Development of a Pyrotechnic Shock Simulation Apparatus for Spacecraft Applications

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This report details the research, design, construction, and testing of a pyrotechnic shock simulation apparatus for spacecraft applications. The apparatus was developed to be used in the Space Environments Lab at California Polytechnic State University. It will be used for testing spacecraft components with dimensions up to 24"x12"x12" as well as CubeSats. Additionally, it may be used as an instructional or demonstrational tool in the Aerospace Department's space environments course. The apparatus functions by way of mechanical impact of an approximately 20 lb stainless steel swinging hammer. Tests were performed to verify the simulator's functionality. Suggestions for improvement and further progress are also given.

I. Introduction

The pyrotechnic shock environment is of particular concern for spacecraft components. Pyrotechnic shock or pyroshock is the transient motion of structural elements, assemblies, subsystems, or systems due to explosive loading induced by the detonation of ordnance devices incorporated into or attached to the structure[1]. On spacecraft, these forces predominately come from the activation of pyrotechnic devices[2] (e.g. separation nuts, pin-pullers, valves). Both the launch vehicle and the spacecraft create shocks, with the former contributing through events like fairing and clamp band separation, and the latter through events such as solar array deployment. The shock environment is quantified through a transformation from the time domain acceleration response, in units of G (32.2 ft/s^2 or 9.81 m/s^2), into a Shock Response Spectrum (SRS), based on an ideal, damped, single degree-of-freedom model[3]. Shock is an important consideration in spacecraft design. The damage that can be caused by shock can lead to partial or total component failure. Electronic spacecraft components are particularly susceptible to damage from the pyroshock environment.

The initial requirements for the Cal Poly shock table project called for an apparatus capable of qualifying units up to 15 lbm with dimensions up to 24" X 12" X 12". Units would be tested to Mil-Std-1540 or NASA GEVS standards, although specific G loadings and frequencies were not yet set. After researching papers concerning common pyrotechnic devices used on spacecraft and their typical G loadings, and other papers detailing typical amplitudes attained by similar shock testing apparatuses[4], a target of 3000 G @ 5 kHz was set, with significant spectral content up to 10 kHz. Table 1 below outlines the target input.

Table 1. Test Level Goals

Frequency (Hz)	Acceleration (G)
100	100
5000	3000
10000	3000

This report details the process of designing an apparatus to test to the levels above, fabricating that design, and performing a series of tests to prove the design's functionality. Additionally, this report includes: a list of recommended modifications and future work that can be done on this design and a basic user's guide (located in the Appendix).

II. Background Research

Preliminary research was performed on past and current methods of pyroshock testing in an effort to gauge the feasibility of building such an apparatus. Several methods and configurations were considered along with factors such as complexity, repeatability, attained G loadings, test area size, and cost. The results are given below.

Tunable Resonant Fixture

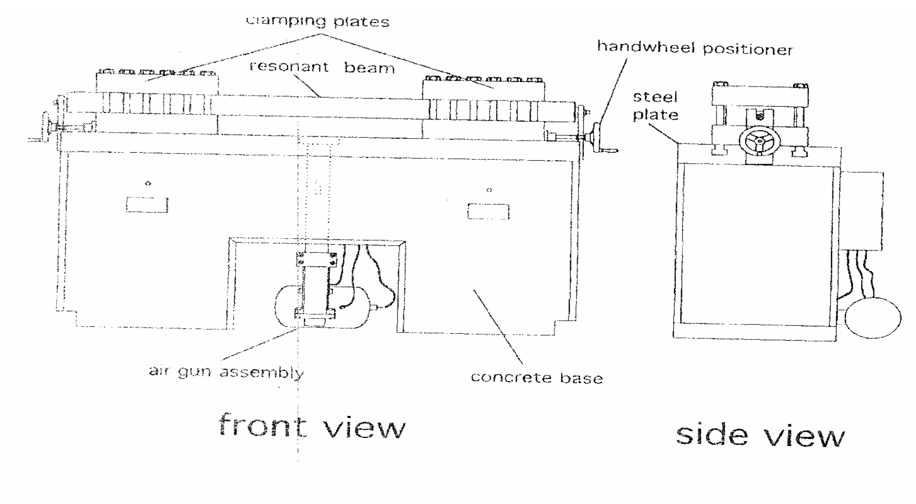

Figure 1. Sandia Labs Tunable Resonant Fixture[5]

Complexity

The resonant fixture itself is of a simple design. A thick beam is clamped at both ends between massive clamping plates. The clamping plates then rest on a solid concrete base (variations in this aspect may be possible). The effective free span of the beam may be adjusted by loosening and moving each clamping plate, thereby tuning the natural frequency of the fixture to provide various inputs.

The most complex component would be the air gun assembly, which would require a breach to be manufactured by which a heavy projectile may be loaded. A pressurized air tank would also be required that could provide enough pressure to propel a projectile to adequate speeds (approximately 300 psi).

Characterization and Repeatability

Because the resonant fixture consists of a thick beam, the first bending mode frequency is closely predicted by equations for beam bending frequencies. This is possibly the most significant advantage of using a tunable resonant beam fixture. The ability to effectively and predictably change the natural frequency of the test fixture allows a wide range of response spectra to be obtained. Parameters such as amplitude and input duration may be varied by using distinct projectiles and introducing damping components such as cardboard or felt strips at the point of impact.

Attainable G Loadings

The Sandia Phase I Report demonstrated that clear knee frequencies in the SRS were able to be tuned in a frequency range of 0.5 KHz to 1.4 KHz, with maximum G loadings ranging from 1000 G to 4000 G. Figure 19 of the report also shows that the setup is capable of higher mode excitations (6 KHz) and loads in excess of 10 KG's, characteristic of a true near-field pyroshock. Unfortunately the report gives few details about how these results were obtained, although it is suspected that the impact speed was increased while decreasing the impact duration.

Test Area

The beam used in the Sandia apparatus measured 75" x 10" x 4", and so the available test area was limited to a 10 inch square. This geometrical constraint is the most significant disadvantage of the resonant beam apparatus. Additionally it was shown that the length of the beam should be 1.5 times the largest dimension of the test specimen to guarantee adequate shock input. Although a beam of greater width would accommodate larger test items, the beam would also need to be unreasonably thick.

