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Design and Calibration of a Six Degree-of-Freedom Thrust Sensor for a Lab-Scale Hybrid Rocket

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A six degree-of-freedom thrust sensor was designed, constructed, calibrated, and tested using the lab-scale hybrid rocket at the University of Arkansas at Little Rock (UALR). The system consisted of six independent legs: one parallel to the axis of symmetry of the rocket for main thrust measurement, two vertical legs near the nozzle end of the rocket, one vertical leg near the oxygen input end of the rocket, and two separated horizontal legs near the nozzle end. Each leg was composed of a rotational bearing, a load cell, and a universal joint above and below the load cell. The leg was designed to create point contact along only one direction and minimize the non-axial forces applied to the load cell. With this system, force in each direction and moments for roll, pitch, and yaw can be measured. Each load cell was individually calibrated using a dead-weight test bed. The six-load-cell system was calibrated with the rocket in place by applying known forces in each direction and mechanically applied roll, pitch, and yaw motions. Calibration curves show linear load cell reaction in the direction of applied force and isolation in all other directions. The system was tested using a lab-scale hybrid rocket using gaseous oxygen and hydroxyl-terminated polybutadiene (HTPB) solid fuel. The thrust stand proved to be stable during initial firing tests.

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Nomenclature

A_i = measured scalar force components of the uniaxial legs, in Newtons (N), $i = 1, \ldots, 6$

V_i = measured voltages from the scalar force components of the uniaxial legs, in Volts (V), $i = 1, \ldots, 6$

a = the separation for the two front vertical legs, in meters (m)

b = the separation for the two mounting brackets, in meters (m)

F_x = total force in x-direction, in Newtons (N)

F_y = total force in y-direction, in Newtons (N)

F_z = total force in z-direction, in Newtons (N)

M_{roll} = roll moment, in Newton-meters (Nm)

M_{pitch} = pitch moment, in Newton-meters (Nm)

M_{roll} = yaw moment, in newton-meters (Nm)

I. Introduction

In 1993, a labscale hybrid rocket facility with computer control and data acquisition system was designed and constructed at the University of Arkansas at Little Rock (UALR). This facility has aided the aerospace community in numerous studies on hybrid rockets[1,2].

UALR's hybrid rocket has used hydroxyl-terminated polybutadiene (HTPB) or polymethylmethacrylate (PMMA) as its fuel and gaseous oxygen as the oxidant. In recent years, HTPB has been the primary fuel under study in the motor. The rocket is operated in a controlled oxygen-to-fuel ratio range of 1.5 to 4.5, by varying the oxygen mass flow in a range of 0.018 to 0.037 kg/s. At an oxygen-to-fuel ratio of 2.074, HTPB burns stoichiometrically to carbon dioxide (CO2) and water vapor (H2O). The temperature in the combustion chamber is above 3000K. With HTPB fuel and a new nozzle, the maximum thrust is approximately 220 N (50 lbf) [2].

The system is ignited when oxygen and propane are introduced into the combustion chamber. A Ramsey Electronics PG13 plasma generator initiates a spark, which lights the propane/oxygen mixture. This heat source ignites the fuel grain and begins the self-sustaining combustion. Once the fuel grain has been ignited, the chamber pressure, measured by a Keller PAA-23S piezoresistive pressure transducer, is controlled by modulating the oxygen mass flow, through a Teledyne-Hastings HFC307 mass flow controller. The digital processor is a PowerPC microprocessor on a dSpace DS1104 controller board[2].

Studies to characterize the physical parameters of the hybrid rocket such as pressure in pre-combustion and post-combustion chambers, plume flicker, acoustical output, plume emission spectroscopy, and axial thrust have been performed at the UALR facility [2-6].

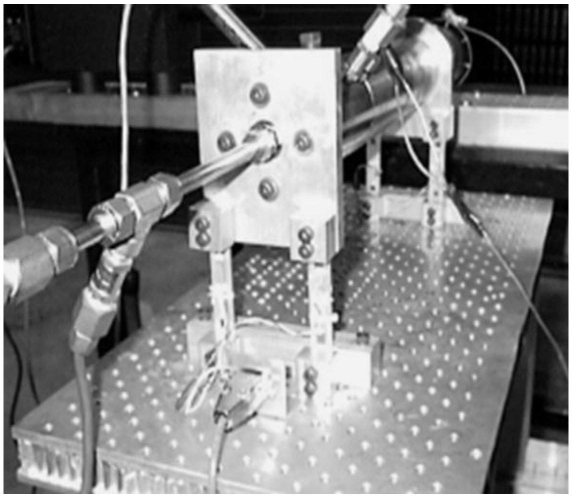

Figure 1 Axial thrust measuring system, including strain gages mounted to four aluminum legs.

