Reduced Gravity Education Flight Program

Overclocking a Pendulum

Simple Harmonic Motion in a Simple Pendulum

Team:
FIRST Team 246 Overclocked
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June 26, 2011

1. Change Page

Document Version	Date	Process Owner	Description
Original	May 11, 2011	Carolynn J. Kanelakos	Initial release
Rev A	June 13, 2011	Carolynn J. Kanelakos	• Added use of bogen arm and camera pole • Added description of aluminum rods made up of standoffs • Added photos of experiment frame and components • Changed description of pendulum to include carabineer for the string, and standoffs for the rigid rod • Replaced free weight set with lead plates and Velcro, including new photos • Updated items to be stowed during takeoff and landing • Updated stress analysis
Rev B	June 26, 2011	Gary Garber	Changed the video camera

2. Quick Reference Data Sheet

Principal Investigator: Gary Garber

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Experiment Title: Overclocking a Pendulum

Flight Date(s): June 27 – July 1, 2011

Overall Assembly Weight (lbs): 30.1 lbs

Assembly Dimensions (LxWxH): 19” x 19” x 13” (inside glove box, not including laptop or camera)

Equipment Orientation Requests: RGO provided Horizontal glove box

Proposed Floor Mounting Strategy (Bolts/Studs or Straps): Standard RGO glove box interface assembly (experiment structure will be captive to mounting plate in the glove box)

Gas Cylinder Requests (Type and Quantity): None

Overboard Vent Requests (Yes or No): None

Power Requirement (Voltage and Current Required): 120VAC, 60 Hz power connection

Free Float Experiment (Yes or No): No

Flyer Names for Each Proposed Flight Day:
Day 1: Gary Garber, James Berkman, Carolynn Kanelakos
Day 2: Rosemary White, Laurie Glenn

Camera Pole and/or Video Support: Camera Pole and Bogen arm

3. Table of Contents

4. Flight Manifest

Table 1: Flight Manifest

Name	Position	Preferred Day of Flight	Previous Experience
Gary Garber	Flyer	Day 1	None
James Berkman	Flyer	Day 1	None
Rosemary White	Flyer	Day 2	None
Laurie Glenn	Flyer	Day 2	None
Carolynn Kanelakos	NASA Mentor	Day 1	None

The flight week is June 24th – July 2nd, 2011. The exact flight days within this week have not been determined at this time.

5. Experiment Background

A common high school physics experiment is to have students explore the effects that different variables, such as mass and length, will have on the period of a simple pendulum. Although the period of a pendulum also depends on the acceleration due to gravity, changing this variable is not easily accomplished in the classroom. By setting a pendulum in motion at various gravitational accelerations on a Reduced Gravity Education Flight, one can obtain a set of data for students to verify the theoretical dependence of the period of a pendulum on gravity. Both a string pendulum and a rigid rod pendulum with bearings will be utilized in this experiment. A Vernier Wireless Dynamic Sensor System will be used as a pendulum bob to obtain string tension and acceleration data during the flight. The information recorded by the dynamic sensor system will provide students with more detailed data for more in-depth analysis of the pendulum dynamics. By obtaining video footage of the experiment with accompanying measurements of acceleration and tension, students in the classroom can use image analysis to verify a standard textbook relationship, or even derive the relationship by observing the video footage.

6. Experiment Description

In this experiment, a simple pendulum is set into motion by hand. The leading piece of data is actually the video recording of the pendulum's motion. Students can use image analysis software (such as Logger Pro) to measure the period of the pendulum back in the classroom under different amounts of gravity.

To hold the pendulum, we have constructed a frame made from C-channel shaped aluminum. This frame holds an aluminum shaft approximately 14" above the attachment plate. There will be two pendulums that can swing from this shaft, a rigid rod pendulum and a string pendulum. These two pendulums will not be used concurrently but in separate trials (to reduce the possibility of coupled vibrations).

As a scale frame of reference for the video image, two wooden yard sticks are attached to the frame. This will allow students to measure the length of the pendulum and calculate the speed solely based on image analysis.

Most of the electronics for this experiment are COTS and manufactured by Vernier Software which is one of the major educational physics providers in the U.S. We will be using a GPS sensor, a low-g accelerometer, and a Wireless Dynamics System Sensor (WDSS) in addition to the corresponding Logger Pro software, which works with all of the aforementioned sensors.

The primary sensor is the WDSS. The WDSS, which is about 6" long and 7 oz. in weight, will actually serve as the pendulum bob in most of the experiments. The WDSS unit provides wireless acceleration and tension data via Bluetooth to the laptop. The laptop has an additional Bluetooth receiver. The WDSS measures the tension in the pendulum string or rod based on the mass of the WDSS itself. It also provides 3 axis-acceleration data. This data can be recorded and analyzed with LoggerPro. The tension and accelerometer values will oscillate in a sinusoidal pattern with the motion of the pendulum. The period of the pendulum can be calculated from the tension and accelerometer data in addition to the image analysis.

Figure 1 shows a sample graph made using the WDSS mounted on a pendulum. The pendulum swung through a wide angle, so the angle of the accelerometer changed significantly. A simple, one-dimensional accelerometer would not have done this job as well. Only the net acceleration is graphed in the figure below. (See the April 1995 issue of The Physics Teacher for a discussion of the acceleration of a pendulum.)

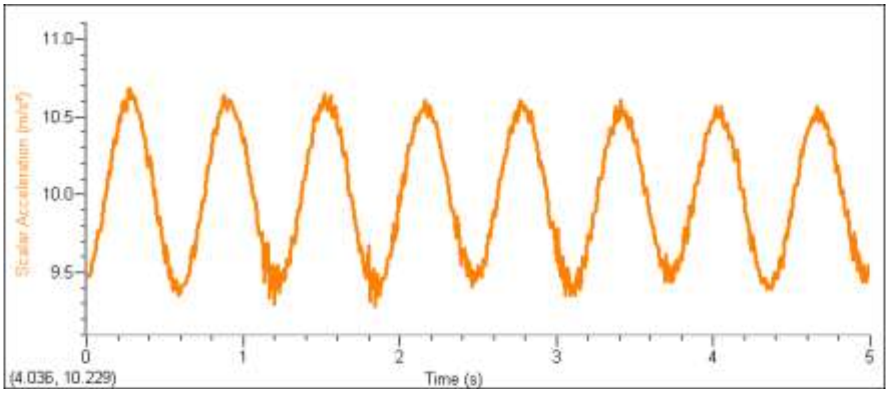


Figure 1: Acceleration of the WDSS used as a pendulum bob

6.1. Equations of Motion and Theory

The motion of a pendulum with a plumb bob on a string can be approximated by the simple pendulum equation, where T is the period, L is the length (to the center of mass of the plumb bob) and g is the acceleration due to gravity. In addition to the WDSS, an extra set of masses will be utilized in the experiment to vary the mass during different trials.

The string pendulum will be attached to a collar that is fixed on the horizontal aluminum shaft. The length of the simple string pendulum can easily be altered by wrapping the string up around the collar. This is traditionally done in ground based experiments for high school students to verify the above equation. Because the string may swing 360 degrees around the shaft, a hook will be used to vary the length of the string.

Since we believe that in the micro-g environment the simple pendulum will cease to swing back and forth, we will also do a set of experiments using a rigid rod (or physical) pendulum. The physics analysis of a rigid rod pendulum is slightly more complicated for the introductory physics student. One must include the moment of inertia of the rigid rod in addition to that of the plumb bob itself for the full physical pendulum equation.

The WDSS will be connected to a thin aluminum rod made up of 1” standoffs connected by ½” long threaded 6-32 rods. The aluminum rod will be connected to a small lightweight pillowblock with a bearing set on the horizontal aluminum shaft. This will allow rotational motion 360 degrees. The motion of the pendulum in hyper-g should be as predicted by the physical pendulum equation given above. In micro-g, it is possible that the pendulum will rotate 360 degrees. The actual motion of the pendulum will depend on the position of the pendulum as it enters the micro-g portion of the flight and can be analyzed considering conservation of energy. Within the scope of simple high school physics equations analyzing the conservation of energy, if the pendulum were at the lowest part of its swing when the experiment enters micro-g, and all of the pendulums energy was kinetic, it would continue to swing around in periodic circular motion. Again, this circular period (and the kinetic energy) could be calculated using image analysis or sensor data. If the pendulum were at the highest point in its swing (where all of the energy is gravitation potential energy) then all motion would cease. This of course, (falsely) assumes an abrupt boundary condition from normal gravity to micro-gravity. In truth, the boundary conditions are not abrupt and the advanced student will have to examine closely this transition.

To provide a closer examination of this transition we have added two additional sensors to the experiment, a GPS sensor and a separate low-g accelerometer. The Vernier GPS sensor will allow students to examine the position and velocity of the airplane's flight and how it related in the gravity conditions. Logger Pro is able to simultaneously analysis the GPS data along with the above tension and accelerometer data. Additionally, a low-g accelerometer will be used for data collection. This accelerometer will be static and attached to the frame of the experiment. The low-g accelerometer, as most sensors manufactured by Vernier, interface with the computer through the LabPro interface unit. Both the low-g accelerometer and the LabPro interface will be Velcro mounted to the glove box externally.

6.2. Trial Description

To document the variation of parameters during the flight, Table 2 was generated. The first two parabolas will be used for aircraft acclimation and experiment setup.