Cost

Cost could be an issue with the resonant beam setup. The beam alone would cost over $700 (assuming Sandia beam dimensions). The air gun assembly may also be excessively costly if a sufficient source of pressurized air is not already available.

Mechanical Impulse Pyro Shock (MIPS) Simulation

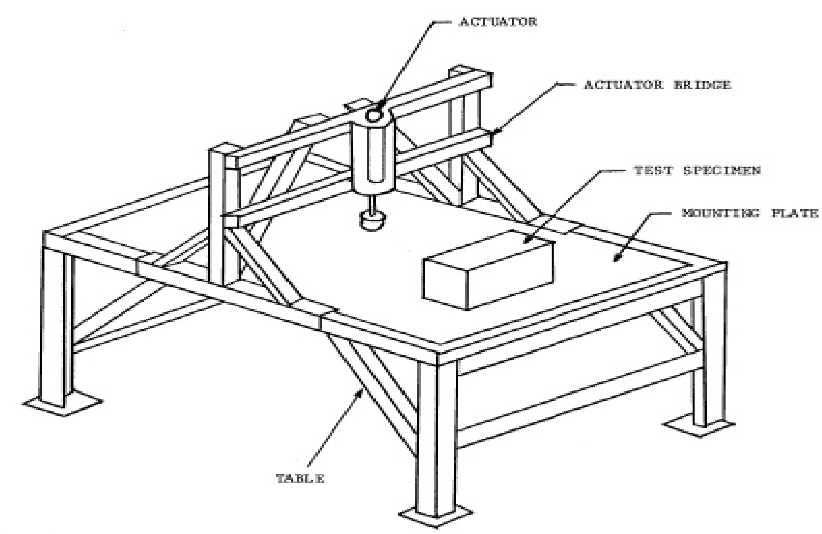

Figure 2. JPL MIPS Simulator[6]

Complexity

The MIPS configuration is slightly more complex than the resonant beam setup. In this setup a moveable pneumatic piston excites the aluminum mounting plate to which the test specimen is attached. The plate rests on a foam pad to provide isolation. The moveable actuator bridge is the most complex aspect of the MIPS configuration. It would need to be extremely adjustable, capable of moving the piston into any position over the table to provide a wide range of attainable spectra. At the same time, the bridge would need to be capable of being clamped in place and be extremely rigid, so that the full impact of the actuator may be transferred to the mounting plate, and not to the bridge and associated components.

Characterization and Repeatability

NASA's Jet Propulsion Lab was unable to characterize the MIPS simulator. Attempts were made using a Buckingham Pi solution, but the modal dynamics of the thick plate proved to be too complex. Instead, JPL created a database that associated all measured shock spectra with the parameters that were used to obtain the response, including actuator position, pressure, impact head material, damping materials, etc. With this tool, the approximate parameters to obtain a desired spectrum could be found, and then trial-and-error with a model of the test specimen could be used to obtain the exact spectrum. GE Astro built a similar apparatus and demonstrated that the setup was very repeatable, with amplitudes varying by not more than 10% between runs.[7]

Attainable G Loads

Jet Propulsion Lab demonstrated that their MIPS simulator was capable of obtaining shock spectra with knee frequencies between 2 KHz and 3 KHz, with amplitudes up to 4000 G and significant shock spectra content up to 10 KHz. A response more characteristic of a true near-field pyroshock was also attained with an approximately 4.3 dB/Octave average slope up to 10 000 G at 10 KHz.

Test Area

The dimensions of the plate used by the GE Astro apparatus measured 6' x 4' x 0.5''. Although specific test item dimensions were not given, "typical black electronic boxes" were qualified on the apparatus with masses up to 23 kg. For these reasons, we believe that a MIPS configuration would not limit us in available test area, and our maximum requirement of 24'' x 12'' could be met.

Cost

The plate used by GE Astro was quite large (6' x 4' x 0.5''), and would cost between $500 and $1000, which is quite expensive for any single component. However, it may be possible that a smaller plate be used still capable of testing our maximum size requirements. The pneumatic actuator and other table components are not expected to be excessively costly. However, the actuator may require pressure requirements up to 900 psi. This requirement could be costly if an adequate source is not already available.

Resonant Plate

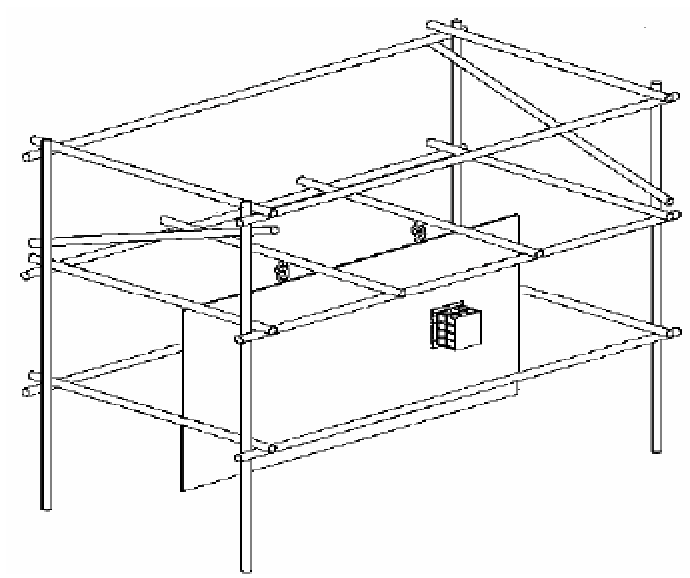

Figure 3. Simple Plate Test Fixture[4]

Complexity

A simple plate fixture like that shown in Figure 3 would be the least complex of the previously described configurations. In this setup, an aluminum plate is suspended from a framing structure via bungee cords or some other isolating tethers. The design allows for a large number of shock inputs, including mechanical impact from a hammer, a projectile, an actuator, or even live ordnance.