Thrust is the reactant force experienced by the rocket due to the ejection of high velocity matter. The function of a thrust stand is to restrain the body yet measure an adequate number of forces to define the thrust vector direction and magnitude. The UALR hybrid rocket facility has measured axial thrust using a custom-designed s-beam sensor element as shown in Figure 1[2]. Thrust was measured using strain gages mounted on four aluminum support beams which supported the rocket. The support beams were fixed on both ends, which forced them to deflect in the shape of a sigmoid curve during the firing. The flexing beams were made from 2024-T81 aluminum with a yield strength of 65 kpsi. General purpose strain gages from Measurements Group (CEA-13-125UW-350) were placed on the beams to convert strain to a voltage proportional to the thrust force. A two stage amplification circuit was built to collect the voltage output of the strain gages and produce a voltage between 0 and 10 volts. The voltage was collected by an A/D board at 1000 Hz [2].

Although the majority of thrust is parallel to the axis of the rocket body, forces perpendicular to the axial direction are also present. In addition to the normal forces, torques can cause motion called roll, pitch, and yaw. In a flying vehicle, the nose is defined as the front of the vehicle, pointed in the direction of motion. Positive roll is defined as a torque that produces a counter clockwise (CCW) rotation about the motion axis. A positive pitch is defined as a torque that brings the nose up. A positive yaw is defined as a torque that brings the nose towards the left side.

An instrument was designed to look down the bore of the UALR rocket while it was firing, and evidence that gases within the combustion chamber are swirling was seen[4]. The momentum transfer due to this turbulent flow will generate an external roll torque. It is unknown if this swirling flow pattern will generate a sufficiently large external torque to induce a hybrid rocket powered vehicle to roll during flight. By measuring the torque experienced by the rocket on the test stand, atmospheric and aerodynamic effects are eliminated and the contribution of the combustion process is isolated.

In order to measure a phenomenon such as roll, force measurements in the plane perpendicular to the axial axis must be measured. Six generalized forces are present in firing and accounting for the total work done by the motor requires knowledge of these components, so that accurate efficiency measurements can be made.

II. Design of Six Degree-of-Freedom Thrust Sensor Stand

The new thrust stand has six uniaxial force elements located so that each element carries a single component of the load: one parallel to the axis of symmetry of the rocket for main thrust measurement, two vertical legs near the nozzle end of the rocket, one vertical leg near the oxygen input end of the rocket, and two separated horizontal legs near the nozzle end (See Figure 2). Each leg was composed of a rotational bearing, a load cell, and a universal joint above and below the load cell (See Figure 3). The leg was designed to create point contact along only one direction and minimize the non-axial forces applied to the load cell. The design was chosen for simplicity of analysis and assembly, ease of changing the fuel in between firings, the ability to use readily available load cells, and the ability to manufacture the pieces using basic machining skills. A free-body diagram of the rocket body and the location of the force measurements are shown in Figure 2.