Table 2: Experiment Overview for Varying Parameters

Parabola	Low g	High g	String/Rod	Length	Extra Mass
1					
2					
3	0	1.8	String	4"	None
4	0	1.8	String	4"	None
5	0	1.8	String	4"	3.5 oz
6	0	1.8	String	4"	7 oz
7	0	1.8	String	4"	10.5 oz
8	0	1.8	String	4"	14 oz
9	0	1.8	String	6"	None
10	0	1.8	String	6"	None
11	0	1.8	String	8"	None
12	0	1.8	String	8"	None
13	0	1.8	Rod	2"	None
14	0	1.8	Rod	2"	None
15	0	1.8	Rod	2"	3.5 oz
16	0	1.8	Rod	2"	7 oz
17	0	1.8	Rod	2"	10.5 oz
18	0	1.8	Rod	2"	14 oz
19	0	1.8	Rod	3"	None
20	0	1.8	Rod	3"	None
21	0	1.8	Rod	4"	None
22	0	1.8	Rod	4"	None
23	0	1.8	Rod	5"	None
24	0	1.8	Rod	6"	None
25	0	1.8	Rod	6"	None
26	0	1.3	Rod	6"	None
27	0	1.3	Rod	6"	None
28	Lunar	1.5	Rod	6"	None
29	Martian	1.5	Rod	6"	None

7. Equipment Description

The elements listed in Table 3 will be used in the experiment. All elements are considered experimental hardware according to section 2.10.1 of the Aircraft Operations Division TEDP Requirements and Guidelines document.

Table 3: Experiment Assembly Elements

SubAssembly	Item	Qty	Part Letter (Figure 2)	Unit Weight (lbs)	Total Weight (lbs)
Inside Glove Box					
Frame	19" C-channel (horizontal to form square)	8	A	0.73	5.84
	4 " c-channel	8	B	0.15	1.23
	14 " c-channel (vertical sides)	4	D	0.54	2.15
	5/8" aluminum shaft (22” long)	1	E	0.71	0.71
	5/8" collars	5	Shown in Figure 4	0.05	0.25
	Pillow Block	3	F	0.32	0.96
	Corner brackets	8	C	0.24	1.92
	1.5" long 1/4-20 bolts	72		0.03	1.80
	1/4-20 Kep-nuts (Lock nuts)	72		0.01	0.45
	Wooden meter sticks	2		0.13	0.25
Pendulum	String	1		0.01	0.01
	WDSS	1		0.44	0.44
	Masses	4		0.22	0.88
	Aluminum rod	1		0.70	0.70
Sub Total					**17.6**
Mounted Externally to Glove Box					
Electronics	LapPro Unit	1		1.12	1.12
	Low g Accelerometer	1		0.14	0.14
	Power switch	1		0.44	0.44
	Laptop DELL Inspiron	1		5.92	5.92
	Sony HandyCAM	1		1.73	1.73
	Vernier GPS Sensor	1		0.14	0.14
	Vernier Bluetooth Adaptor	1		0.03	0.03
Other	Padding	5		0.60	3.00
Sub Total					**12.52**
Overall Experiment Assembly (Excluding RGO Provided Glove Box)					
TOTAL					**30.1**

The total weight of the experiment elements inside the box is approximately 19 lbs. The total weight of the experiment with all electronic equipment and components mounted inside the glove box is approximately 31.1 lbs, excluding the weight of the RGO provided glove box.

An overview of the experiment structure that will be mounted inside the glove box is shown in Figure 2.

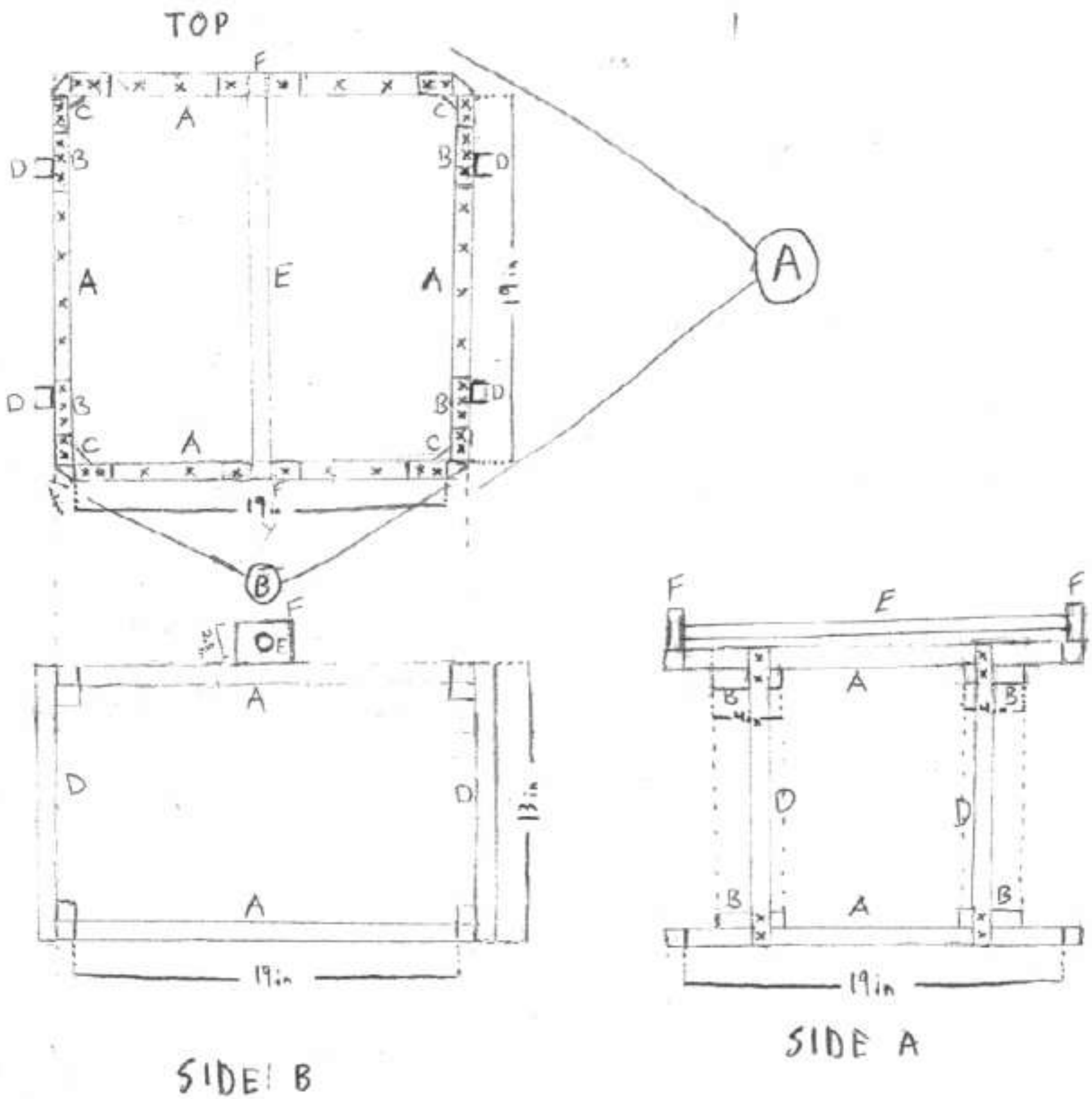


Figure 2: Frame Structure Assembly with Parts Labeled

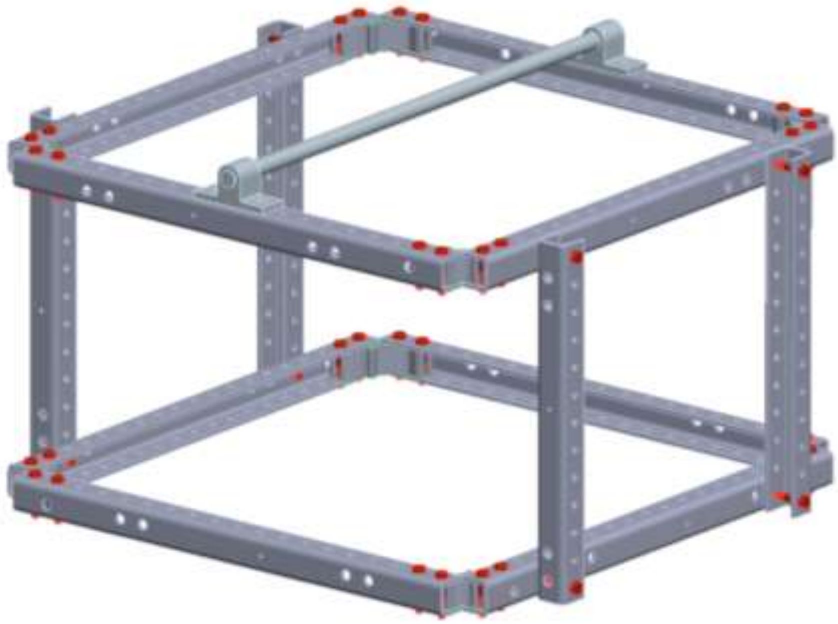


Figure 3: Iso view of frame structure assembly

7.1. Frame Structure Assembly

An overview of the full frame structure assembly including the pendulums is provided in Figure 4. The frame structure assembly consists of COTS AndyMark C-channel that will be bolted to the attachment plate inside the RGO provided glove box with ¼-20 bolts and lock nuts. A picture of the aluminum C-channel is provided in Figure 5. The C-channel is made of 5052 bent aluminum and is 1.25 in tall and 1.13 in wide, with a wall thickness of 0.125 in.

All frame components are held together with ¼-20 bolts and lock nuts, which can be tightened with a 7/16" wrench. The frame structural assembly is 19" square and the corners are held together with COTS corner brackets from AndyMark, as shown in Figure 6. The corner brackets, made of 6061T6 aluminum, are 0.995 inches thick and fit inside the "channel" of the C-channel structure. A maximum of 4 bolts may be used to bolt the brackets and C-channel together, 2 bolts in each piece of C-channel.

The view from side B (Front View) shows the pillow block that will be mounted to the frame to hold the 5/8" diameter aluminum shaft. The pendulums will be attached to the shaft via a collar for the string pendulum and a bearing block for the rigid rod pendulum. The frame is 13" high. The shaft is mounted 14" above the attachment plate. Photos of the pillow blocks and bearing blocks are shown in Figure 7and Figure 8, respectively.