Characterization and Repeatability

Like the MIPS simulator, a simple plate fixture could not be characterized with an accurate model, and significant trial-and-error or an extensive database would be required to obtain the desired shock input. Repeatability is also a major concern. If a suspended hammer were used, it would be difficult to impact the same

point between runs, which could potentially produce distinct shock response spectra, resulting in an over-test or a re-test.

Attainable G Loads

The maximum expected amplitudes would depend on the method of impact. Alcatel Labs showed that knee frequencies with amplitudes up to 2000 G at 2 KHz were possible with a dropping mass input, although higher amplitudes can be expected if the drop height is increased. The impact head material can also be changed to effectively change the amplitude in low or high frequency ranges. A dropping hammer method proved to be capable of approximately 3000 G at 3 KHz with significant spectra content up to 10 KHz. If an air gun were used, more amplitude at higher frequencies could be expected as compared to a falling mass or hammer. Live ordnance would provide shocks in excess of 10 000 G and 10 KHz, if necessary.

Test Area

If the size of the plate were in line with the plate used on the MIPS simulator, then comparable test item sizes would be possible. Further, Alcatel qualified a large range of electrical units weighing up to 50 kg. For these reasons, the simple plate setup would be capable of meeting our maximum required test size requirements.

Cost

The simple plate setup is expected to be the least costly of all previously described configurations. The mounting plate itself would be the single most expensive component, expected to be between $500 and $1000 like the MIPS plate. If a falling mass or hammer were utilized, costs associated with pneumatic actuators or projectiles and their auxiliary components would be eliminated.

III. Mechanical Design

Because of its simplicity, large available test area, low cost, and demonstrated results the suspended plate was chosen as the most viable configuration to design around. Aluminum was chosen as the desired material with dimensions 6'x4' and half an inch thick. Such a plate would weigh approximately 175 lbs and require a stable, rigid, and robust framing structure from which the plate could be suspended. A slotted extruded aluminum framing material with the trade name 80/20® was chosen based on its quality and versatility. It was also decided that the plate should be vertically suspended to conserve space. The plate would be excited via a swinging pendulum type hammer which would have its own frame made of 80/20® so that any point on the plate could be impacted. The plate assembly is semi-portable by means of leveling casters which provide a solid foundation during impact but also contain wheels that can be utilized for impact locating or transport. Because 80/20 material was used, absolutely no welding was required on any of the framing structures.

SolidWorks was used extensively to model structures, gauge volume requirements, estimate material requirements, and locate fasteners. Several designs were promoted and iterated until the final design was established, shown in the figures below.

The plate frame assembly was constructed of 80/20®'s 2020 profile slotting material which has a 2'' square cross section. Corners were supported by 45 degree members made of 1020 material to increase rigidity. All slotting material was cut to length using a chop saw with a carbide blade which provided clean and accurate finishing surfaces. The 45 degree support members required two counter bores and thru holes on each of their ends to be fastened, as detailed in 80/20®'s complete product catalogue. The plate is supported by a 2020 free span member shown above the plate. Six 3/16'' thick steel cable loops run between the plate and the free span member.

The plate itself is made of 5052 aluminum and contains 77 total holes that were tapped with ¼''-20 threads. The threaded hole pattern begins six inches from any edge and follows a six inch linear pattern. The design also called for an aluminum side impact plate to be welded to either one of the sides of the main base plate. This plate would serve to provide adequate area for impact and reduce the likelihood of any permanent deformation on the sides of the plate. A thin sheet of steel is also required as an interface or sacrificial anvil between the hammer and aluminum base plate to prevent permanent deformation in the actual base plate.

The pendulum hammer frame consisted of 8' vertical 2020 members supporting a 5' 2020 profile rigid arm. The arm pivots about a 1'' shaft using two roller bearings that were press fit into two pivot arm plates. The offset between the rigid arm and its pivot point was required to allow changes in the length of the rigid arm so that all points along the plate could be impacted. The 1'' shaft and thus the pivot point may also be changed in height by loosening the bolts on each of the two supporting stanchions and sliding them along the length of the 8' members.

The hammer is made of type 303 stainless steel with dimensions 2”x3”x12” and weighs approximately 20 lbs. Stainless steel was chosen for its anti-corrosion properties, strength, and density. The hammer is fastened to the rigid arm by two eight-hole rectangular brackets in such a way that its center of mass lies below the pivot point and no offset from vertical is seen at rest. The hammer was machined with a 1.042” bore approximately ½” deep to accommodate a sacrificial and removable cylindrical impact nose, fastened with a ¼”-20 set screw. Currently only one nose has been created and is made of titanium, although other noses could be created from other metals such as brass or steel to obtain different response spectra.

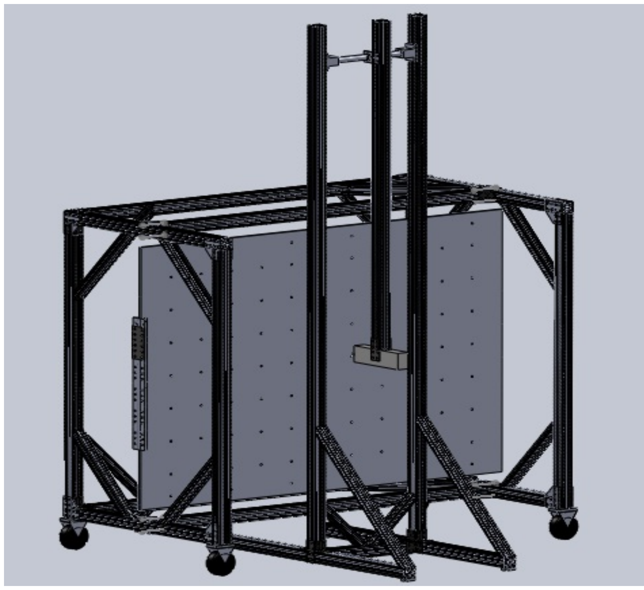

Figure 4. Final design solid model with side impact plate.

Manufacturing Procedure

As outlined in the design of the main plate, frame, and hammer assemblies, the main stock pieces were ordered and then machined for this application. The major steps in the process are outlined below.

The plate

The plate came pre-cut to the correct dimensions, but needed to be drilled to allow test pieces to be mounted to it and to provide a point where the plate could be mounted to the frame.