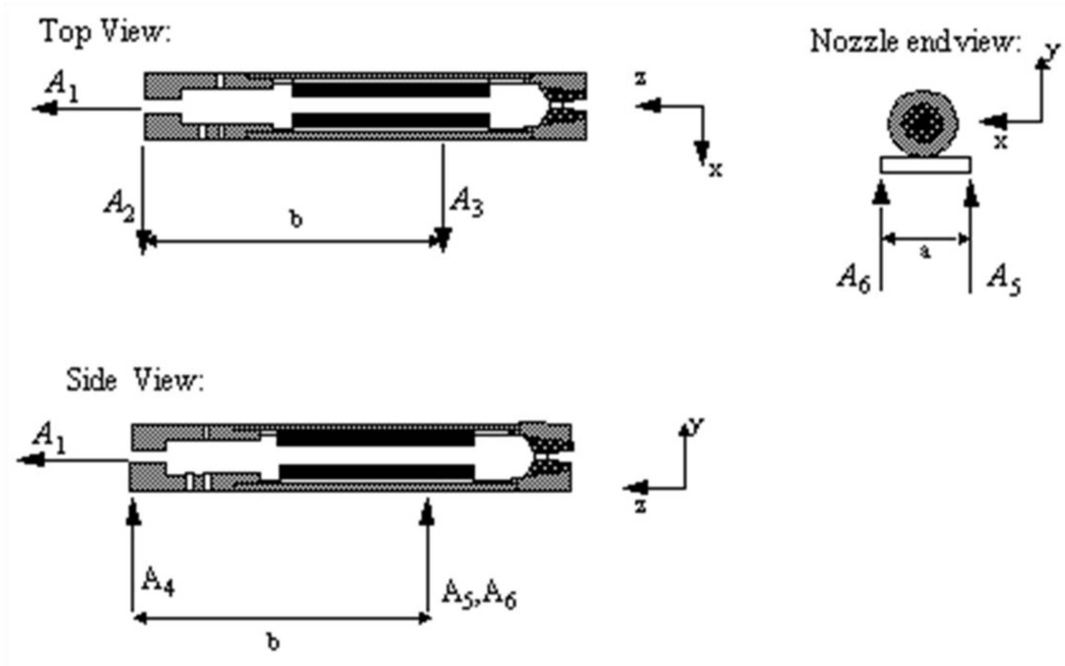

Figure 2 Freebody Diagram of rocket body and six degree of freedom thrust sensor arrangement.

Moments are measured by at least two elements and a couple is calculated from the two uniaxial forces and the known distances between the elements, *a* and *b*. For this stand, *a*=0.122 m and *b*=0.292 m. A matrix resulting from the static analysis of the frame gives the relation between the measured forces and the resultant forces and moments acting on the frame as shown in Equation 1:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & a & -a \\ 0 & b & -b & 0 & 0 & 0 \\ 0 & 0 & 0 & b & -b & -b \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{bmatrix} = \begin{bmatrix} F_z \\ F_y \\ F_x \\ M_{roll} \\ M_{yaw} \\ M_{pitch} \end{bmatrix} \tag{1}$$

where A_i are the six measured scalar force components of the uniaxial legs, a is the separation for the two front vertical legs, and b is the separation for the two mounting brackets.

Uniaxial elements for the thrust sensor were designed using ProEngineer and ProMechanica software. In order for this measurement to be valid, each element must be subjected to only an axial load. In large rocket systems, this is accomplished through a universal flexure[7]. However, such a mounting end does not exist in the small scale of the UALR hybrid rocket. A custom mounting end was designed which combined features of two universal joints and a roll element to remove constraints from the five non-axial degrees of freedom. This mounting was made principally at the rocket motor connection, rather than at the frame mounting point, so that no possibility of deflection in the element could affect the measurement. The universal joint at the frame mount side provides relieving constraint in the non-axial Cartesian directions. Because of the expected low values of these forces, roller bearing elements were used to keep the friction losses minimal. The joints were fabricated at Hendrix College and at UALR. The force measurements were made using load cells from FGP Sensors and Instrumentation with maximum loads of 500 N, 100 N, and 50 N.