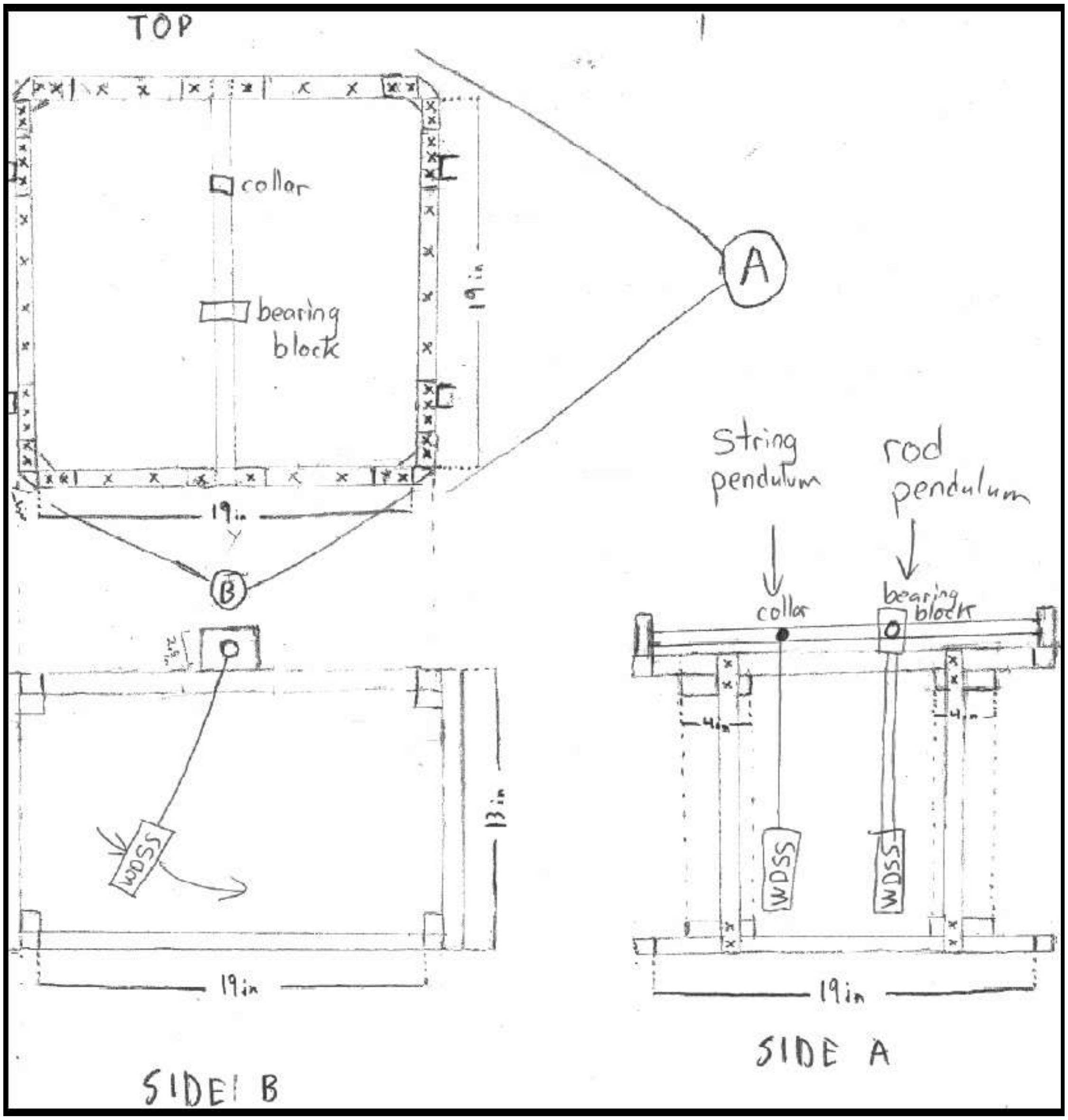


Figure 4: Pendulum Frame Structure Assembly

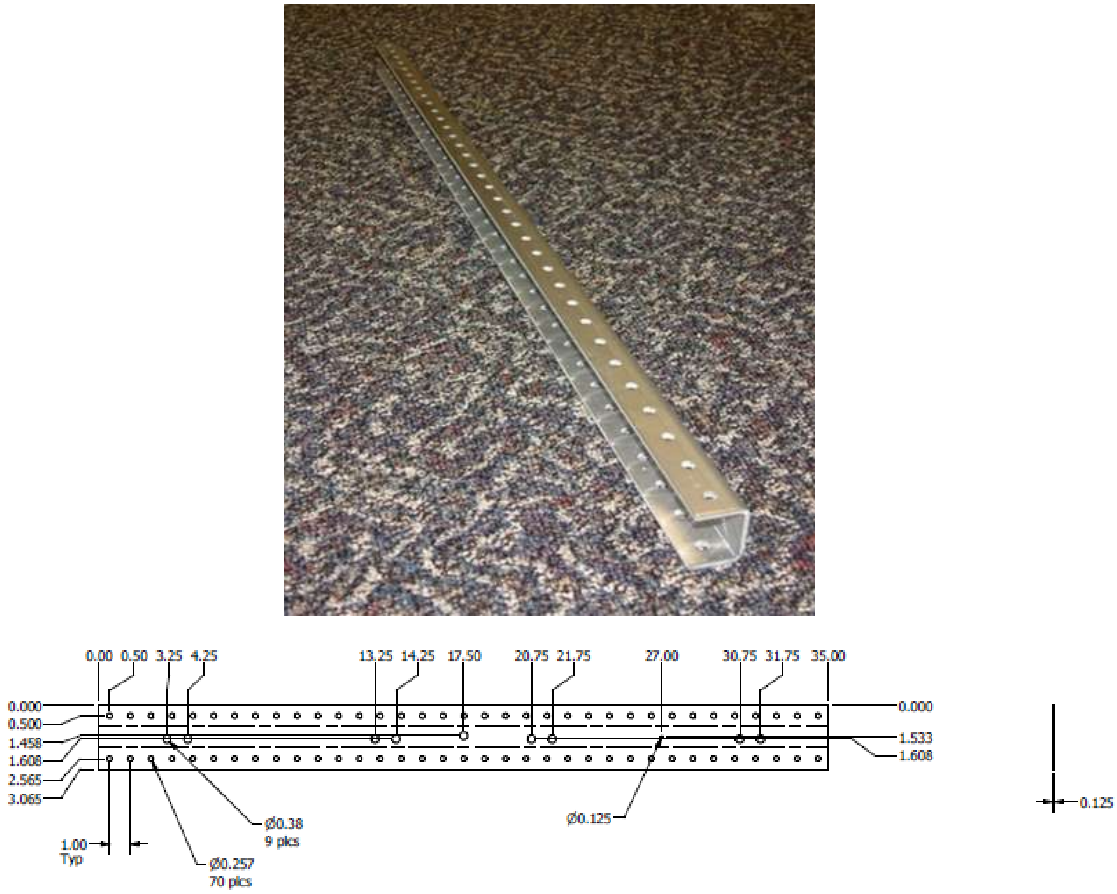


Figure 5: Aluminum C-Chanel

Figure 6: Aluminum Corner Bracket

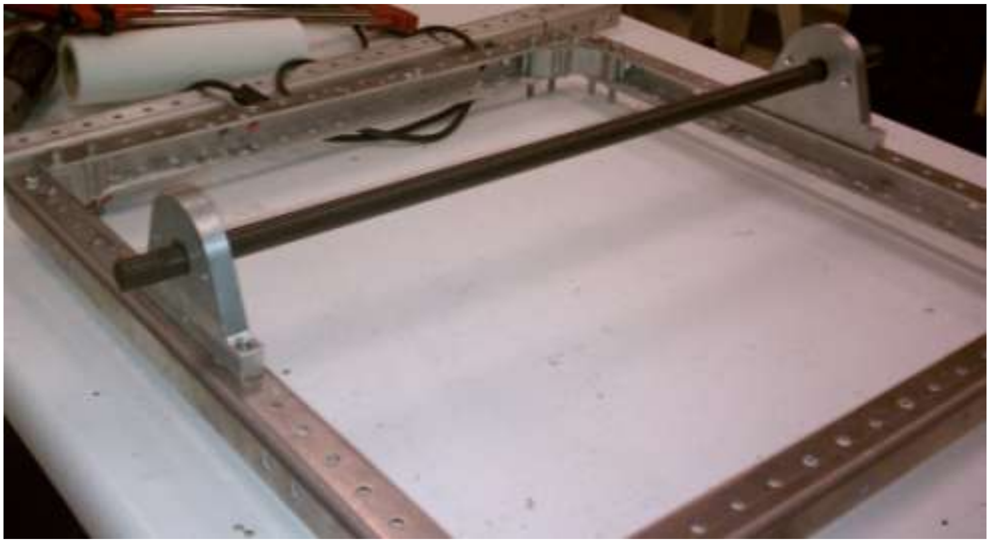


Figure 7: Photo of pendulum rod pillow blocks

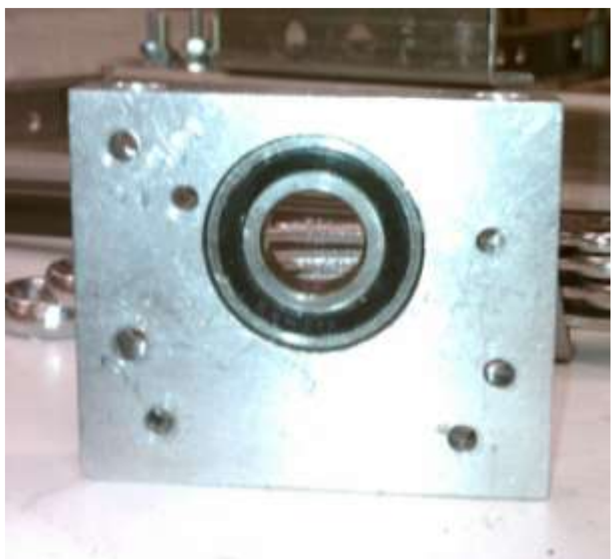


Figure 8: Photo of pendulum bearing block

Photos of some actual structural frame components and assemblies are provided below.