Step 1. Drill 1/4 inch holes in a grid pattern, with 6 inch spacing, resulting in a total of 77 holes for mounting test pieces.

Step 2. Tap the above 77 holes to 1/4" x 20 thread pattern.

Step 3. Drill six evenly spaced 3/8 inch holes along the top of the plate (3 inches from the top of the plate) to provide a place for cables to pass through and mount the plate to the frame.

Step 4. Drill three more 3/8 inch holes along the bottom of the plate, also for mounting to the frame.

The frame

The material for the frame was ordered based on the 3-D drawing shown in the design section. All material was ordered from 80/20.

Step 1. Cut all straight pieces to the desired length.

Step 2. Cut all angled pieces to length, with a 45 degree angle at the ends.

Step 3. Using included hardware, construct frame as shown in the drawing.

Step 4. Drill holes the along top and bottom cross bars to allow for mounting the plate.

Step 5. Set frame on its side and attach plate by passing the steel cable through the mounting holes and securing with clamps. Then raise frame and plate back to the vertical position.

Hammer assembly

The hammer assembly used the same 80/20 stock as used on the main frame, as well as a separate machined hammer head.

Step 1. Cut all 80/20 frame pieces and construct frame based on the drawing.
Step 2. Attach cross bar and bearings that the hammer arm will attach to.
Step 3. Cut hammer arm to length and mount using included mounting plates.
Step 4. Machine hammer head to provide space for the impact head.
Step 5. Insert impact head and secure with set screw.
Step 6. Mount hammer head to arm with included mounting plates.

Figure 5. Final design at completion of build.

IV. Electronic Design

In order to obtain an SRS curve, accelerometers are required to be mounted to the apparatus. However, these devices require certain support hardware in order to collect data. This includes a signal conditioner, a data acquisition device, and a computer running data acquisition software. The entire electronic set-up requires, at most, only two standard 120V, 60 Hz power outlets. The accelerometer chosen for this project was the Dytran 3200B4 model. It is a single-axis, piezoelectric device with a range of ±10 kG and 1to 10 kHz. This model features integrated electronic piezoelectric (IEPE) capabilities, meaning it has built-in amplification circuitry. This eliminates additional complexity from the system (in the form of an additional power supply and low noise coaxial cable). Three of these units were used to capture data in all three coordinate axes, ensuring that accelerations in the axes not being tested can also be monitored. Three separate single-axis accelerometers, while more expensive, were chosen over a single 3-axis unit because one could not be found off-the-self in a G range that allowed sufficient margin. Additionally, if one of the three single-axis units is damaged, testing can still be performed, which would not be the case if a 3-axis alone was chosen. Each of the accelerometers includes a mounting stud with ¼"-28 threading and connects to a separate coaxial cable with a 10-23 connector. The 10ft coaxial cable connects to a PCB 482C05 Signal Conditioner. This device provides a controlled current source to the accelerometers in order to power the integrated electronics on the units. Voltage changes are then passed back

through this device to an output channel. This particular model features 4 available power and output channels. From this signal conditioner, three coaxial cables run to a National Instruments USB-6009 Data Acquisition Device (DAQ). This device converted the analog signal generated by the accelerometers into a digital one that can be read into a computer. The USB-6009 model was chosen for its four available analog input channels and a sampling rate of 48,000 samples per second for a single channel. With three channels this number goes down to 16,000 samples per second, which is sufficient for the project. From the DAQ, the signal is read into a computer, via USB cable, running a LabView virtual interface. For the purposes of testing the entire apparatus, a simple interface was created to collect the voltage data from the three accelerometers and save it to file to be processed later. That processing was done in Matlab, with a slightly modified script originally developed by Martin, et al.[8] The script uses a corrected version of the Kelly-Richman recursive algorithm for creating an SRS curve. Figure 6 below is a simplified schematic of the electronic setup. Figure 7 shows the accelerometer block attached to the plate before a test run. Figure 8 shows a detail of the wiring from the signal conditioner coaxial cables into the DAQ.

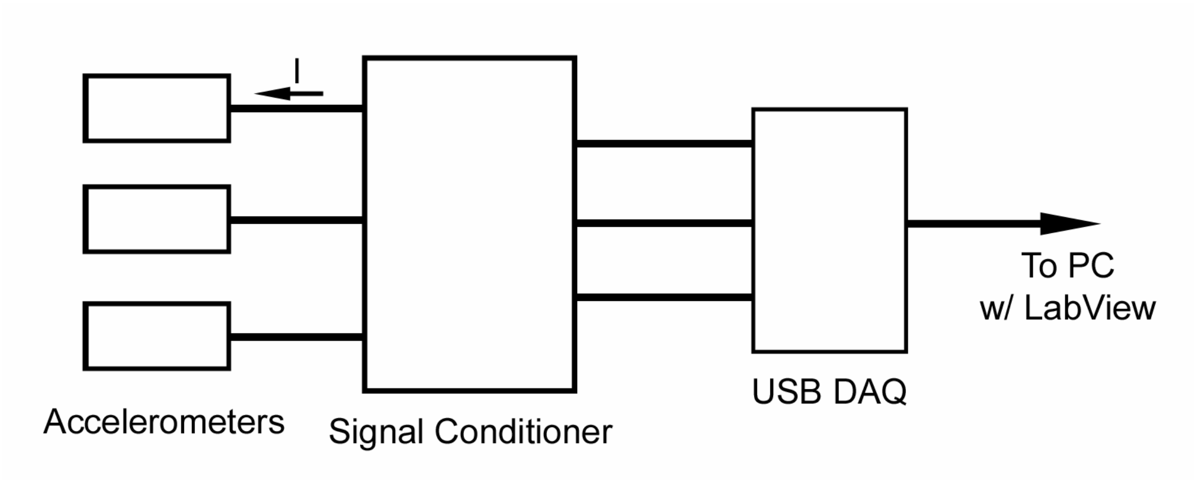

Figure 6. Simple schematic of the electronic half of the apparatus.