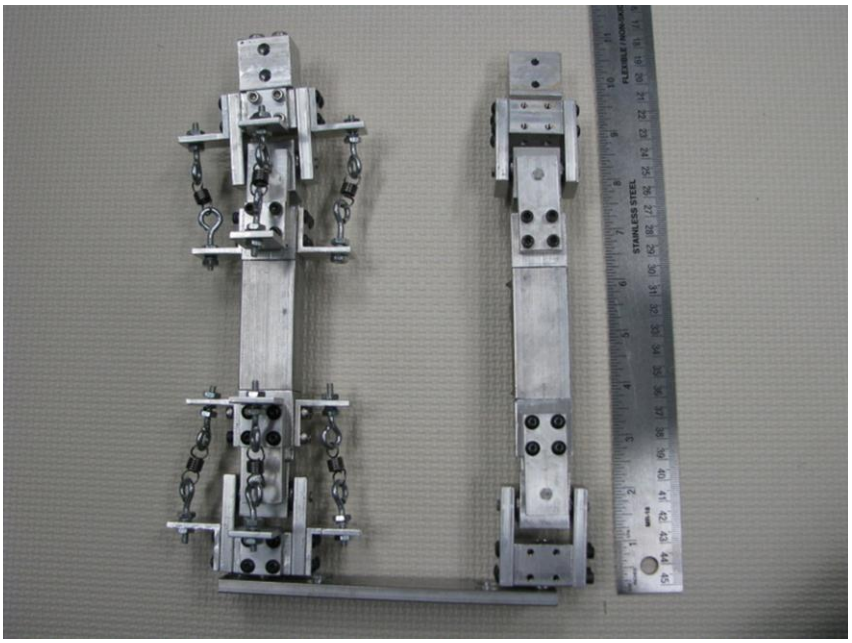

Figure 3 Uniaxial leg with support springs (on left) and without springs (on right). The central block is a spacer for the load cell.

At first, the leg was designed with small angle brackets bolted above and below each universal joint as shown in Figure 3 on the left side of the figure. Springs were mounted on these brackets in order to provide stiffness for the entire assembled structure. It was later determined that the extra stiffness provided by the springs was not necessary to protect the integrity of the thrust stand. Since the springs were a potential source of error in the measurement, the brackets and springs were removed once the entire assembly proved stable. The leg on the right side of Figure 3 shows the simplified leg. In both legs shown in Figure 3, the central aluminum block holds the place for the load cell.

One of the benefits of a labscale rocket system is the ability to conduct multiple firings with measurements such as fuel mass and nozzle diameter in between each firing. Therefore, the thrust stand must be stable during the insertion and removal of the rocket body in between firings. To provide stiffness and protection of the load cells during this process, custom aluminum bars were created to use the spring bracket hole patterns that spanned the load cells, providing protection against hyper extension or compression for the load cells. These aluminum bars were placed on the legs during assembly and disassembly when the rocket body was removed for fuel changes and measurements and cleaning. The bars were removed during all measurements. Figure 4 shows four views of the assembled thrust stand in firing and measuring configuration.