Figure 9: Frame corner with vertical strut mounted

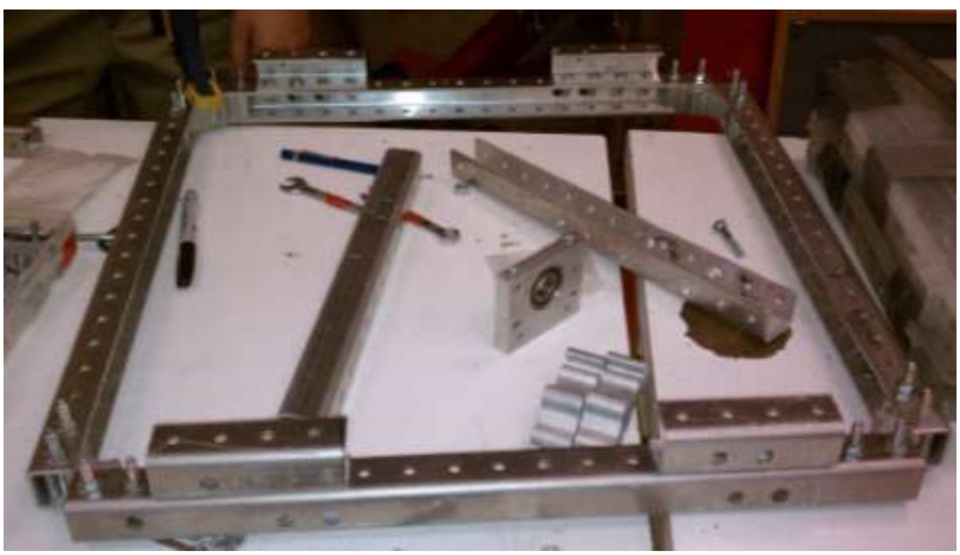


Figure 10: Frame horizontal sub-assembly with horizontal supports added (to add rigidity for vertical struts)

Figure 11: Assembled frame structure

7.2. Pendulum Subassembly

The WDSS has a built in 6-32 threaded hole. An closed eye hook with 6-32 threads will hook into the WDSS. A carabineer will connect the eye hook to the string which is 20 pound fishing line.

Detailed sketches of the pendulum subassemblies are provided in Figure 12. Figure 13 shows a picture of the Vernier WDSS.

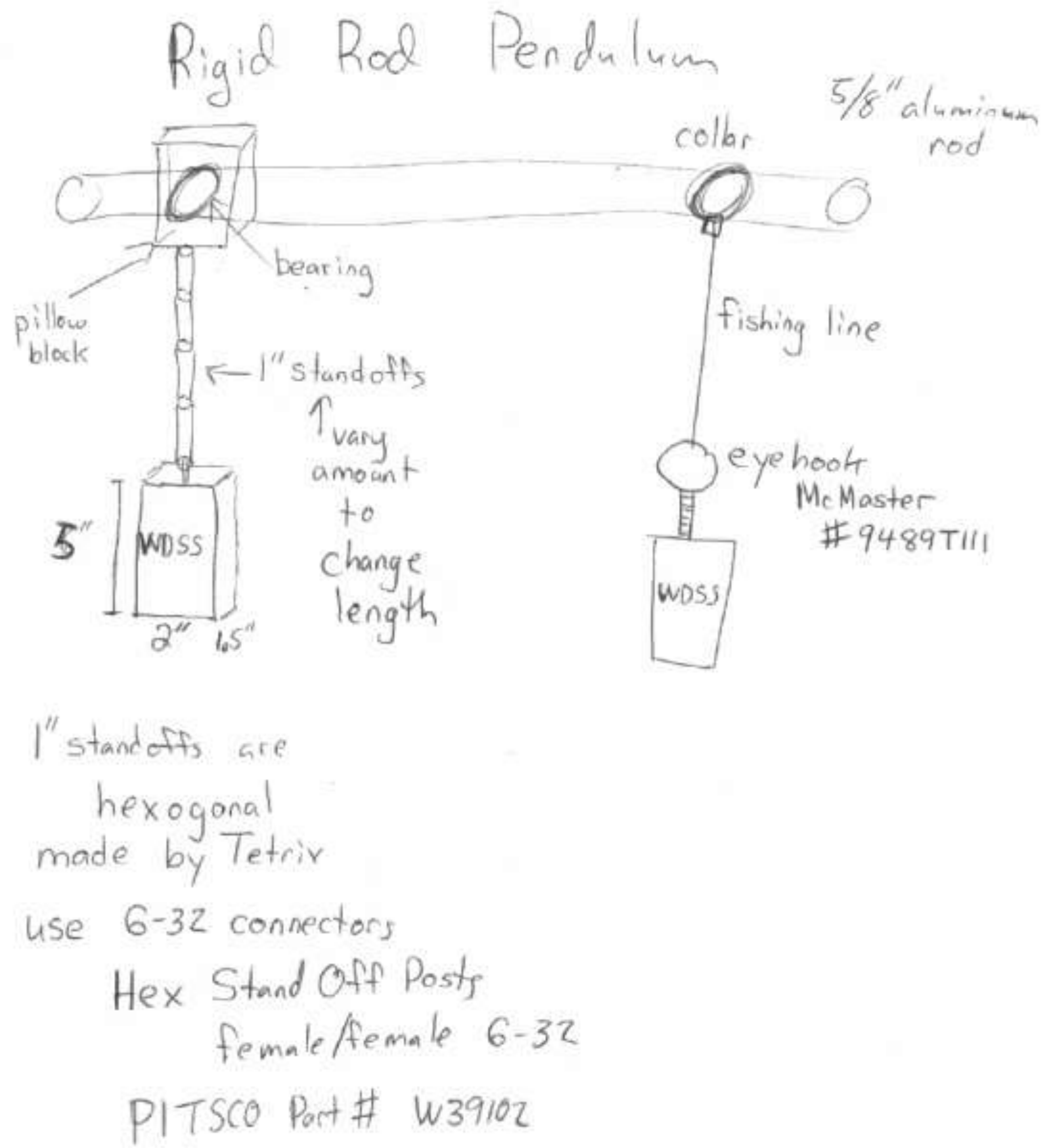


Figure 12: Detailed sketches of pendulum assemblies

Figure 13: Vernier Wireless Data Sensor System (WDSS)

Various weights will be attached to the pendulum as a varying parameter during the experiment. The weights will consist of thin lead plates which will be attached to the WDSS with Velcro. Between trials, these weights can be attached to the attachment plate with Velcro for easy storage. Each lead plate has a weight of about 3 ounces.

Figure 14: Lead Plate attached to WDSS with velcro

7.3. Electronics Subassembly

The LabPro unit, shown in Figure 15, is used to transmit data from the WDSS to the laptop. The low g accelerometer, shown in Figure 16, will be used to collect aircraft accelerations. A USB GPS sensor, Figure 17, will be used to collect aircraft altitude and location. The accelerometer and GPS will collect data that can be used in conjunction with the WDSS data. The LabPro unit and low g accelerometer will be constrained to the glove box with Velcro and cable ties.

The LabPro box connects to the laptop via a USB cable and will require power to be supplied via the power strip.

Figure 15: Vernier LabPro data collection system

Figure 16: Low g accelerometer

Figure 17: USB GPS Sensor

The pendulum, rods, and weights will all be stored inside the cargo compartment during takeoff. Because everything attaches with 6-32 threaded rods, Velcro, or the carabineer, set-up will only take a few minutes.

The video camera Labpro, accelerometer and laptop will be stowed in the storage container for takeoff and landing. The camera and laptop will then be mounted on opposite sides of glove box for the experiments. This will allow the laptop image to be captured in the video image.

Two operators will be on opposite sides of glove box to independently control the video camera and laptop.

Personal items that will be brought on board the airplane include small vinyl signs/banners for sponsors. These items may be rolled up and stowed when not in use.

Experimental glove box will not free float.

Because the string pendulum only works in tension, the WSDD or pendulum mass may free float (although attached to the string) within the glove box.

8. Structural Verification

The team will use a horizontal RGO provided glove box. The structural analysis of the glove box assembly is already on file.

Several different analyses were conducted to verify the structural integrity of the pendulum frame structure that will be mounted inside the glove box. The first analysis assumes that the entire structure, including corner brackets and joining fasteners, function together as a rigid body. In this analysis, only the bolts that will mount the frame to the mounting plate were analyzed; these are referred to as Bolts A.

Figure 18 and Figure 19 show the bolts (1/4 inch diameter, Bolts A) that will attach the entire structural frame of the experiment to the mounting plate inside the RGO glove box. The stress analysis assumes that the load is evenly distributed among all 16 bolts from the structure into the mounting plate.

The figures also show the bolts that attach the vertical struts of the frame to the horizontal components of the structural frame. This analysis assumes only one bolt from each vertical strut into the adjacent horizontal strut. Shorter horizontal struts were also added to the assembly for stability/rigidity and are accounted for in the total mass of the structure. These struts are shown in the configuration photos provided in the “Equipment Description” section of this document. For “worst case” analysis, however, the additional short horizontal struts were not used in the structural analysis.

The load cases utilized were those provided by the Reduced Gravity Office for the aircraft, Forward 9g’s, Aft 3g’s, Down 6g’s, Up 2g’s, and Lateral 2g’s. The worst case load conditions were utilized when applicable and redundant calculations were not made for lower load cases.

All margins of safety were found to be positive. All load tests showed no failure under applied loads for anticipated maximum loading conditions.