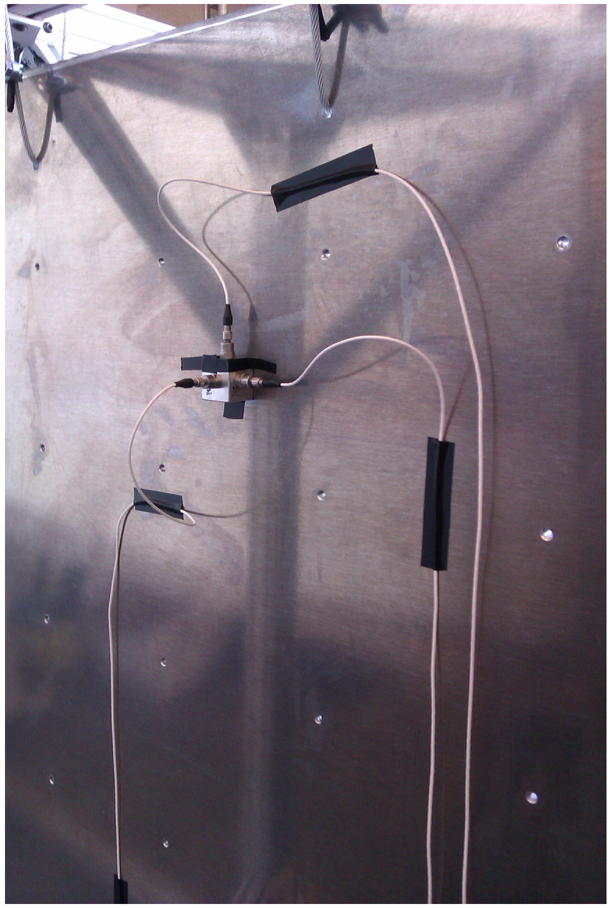

Figure 7. Detail of accelerometer interface block attached to impact plate.

Figure 8. Detail of wiring from signal conditioner into USB DAQ.

V. Functionality Test Results

The ultimate goal this project was to create a functional pyrotechnic shock simulator. There were many other peripheral goals as well, but various constraints (time, cost, and knowledge) led to these goals being relegated to the Suggestions for Improvement and Further Progress section of this report. However, time did permit for a simple functionality test of the entire system, from strike to SRS. This test had the accelerometer block placed on the opposite side from the hammer at a location approximately 5 ft from the strike location (bottom corner). The results of this test can be found in the following figures. Data was collected for all three axial directions, but the critical one was the z-direction, which is presented below.

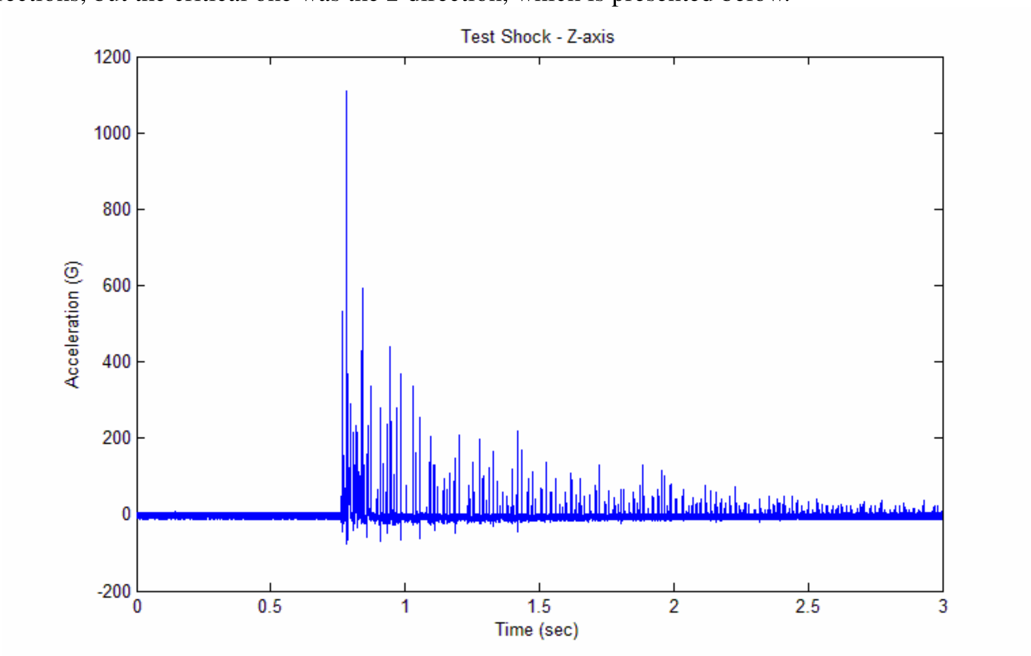

Figure 9. The time domain response from the z-axis accelerometer.