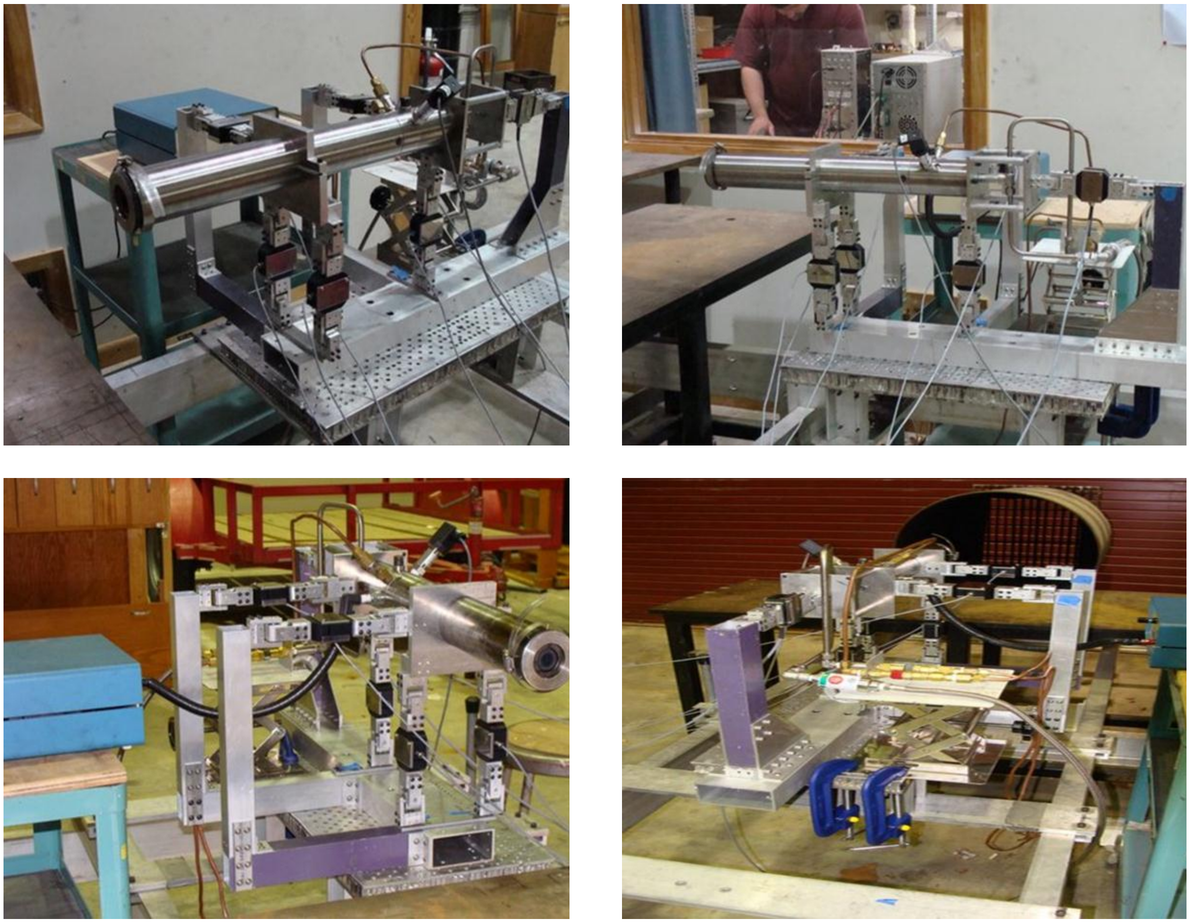

Figure 4 The assembled thrust stand.

III. Calibration of the thrust stand.

Each load cell output was connected to a conditioning circuit, whose voltage output was measured by a voltmeter during individual loadcell calibration and by Vernier's LoggerPro software running on a personal computer during assembled stand calibrations and firing. LoggerPro collected data at 250 Hz.

The calibration process began with the characterization of each individual load cell. The load cell was placed in a dead-weight tester, with the output voltage put through the conditioning circuit before being measured by a voltmeter. Known weights were gradually applied and removed to create a hysteresis curve for each load cell. A line fit was performed to each curve. The line fit equation was later used to translate the voltage output from each loadcell into a force measurement. Each loadcell was verified to have very little variation due to cycling and showed very high degree of linearity between applied force and voltage output. The results of these calibrations are presented in Table 1.

Table 1 Individual load cell calibrations. A_i is the force on leg i in Newtons, V_i is the voltage output from the load cell on leg i in Volts.

Leg #	Direction	Load cell ID	Load cell limit , N	Calibration curve
1	z	3606	500	$A_1 = 174.20V_1 - 0.42$
2	x	3310	50	$A_2 = 10.854V_2 - 3.725$
3	x	3307	50	$A_3 = 9.805V_3 + 0.0$
4	y	3996	100	$A_4 = 45.525V_4 - 0.594$
5	y	3994	100	$A_5 = 44.119V_5 - 2.021$
6	y	3995	100	$A_6 = 40.935V_6 + 0.623$

The next step in the calibration process was to assemble the thrust stand with the rocket body in place, then apply known forces in each special direction using steel cables, a pulley, and a dead weight platform. The cable applying force to the rocket body was placed near the center of mass. Applied forces varied from zero to close to the load cell limits for each direction. The goal for this experiment was to show that the forces are isolated by the uniaxial legs. Graphs were plotted with applied force magnitude on the x-axis and voltage output on the y-axis. The slopes of these lines were calculated. A slope close to zero on the off-axis legs indicate force isolation by the uniaxial legs. Results are given in Tables 2-4.

Table 2 Force applied in x direction.

Leg #	Leg direction	Calibration slope (V/N)
1	z	3×10^{-4}
2	x	2.03×10^{-2}
3	x	5.23×10^{-2}
4	y	3×10^{-4}
5	y	9×10^{-4}
6	y	1.2×10^{-3}

Table 3 Force applied in y direction.

Leg #	Leg direction	Calibration slope (V/N)
1	z	2×10^{-5}
2	x	4×10^{-4}
3	x	5×10^{-4}
4	y	9.8×10^{-3}
5	y	3.3×10^{-3}
6	y	8.6×10^{-3}

Table 4 Force applied in z direction.