Table 4: Material Properties

Bolt Material Tensile Yield Strength (lbs), $\sigma_{yield, tens}$	Bolt Material Ultimate Tensile Strength (psi), $\sigma_{ult, tens}$	Bolt Shear Strength (psi), $\tau_{y, shear}$	Corner Bracket Allowable Stress (psi)	Aluminum C-channel Tensile Yield Strength (psi)	Aluminum C-channel Ultimate Tensile Strength (psi)
Bolt material property data	Bolt data sheet, McMaster-Carr	Assumed as ~60% bolt ultimate tensile strength	6061 T6 aluminum material property data	5052 aluminum material property data (Matweb.com)	5052 aluminum material property data (Matweb.com)
36,000	60,000	36,000	60,000	31,000	38,000

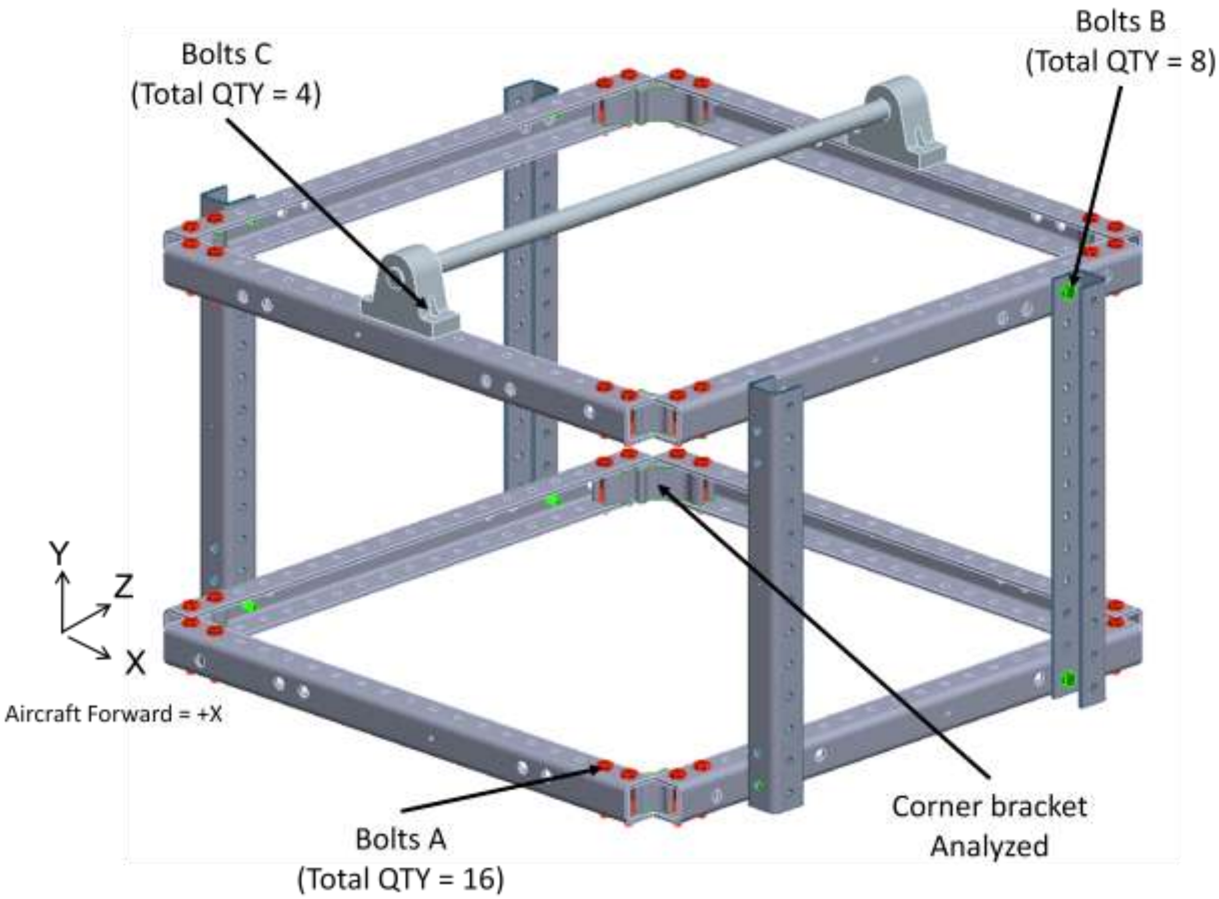


Figure 18: Iso View of Bolt Locations for Stress Analysis

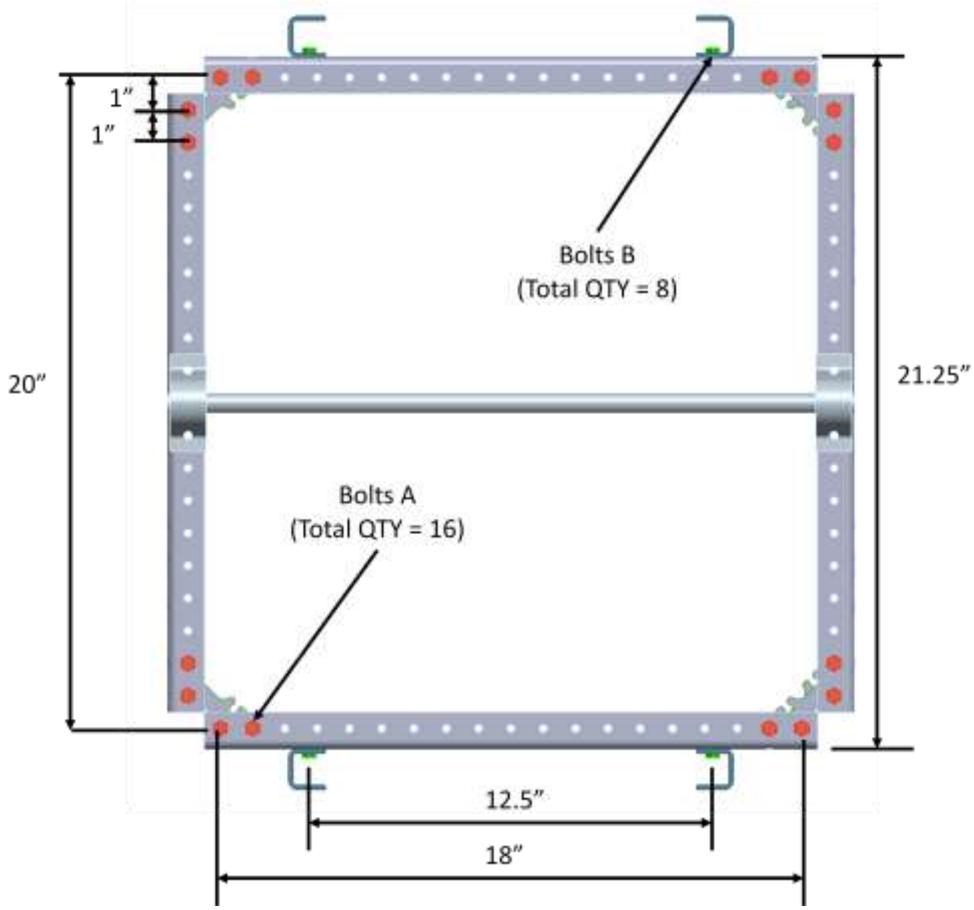


Figure 19: Top View of bolt locations for stress analysis

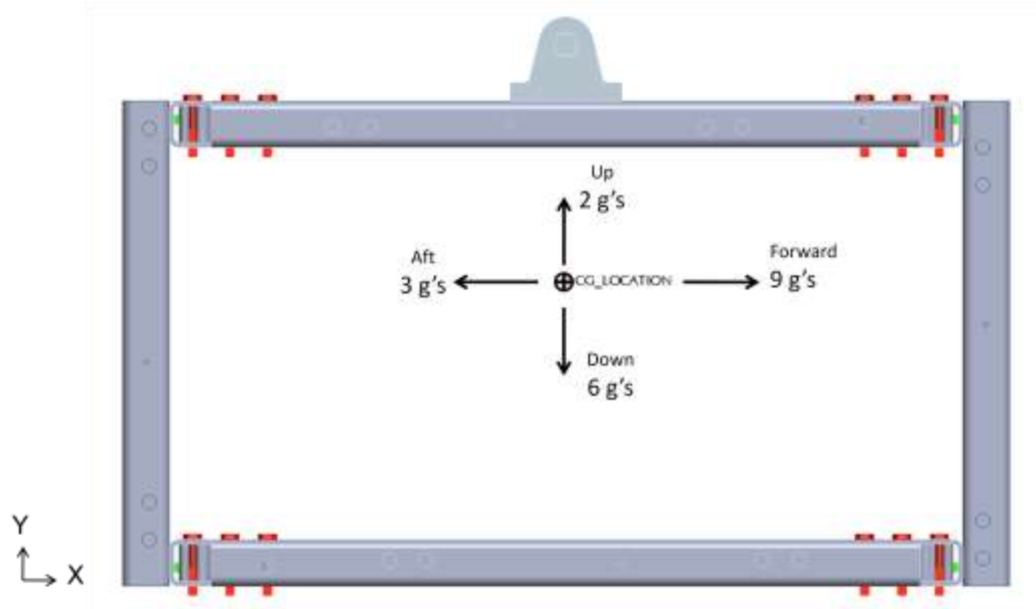


Figure 20: Overview of Load Cases with respect to frame structure (Aircraft Forward to right on page, X-direction)