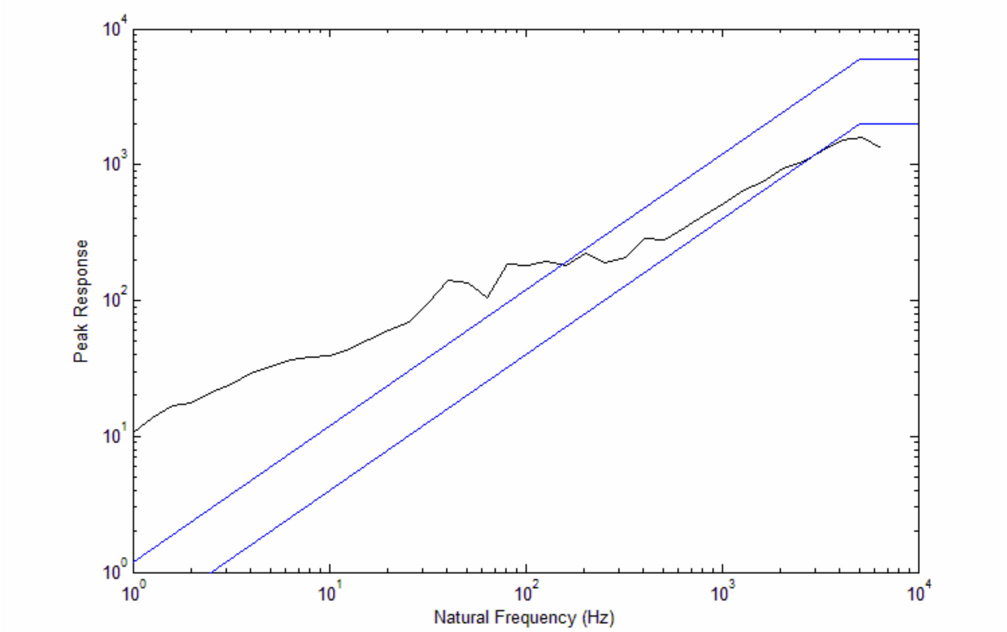

Figure 10. SRS from above time domain information with +6dB/-3dB tolerance bands

As can be seen, the SRS did not meet the goals for the design. It only reached to slightly less than 2000G in the higher frequencies, and has no distinct knee feature. However, this was merely a test of the functionality of the apparatus as a whole, not a proof of its capabilities. Significant over testing in the lower frequencies can also be seen as the SRS strays above the margin lines. These margin lines follow the NASA GEVS[9] and MIL-STD 1540C tolerances of +6dB/-3dB about the target response. The swing angle for the hammer was fairly shallow in relation to its full range and there are hundreds of ways the curve can be adjusted by modifying the boundary conditions of the system. Several difficulties were also identified during the test: the plate tended to swing back into the hammer before the operator could pull the arm back, the plate seemed to ring longer than was anticipated, and the superglue used to affix the accelerometer block did not hold up well to the shock environment. Suggestions for correcting these issues are offered in the next section. Overall, the goal of the test was accomplished, strikes were performed on the plate, signal travelled from sensor to computer, and the data was transformed into usable information.

VI. Suggestions for Improvement and Further Progress

There are many opportunities for improvement and further progress in the current design. Because of the short amount of time that was available to design and build the apparatus, many aspects of the original design were not completed. One of these is an accurate and repeatable way to measure the angle of the hammer swing. To obtain repeatable results between runs, user error in drop height must be minimized. This could be accomplished by attaching some sort of angle measuring plate at the pivot point of the rigid arm to measure degrees off of vertical. Another possibility is the attachment of a digital level to any point along the length of the rigid arm that would output a digital reading of degrees off of vertical, although such a device would have to survive the inevitable shocks transferred by the hammer upon impact.

There was also not sufficient time to machine and attach the aluminum side impact plate and so currently impacts on the edge of the plate are not possible. This side plate must be machined to provide adequate weld area and reduce the amount of attenuation between the hammer and base plate. Holes are also required to mount the steel interface plate. A SolidWorks drawing of the original design for the side impact plate is also given in the appendix.

The accelerometers require a mounting block to be attached to the base plate. There were problems with gluing the block to the plate. The current mounting block contains three holes threaded with ¼''-28 threads to accommodate each accelerometer in each orthogonal direction and one ¼''-20 hole to be fastened to the base plate. This setup allows the mounting block to be fastened to the plate but it does not allow the directions of the accelerometers to be specified. It is suggested that a new block be machined but with a smaller fastening thread so that a smaller bolt may be used to fasten the block to the plate without contacting the base plate threads. This setup would allow the block to be fastened to the base plate as well as specifying the accelerometer directions.

In order to prove the plate's capabilities, testing will have to be done to characterize how it responds to different boundary conditions. Variables to test should include: swing angle, impact hammer head material, impact interface material, strike location, swing arm length, test article location and size, addition of extra mass on the plate, rigidly clamping one or more edges of the plate, etc. There are literally thousands of permutations that can be tested. A database of some sort that correlates all the above mentioned variables and typical shock response spectra resulting would aid greatly in the trial-and-error process required with this setup.

At an early stage in the design process, it was planned to produce multiple shock inducing mechanisms, however time and cost only permitted the hammer to be produced. The system is designed to be modular; multiple methods of creating shock can be used without ever needing to modify the plate. Other mechanisms that showed promise were projectile and pneumatic impactors. Both systems have research supporting them as highly effective pyrotechnic shock simulators.

A low pass filter was initially included in the design, though it was not used for the functionality test. The filter may need to be integrated into the electronics setup to mitigate aliasing caused by high frequency noise. Testing should be done on the effects of including this into the design.

Finally, a more robust data acquisition and SRS generation interface should be created. The interface used for the functionality test was extremely simple, only gathering voltage data that had to be converted to G loads later. For an actual test (e.g. for outside contract work) it would be extremely beneficial to see the SRS as soon as possible after the strike. Though for the lab environment, a simpler interface would allow students to analyze the data on their own.

Acknowledgements

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Appendix:

Attached to this report are full page drawings for the parts of this project that were designed, but may need to be machined, as well as a one page user’s guide for setting up and operating the table.

References

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[7] Dwyer, Thomas J., “Pyro Shock Simulation: Experience with the MIPS Simulator,” GE Astro Space Division, Valley Forge, Pennsylvania.

[8] Martin, Justin N., Sinclair, Andrew J., Foster, Winfred A., “On the Shock-Response-Spectrum Recursive Algorithm of Kelly and Richman,” Auburn University, Auburn, Alabama, 2009.

[9] NASA, “General Environment Verification Standard (GEVS) For GSFC Flight Programs and Projects,” NASA, April, 2005.

User's Guide for Cal Poly's Pyrotechnic Shock Simulator:

Safety: Ear and eye protection should be worn at ALL times when using the shock simulator. There is a metal-to-metal impact that could potentially send shattered fragments of metal into the eyes of the operators. People in the vicinity of the testing should also at least wear ear protection. Before every strike, announce loudly so that others can prepare.

At least two people are required to operate the shock simulator at this time. Though, three would be preferable. One person must run the electronic side of the test, ensuring all connections are solid and running the virtual interface. A second person is responsible for the swinging hammer. Ideally, one person would pull back, release, and catch the hammer while another identifies the proper angle for the swing arm.