Leg #	Leg direction	Calibration slope (V/N)
1	z	5.8×10^{-3}
2	x	9×10^{-4}
3	x	7×10^{-5}
4	y	6×10^{-4}
5	y	1×10^{-4}
6	y	2×10^{-5}

Next, the motions of roll, pitch, and yaw were generated by gently applying forces to the rocket body. The purpose of this test was not to generate a known quantity of each moment, but instead was to see the reaction of each load cell under a pure rotation. A roll was generated by gently twisting the rocket counter clockwise as viewed from the nozzle end. Figure 5 shows the results in legs 5 and 6. Notice that V_6 is negative, indicating compression of the load cell, and V_5 is positive, indicating extension of the load cell as expected. Responses from the other load cells were minimal, indicating proper isolation. A pitch was generated by gently pressing the nozzle end of the rocket body down. The responses for legs 4, 5, and 6 are shown in Figure 6. Finally, yaw was simulated by gently pressing the nozzle end in the positive x direction. Responses of legs 2 and 3 are presented in Figure 7.

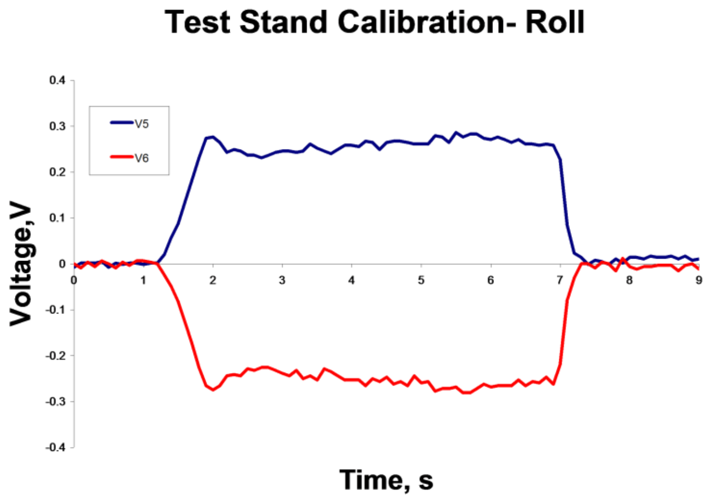

Figure 5 Response of legs 5 and 6 to simulated roll.

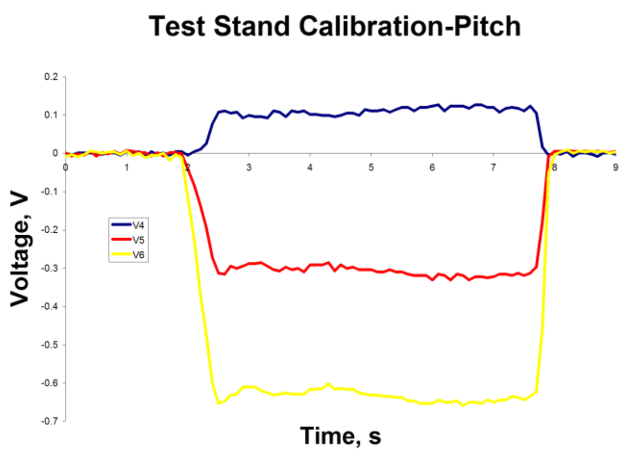

Figure 6 Response of legs 4-6 to simulated pitch.

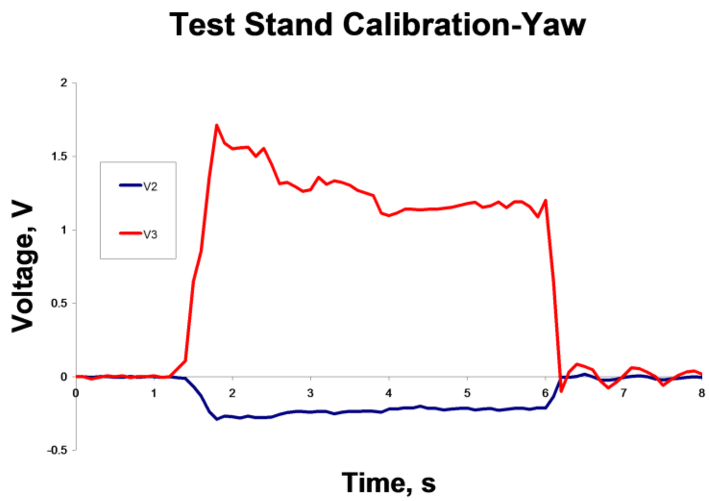

Figure 7 Response of legs 2 and 3 to simulated yaw.