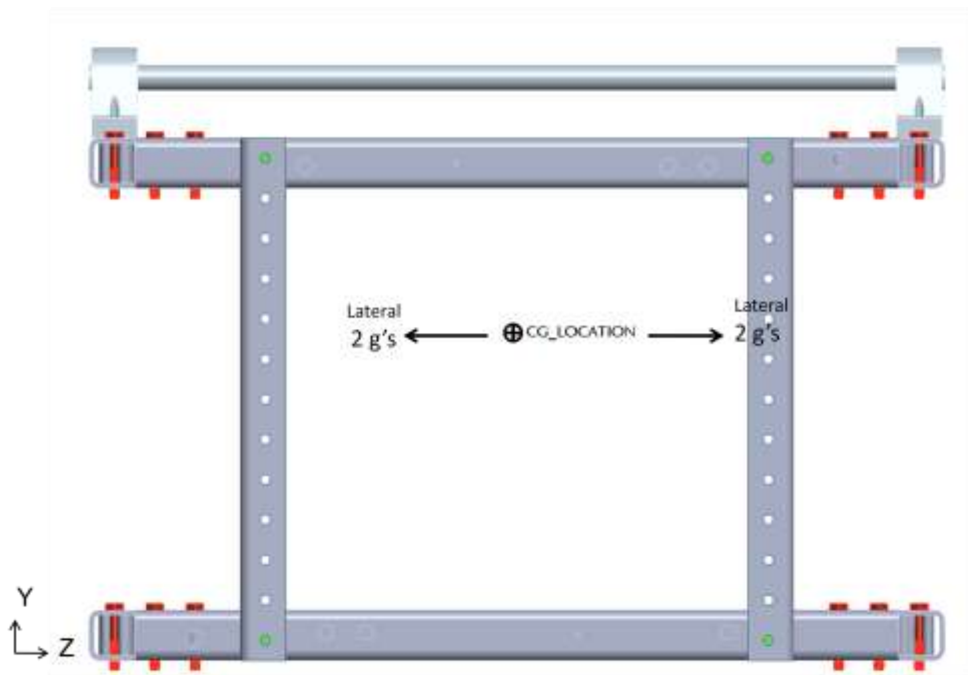


Figure 21: Overview of Load Cases with respect to frame structure (Aircraft Forward into page)

8.1. Analysis of Frame Structure Assembly as if Rigid

8.1.1. Bolt A Analysis: Connects frame structure to RGO glove box mounting plate

For analyzing the bolts that attach the frame structure to the mounting plate inside the glove box, the 9g's forward loading was utilized as the worst-case load that would impart a moment on the A bolts. Because the bolt spacing is symmetric about the center of gravity in the direction of the YZ plane and the XY plane, the moment induced on the A bolts from the 3g's aft loading and the 2g's lateral loading would be lower than the moment induced on the A bolts from the 9g load case. Therefore, only the 9g load case was analyzed for horizontal loading.

Both vertical load cases (6g's down and 2g's up) were analyzed for the tensile load applied to the A bolts.

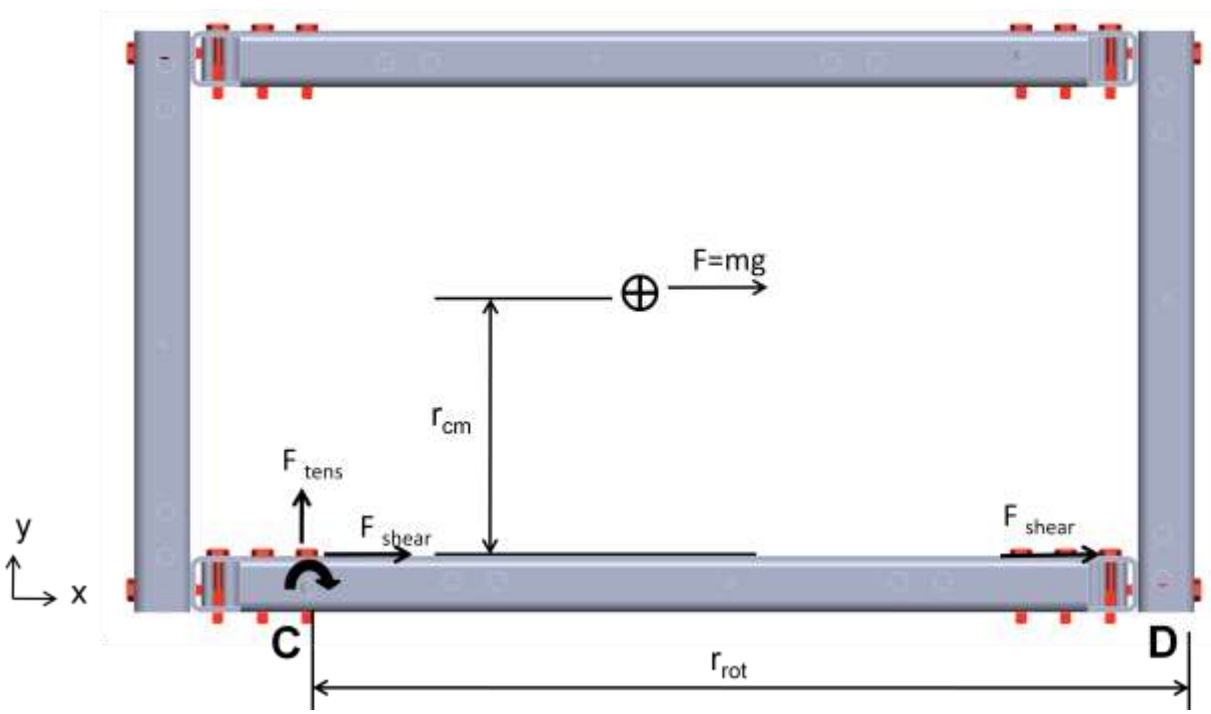


Figure 22: Bolts A Forward Loading (Aircraft Forward to right on paper)

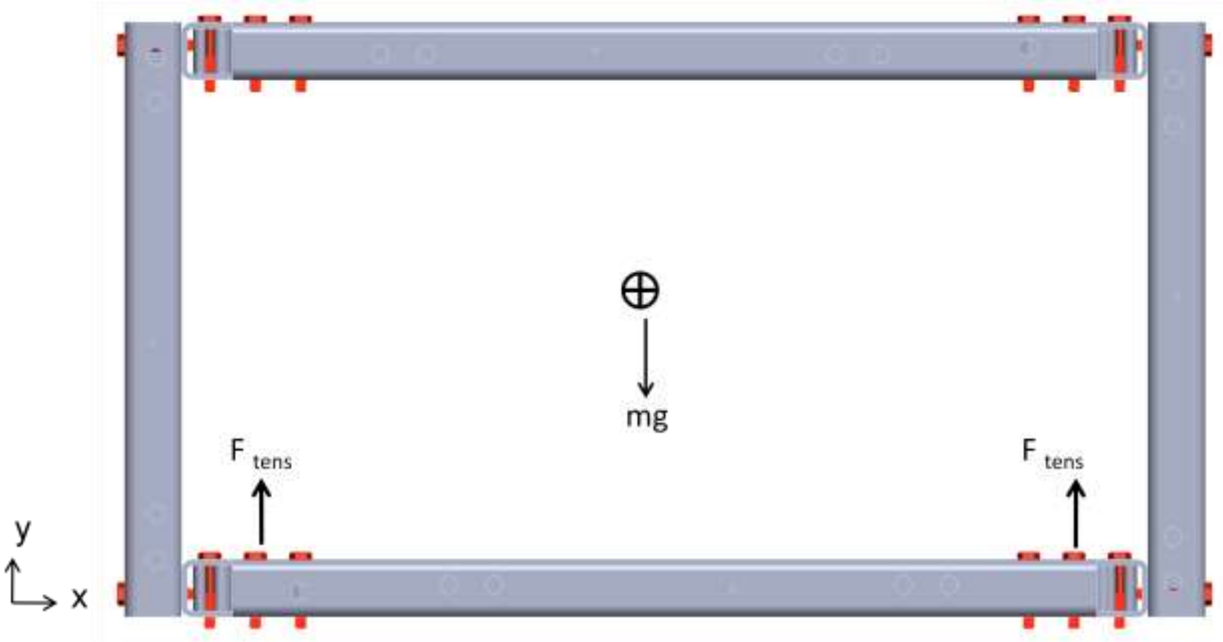


Figure 23: Bolts A Vertical loading (Aircraft Forward to right on paper)

Calculations for Tensile Stress in Bolts A due to forward loading (see Figure 22 and sketch below):

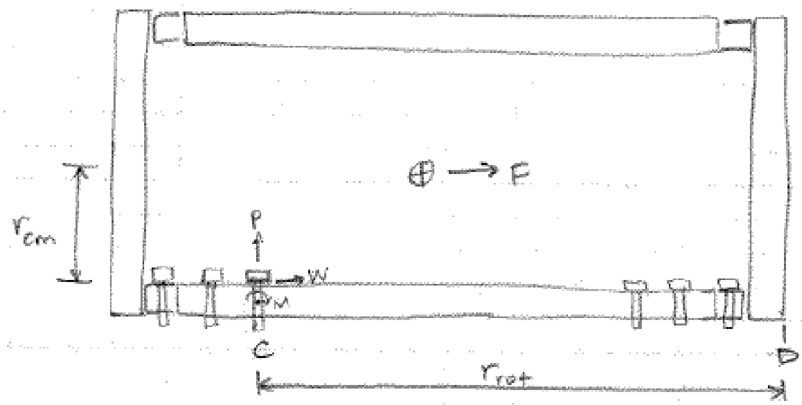
Bolt A Analysis – Bolts connecting Frame Assembly to glove box mounting plate.

Total number of bolts from frame to plate, $N = 16$

Maximum Forward Load = 9 g's

Frame mass, m = 18 lb

Factor of Safety, $FS = 2$



Distance from bolt head to center of mass, $r_{cm} = 7.5$ in

Distance from bolt A to tipping point, $r_{rot} = 19.875$ in

$F = mg = 9(2)(18 lb) = 324$ lbf

Assumptions:

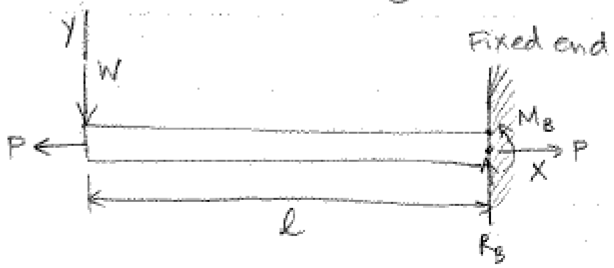
For shear loads:

1) Each bolt experiences uniform applied load, W.