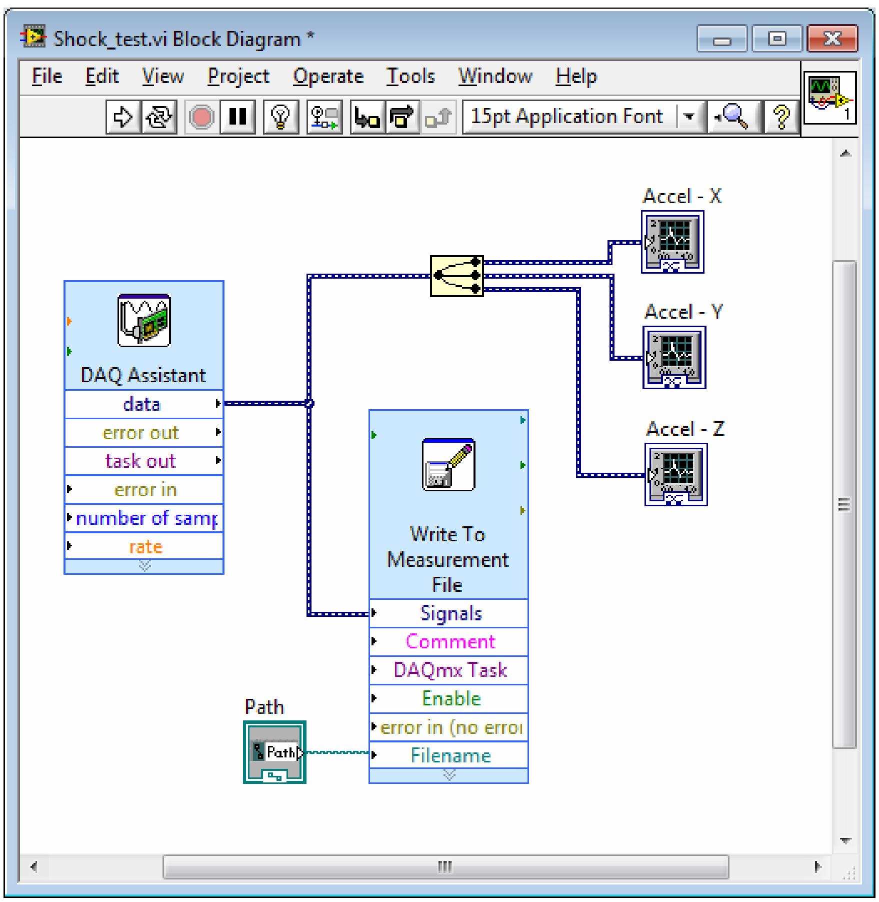
Setup: Roll the plate frame to the desired location for the test. Affix the impact interface plate to the impact side of the plate and position the hammer frame in front on this location. Adjust the hammer pivot height and/or arm length such that the hammer impacts the interface plate. Level the hammer frame with shims and weigh it down if required. Raise the plate frame off its wheels with the adjustable feet and level it. Place test article on opposite side of the plate and tighten down. Affix any attenuation and adjustment devices to the plate. Affix the accelerometer cube in the desired position without the accelerometers. Plug in the signal conditioner and connect all of the necessary wires between it and the DAQ and the DAQ to the computer. Attach the accelerometers to the cube. Run the final cables from the signal conditioner to the accelerometers. Tape the cables from the accelerometers loosely to the plate, leaving sufficient slack near the accelerometers. Power on the signal conditioner and wait until the sensors reach a steady state level. Check to make sure the DAQ is being recognized by the computer and the data acquisition software.

Running a test: Ensure that everyone in the vicinity of the test is wearing the proper eye and ear protection. Announce loudly that there will be a shock test. Pull the hammer back to the desired angle. Once everything is in position, the electronic operator should countdown for the swing to start and run the data collection interface. Immediately after the impact, the operator should catch the hammer on its rebound, to prevent multiple strikes. Once the hammer is arrested, save the data to file.