The final test for the new thrust stand was to see if it remained stable during firing. Hybrid rockets have significant pressure and thrust oscillations. It was unknown if the thrust oscillations would cause the thrust stand to become unstable and collapse during firing. The stand remained stable while the rocket was fired at low, medium, and high oxygen flows. A picture of one of the test firings is presented in Figure 8.

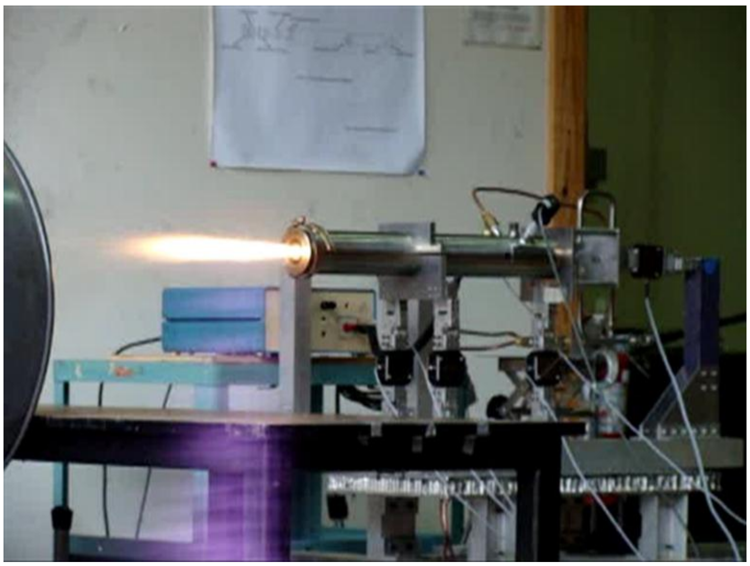

Figure 8 The thrust stand remained stable during a rocket firing test.

IV. Conclusion

A six degree-of-freedom thrust stand was designed and constructed for the lab-scaled hybrid rocket at the University of Arkansas at Little Rock. The stand consisted of six uni-axial legs. Each leg is composed of two universal joints, a load cell, and rotational bearings. The load cells were calibrated both separately and in the stand. Calibration tests showed good isolation of force components, and a predictable response to a pure roll, yaw, and pitch motion. Finally, the stand was tested with several rocket firings, and proved stable during firing.

Acknowledgments

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References

[1] R. Shanks and M. K. Hudson, "A Labscale Hybrid Rocket Motor for Instrumentation Studies," *Journal of Pyrotechnics,* vol. 11, pp. 1-10, 2000.

[2] A. B. Wright, M. W. Teague, A. M. Wright and E. Wilson, "Instrumentation of UALR labscale hybrid rocket motor," in *SPIE Defense and security Symposium*, Orlando, FL, 2006.

[3] A. M. Wright, M. W. Teague, M. K. Hudson, A. B. Wright and P. Foley, "A Thrust and Impulse Study of Guanidinium Azo-Tetrazolate as a Fuel Additive for Hybrid Rocket Motor," *Journal of Pyrotechnics,* vol. Winter, no. 22, 2005.

[4] A. B. Wright and A. M. Wright, "Optical Studies of Combustion Chamber Flame in a Hybrid Rocket Motor," *Journal of Pyrotechnics,* 2004.

[5] A. B. Wright and A. M. Wright, "Pressure Measurement in the Post-Combustion Section of a Hybrid Rocket Motor," in *AIAA-99-2536*, 1999.

[6] A. Chouinard, A. Adams, A. M. Wright and M. K. Hudson, "Multi-wavelength Laser Opacity Study of a Hybrid Rocket Plume," *Journal of Pyrotechnics,* no. 15, 2002.

[7] R. B. Runyan, R. N. Haynes, A. F. Gwinn and B. R. Jennings, "Basic Principles of Thrust Stand Design," AFAL-TR-88-060, 1988.