For tipping moment:

2) Frame tips along edge located at point D.
3) The 8 bolts on the right hand side of the Free Body Diagram offer no support against tipping.
4) The 8 bolts on the left hand side are all located at point C (shortest lever arm), and each bolt experiences the same axial force, P.
5) Bolt acts as a beam, fixed at threaded end and free at head.
6) Applied load W, acts at half the height of the C-channel.

Roark's Formulas for Stress and Strain was used to calculate the combined bending moment, M, from axial tension plus lateral loading (p. 242, 7th Edition)



M_B ≡ Reaction moment at fixed End
R_B = Reaction shear force at fixed end
ℓ = Bolt lever arm

$$M = \frac{\theta_A P}{k} F_2 + LT_M$$

$x = \ell$
$a = 0$

$$\theta_A = \frac{W}{P} \cdot \frac{C_{a3}}{C_1}$$

$$W = \frac{F}{16} \Rightarrow W = 20.25 \text{ lbf}$$

To obtain P,

$$+\circlearrowleft \Sigma M_b = 0 = F(r_{cm}) - NP(r_{rot})$$

$$P = \frac{F(r_{cm})}{N(r_{rot})} = \frac{324 \text{ lbf } (7.5 \text{ in})}{8 \; (19.875 \text{ in})}$$

$$P = 15.28 \text{ lbf}$$

$$C_{a3} = \cosh(k\ell) - 1$$

Assuming applied load W acts at ½ height of c-channel.

$$\ell = \frac{1.25 \text{ in}}{2} = 0.625 \text{ in}$$

$$k = \left(\frac{P}{EI}\right)^{1/2}$$

d = 0.201" = minimum thread Ø of bolt

$$E = 30 \times 10^6 \text{ psi}$$

$$I = \frac{\pi}{64}(0.201 \text{ in})^4 = 8.01 \times 10^{-5} \text{ in}^4$$

$$k = 2.522 \text{ in}^{-1}$$

$C_{a3} = \cosh(2.522\ in^{-1} \cdot 0.625\ in) - 1$

$C_{a3} = 1.52$

$C_1 = \cosh(k \cdot l) = 2.52$

$\theta_A = \frac{W}{P} \cdot \frac{C_{a3}}{C_1} = \frac{20.25\ lbf}{15.28\ lbf}\left(\frac{1.52}{2.52}\right)$

$\theta_A = 0.799$ rad

$F_2 = \sinh(k \cdot l) = 2.314$

$LT_M = -\frac{W}{k} \cdot F_{a2}$

$F_{a2} = \sinh(k \cdot l) = 2.314$

$LT_M = -\frac{20.25\ lbf}{2.522\ in^{-1}}(2.314) = -18.59$ in·lbf

$M = \frac{\theta_A P}{k} F_2 + LT_M = \frac{0.799\ (15.28\ lb)\ (2.314)}{2.522\ in^{-1}} - 18.59$ in·lb

$M = -7.37$ in-lbf (Moment occurs in opposite direction shown.)

Total tensile stress $\sigma_T = \sigma_M + \sigma_P$

stress from bending moment $\sigma_M = \frac{My}{I}$ where $y = \frac{1}{2}d = 0.10$ in

Stress from pure tension $\sigma_P = \frac{P}{A}$

$\sigma_M = \frac{(7.37\ in\text{-}lbf)(0.10\ in)}{8.01 \times 10^{-5}\ in^4} = 9247$ psi

$\sigma_P = \frac{15.28\ lbf}{0.0317\ in^2} = 482$ psi

$\sigma_T = 9{,}729$ psi

Margin of Safety $MS = \frac{\sigma_T}{\sigma_{ult,tens}} - 1 = \frac{9{,}729}{60{,}000} - 1$

$\boxed{MS = 5.17}$

Calculations for Tensile Force in Bolts A due to vertical loading (see Figure 23):

Sum forces in the y direction and set equal to zero, where N is the number of bolts in tension:

Solving for F_{tens}:

Tension/compression from vertical loading, Ftens				
	Weight, m (lbm)	g (with FS=2)	Number of bolts, N	Total Axial Force (lbf)
				=m*g/N
Up	18	4	16	4.5
Down	18	12	16	13.5

From table above, maximum axial force per bolt from pure vertical loading is 14 lb.

Calculated Margin of Safety per bolt for Bolts A under maximum tensile load from vertical loading:

Bolt Head Compression Tearout				
Minimum Area, A (in^2)	Max Tensile Force, Ftens (lbf)	Stress, σ_{max} (psi)	Allowable Stress, $\sigma_{ult,tens}$ (psi)	Margin of Safety
$= \pi * r \wedge 2$		$= F_{tens}/A$		$= \sigma_{tens,ult}/\sigma_{max} - 1$
0.0317	14	425.45	60000	**140.03**

Calculations for Shear Force in Bolts A due to forward, lateral, and aft loading (see Figure 22):

Sum forces in the x direction and set equal to zero, where N is the number of bolts in shear:

Solving for F_{shear}:

—

Maximum total shear load reacted by the frame structure (all N bolts combined) is F_{shear} = mg

Shear Load, F_{shear}				
	Weight, m (lbm)	g (with FS=2)	Total shear force (lbf) = mg	Shear force per bolt (lbf) = mg/N
Forward	18	18	324	20.25
Lateral	18	4	72	4.5
Aft	18	6	108	6.75

Maximum total possible shear load = 324 lbf

Maximum possible shear load per bolt = 20.25 lbf

Calculated Margins of Safety per bolt for Bolts A under maximum shear loads:

Assuming that the total shear load is applied to only one bolt:

Shear Stress Margin of Safety				
Minimum Area, A (in^2)	Max Shear Force, F_{shear} (lbf)	Shear Stress, τ_{max} (psi)	Allowable Stress, $\tau_{shear,ult}$ (psi)	Margin of Safety
= π*r^2		= Fshear/A		= τ_{ult}/τ_{max} - 1
0.0317	324	10,210.88	36,000	**2.53**

Assuming that the total shear load is distributed among all 16 bolts:

Shear stress margin of safety				
Minimum Area, A (in^2)	Max Shear Force, F_{shear} (lbf)	Shear Stress, τ_{max} (psi)	Allowable Stress, $\tau_{shear,ult}$ (psi)	Margin of Safety
= π*r^2		= Fshear/A		= τ_{ult}/τ_{max} - 1
0.0317	20	638.18	36,000	**55.41**

Calculated margin of safety for bearing stress in c-channel:

Bearing Stress						
C-channel thickness, t	Bolt diameter, d (in)	Bearing Area (in^2)	Max possible load, F_{shear} (lbf)	Max bearing stress, σ_{max} (psi)	Allowable Stress of c-channel, σ_{ult} (psi)	Margin of Safety
= t * 2		= t * d		= F_{shear}/A		= $\sigma_{ult,tens}/\sigma_{max}$ - 1
0.25	0.201	0.0503	324	6447.8	38,000	**4.89**

8.2. Analysis of Frame Structure Assembly

8.2.1. Bolt B Analysis: Connects vertical c-channel components to frame structure

For analyzing the bolts that attach the vertical struts of the frame structure to the horizontal struts, the 9g's forward loading was utilized as the worst-case load that would cause the frame to parallelogram (deform) and impart a tensile load on the B bolts. Because the bolt spacing is symmetric about the center of gravity in the direction of the YZ plane and the XY plane, the load imparted on the B bolts from the 3g's aft loading would be lower than the moment induced on the A bolts from the 9g load case.

Both vertical load cases (6g's down and 2g's up) were analyzed for the shear load applied to the B bolts.

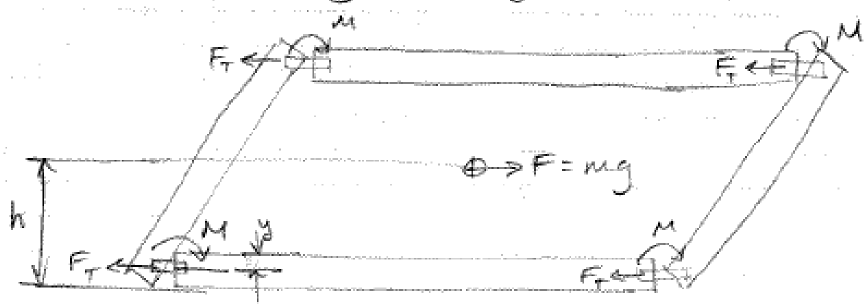
Calculations for Tensile Force in Bolts B due to forward loading:

Assumptions:

- Base of frame is fixed to mounting plate and vertical struts are forced to rotate due to the applied moment from the forward force.
- Tensile load from bolts during parallelogram motion is significantly greater than shear load resulting from forward force.
- Maximum moment arm is from center of gravity location to base of frame (h distance shown in sketch).
- Rotation between vertical c-channel strut and horizontal c-channel on base frame occurs at the upper edge of the horizontal c-channel (y distance shown in sketch).

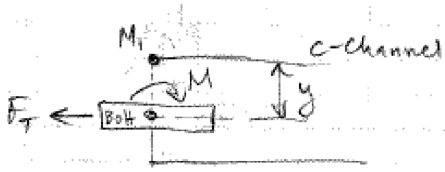
Bolt B Analysis - Bolts connecting vertical struts to frame assembly

Forward Loading causing parallelogram in frame assembly



Assume base of frame is fixed and vertical struts rotate with applied force, causing tensile load in the bolts due to the applied moment.