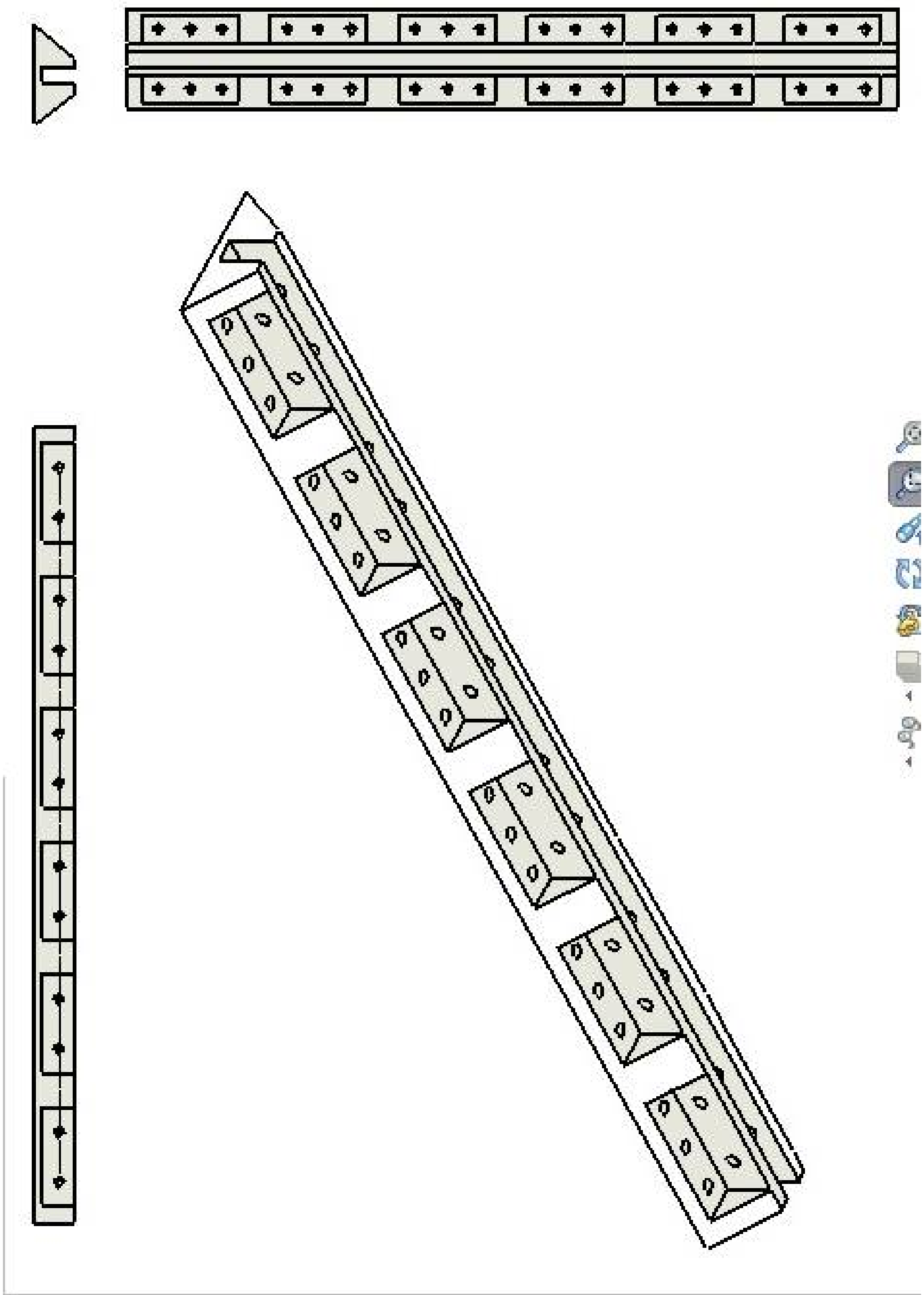
Inventory

Below is a list of all extra materials that were not used or have yet to be incorporated in the apparatus at the time of the writing of this report.

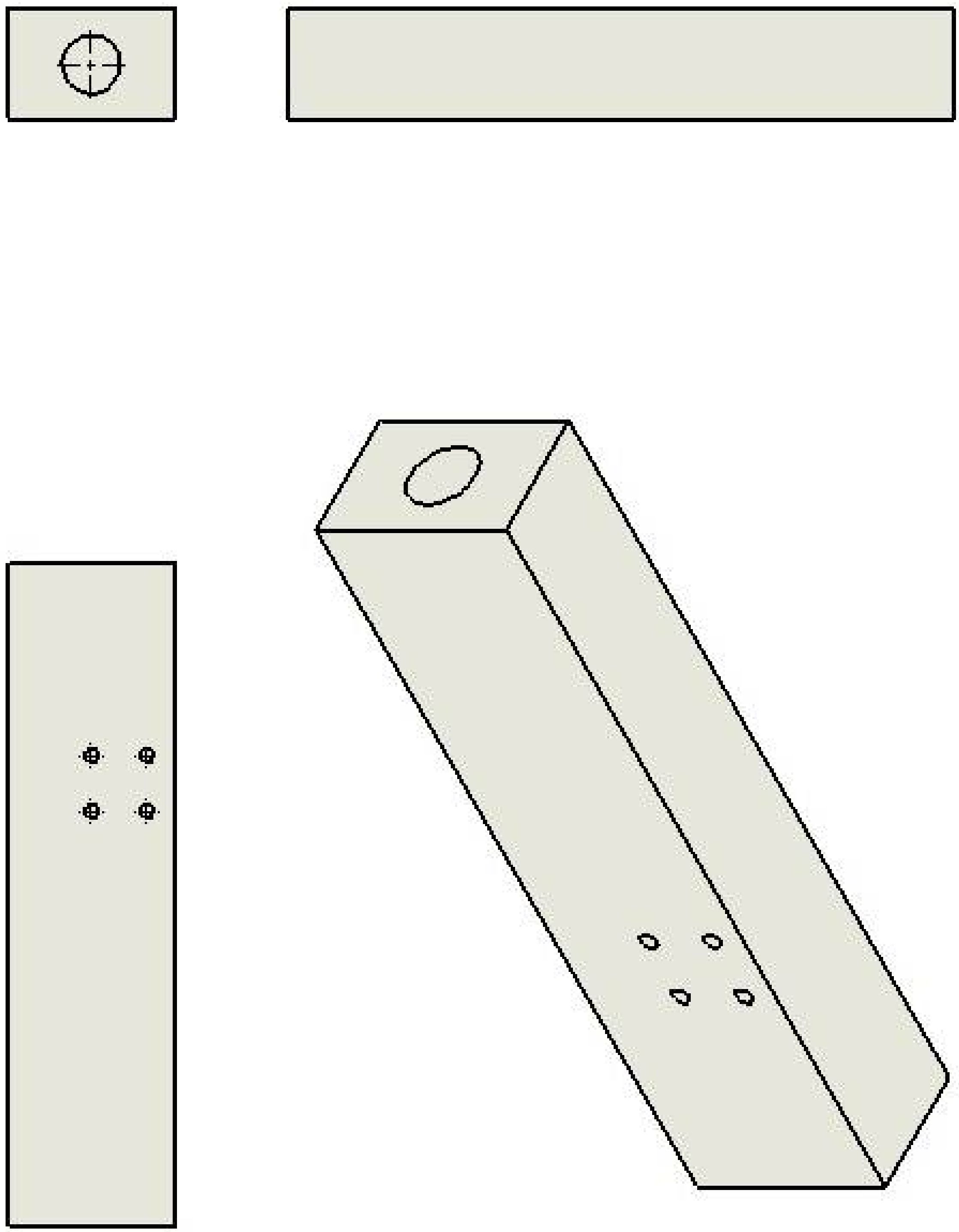
1. 6061 aluminum stock for impact plate
2. Framing material 2020 profile
1 x 10' 8"
1 x 3' 7"
1 x 1' 3"
1 x 11"
1 x 9"
2 x 4"
3. Framing material 1020 profile
1 x 11"
1 x 2' 9"
4. 6 inches aluminum bar material used for hammer support arm
5. 2 feet steel cable
6. 4 8020 mounting brackets
7. 6 inches of steel impact plate material
8. Large bag of 8020 mounting hardware
9. Can of tapping fluid
10. 1 inch aluminum accelerometer mounting cube material



Labview Data Acquisition Block Diagram



Side Impact Plate (Machined)



Impact Hammer (Type 303 Stainless Steel)