changes in the hybrid rocket oxidizer flow rate will produce changes in the motor thrust, as will changing the diameter of the nozzle. The thrust sensor was sampled at 2 kHz. Figure 5 is a sample of the thrust vs. time data. Since the sensor was being proven, the diameter of the nozzle was not changed during the experiment, so effects from a change in nozzle size were not determined. The rocket produced a maximum of 41 lbf at 0.12 lbm/s flow rate. Figure 6 is the characteristic oxidizer flow rate curve for HTPB/N100, the values for the flow rate were calculated by the control computer[1,5] and thrust values were an average of the thrust produced during the steady state combustion (from 3 to 4.75 seconds).

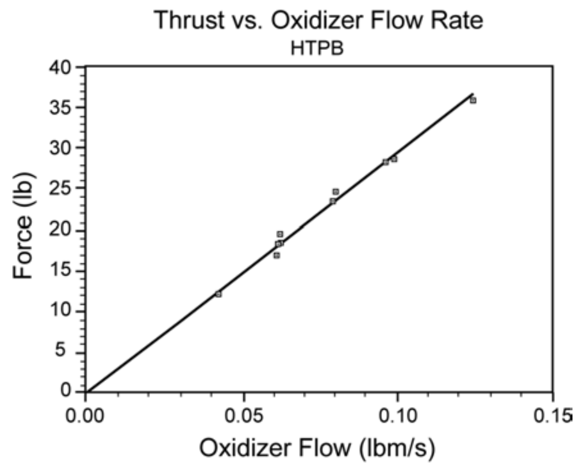


Figure 6. Plot of the thrust vs. oxidizer flow rate for HTPB.

Conclusions

Addition of the thrust transducer provided the thrust output of the Hybrid Rocket Facility motor for the first time. It showed that our rocket motor did produce a maximum of 41 lbf at 0.125 lbm/s oxidizer flow rate during this testing, verifying the design thrust max of 50 lbf.[1,5] The system, or variants thereof, can be used on small to medium hybrid motors, solid motors, and on certain liquid engine systems, depending on fuel/oxidant feed line and mounting considerations. The system can be scaled up by using mounting beams of a larger size to achieve higher thrust capacity, and should be usable to at least several hundred pounds thrust. Also, the system can be left in place over several weeks and remain calibrated, and so it is stable. For greater periods of time, re-calibration is suggested. Over a several month period, the bonding materials may decompose or soften, especially if the system is left in the elements. Since the actual strain gages are inexpensive, a new set can be bonded to the beams, renewing the measurements sensors when necessary.

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