Assume maximum moment, M, applied at bolts near base of the frame.



Applied moment from forward motion:

$$M = F(h) = mgh$$

$m = 18$ lb
$g = 9g\text{'s}\,(2) = 18g\text{'s}$ (Includes Factor of Safety = 2)
$h = 8.2$ in

$$M = 18(18)(8.2) = 2656.8 \text{ in-lbf}$$

Set reaction moment between c-channel equal to moment applied to bolt and solve for tensile force in bolt.

$$N F_T y = M$$ N = 8 bolts

$$F_T = \frac{M}{Ny}$$ y = reaction distance from c-channel = 0.625

$$F_T = \frac{2656.8 \text{ in-lbf}}{8(0.625 \text{ in})} = 531.4 \text{ lbf per bolt}$$

$$\sigma_T = \frac{F_T}{A}$$

For $\phi = 0.25''$, Stress area of bolts (using minimum thread diameter)
$A = 0.0317\ in^2$

Tensile stress per Bolt

$$\sigma_T = \frac{531.4\ lbf}{0.0317\ in^2}$$

$$\sigma_T = 16{,}762.15\ psi$$

$$\sigma_{allowable} = 60{,}000\ psi$$

$$\text{Margin of Safety } MS = \frac{\sigma_{allow}}{\sigma_T} - 1$$

$$MS = \frac{60{,}000}{16{,}762} - 1$$

$$\boxed{MS = 2.58}$$

Assume for forward loading condition that shear force in joints (bolts) is minimal compared to tensile load.

Calculations for Shear Force in Bolts B due to vertical loading (see Figure 24*):*

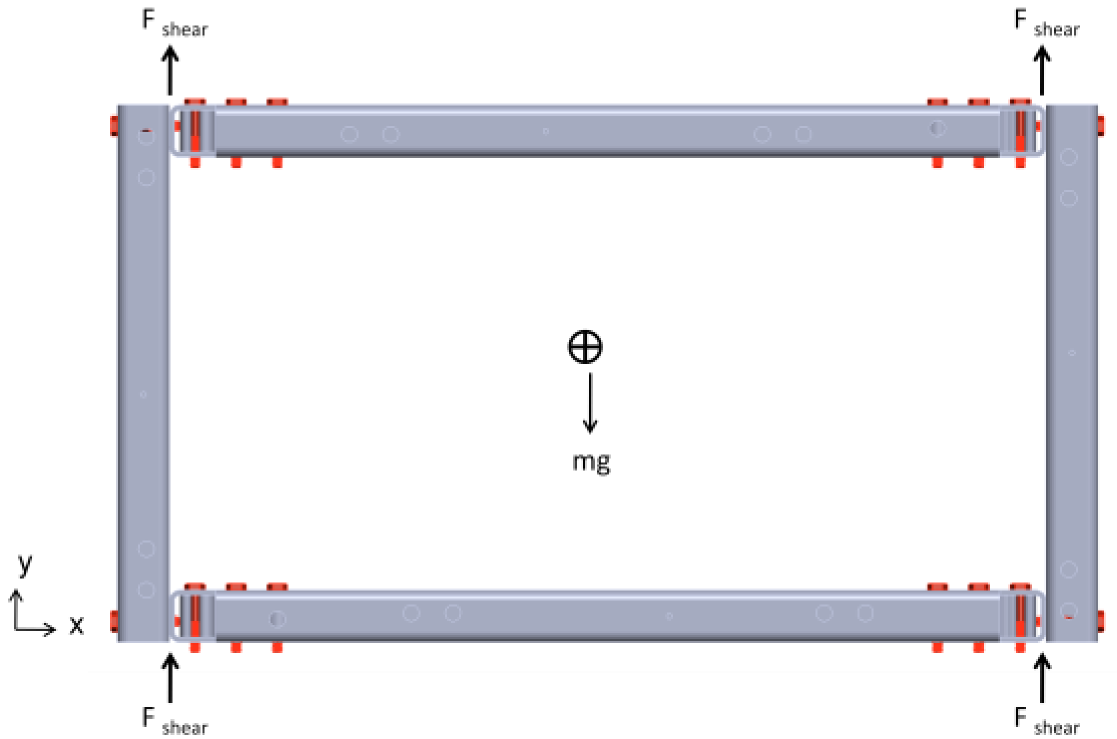


Figure 24: Bolts B vertical loading (Aircraft Forward to right on paper)

Sum forces in the y direction and set equal to zero, where N is the number of bolts in shear:

Solving for F_{shear}:

Shear from vertical loading, Fshear					
	Weight, m (lbm)	Forward g (with FS=2)	Total shear force, $F_{shear,tot}$ (lbf)	Number of bolts, N	Shear force per bolt (lbf)
			=m*g		$=F_{shear,tot}/N$
Up	18	4	72	8	9
Down	18	12	216	8	27

Max possible shear from vertical loading = 27 lbf per bolt

Bearing Stress in C-channel						
C-channel thickness	Bolt diameter, d (in)	Bearing Area (in^2)	Max possible load, F_{shear} (lbf)	Max bearing stress, σ_{max} (psi)	Allowable stress in c-channel, σ_y (psi)	Margin of Safety
= t * 2		= t * d		$= F_{shear}/A$		$= \sigma_y/\sigma_{max} - 1$
0.25	0.201	0.0503	14	268.7	31,000	114.4

8.2.2. Bolt C Analysis: Connects Pendulum Rod Pillow Blocks to Frame Structure

For analyzing the bolts that attach the pendulum rod pillow blocks to the frame structure, the 9g's forward loading was utilized as the worst-case load that would impart a moment on the C bolts. Because the bolt spacing is symmetric about the center of gravity in the direction of the YZ plane and the XY plane, the moment induced on the C bolts from the 3g's aft loading and the 2g's lateral loading would be lower than the moment induced on the C bolts from the 9g load case. Therefore, only the 9g load case was analyzed for horizontal loading.

Both vertical load cases (6g's down and 2g's up) were analyzed for the tensile load applied to the C bolts.

Bolt C Analysis - Bolts connecting pillow blocks to frame structure.
(Pillow blocks hold pendulum rod to frame structure)

Total number of bolts from pillow blocks to frame, $N = 4$

Maximum forward Load = 9 g's

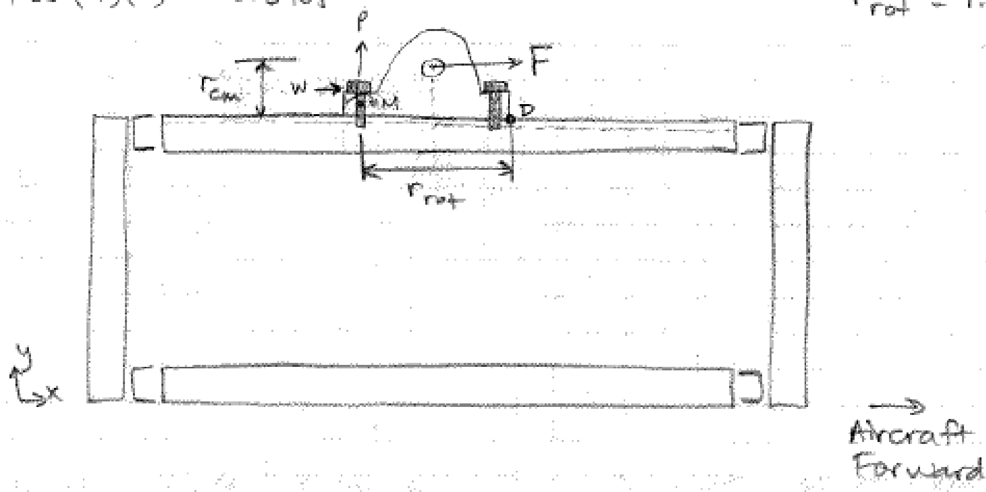
Mass of components on pendulum rod, rod, and pillow blocks
$m = 1.86$ lb

Factor of safety, $FS = 2$

$F = 1.86(9)(2) = 33.5$ lbf

$r_{cm} = 1.75$ in

$r_{rot} = 4.25$ in



Assumptions:

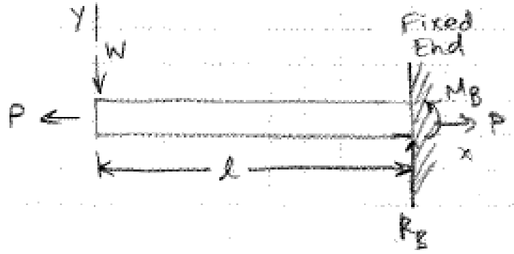
1) Frame structure is rigid. Applied loads to be reacted by C bolts are only from the pillow blocks, pendulum rod, bearing block, and collars that hold the pendulum rod and string pendulum.

2) Each of the 4 bolts experiences uniform applied load, W. Bolts are 1/4"-20, same as Bolts A.

For tipping moment:

3) Pillow blocks tip along edge located at point D.
4) The two bolts (one per pillow block) to the right of the applied force F offer no support against tipping.
5) The two bolts to the left of the applied load each experience the same axial force, P.
6) Applied load W acts at 1/2 the distance of the pillow block thickness plus the C-channel thickness.

Using the same equations as in Bolt A Analysis (Roark's, p.242) to calculate the combined bending moment, M, from axial tension:



M_B = Reaction Moment at fixed end

R_B = Reaction shear force at fixed end

l = Bolt lever arm

$x = l$, $a = 0$

$$P = \frac{F(r_{cm})}{n(r_{rot})} = \frac{(33.5\ lbf)(1.75\ in)}{2(4.25\ in)}$$

$P = 6.9$ lbf

$W = \frac{F}{4} = \frac{33.5\ lbf}{4} \Rightarrow W = 8.4$ lbf

$$M = \frac{\theta_A P}{k} F_2 + LT_M$$

$\theta_A = 0.209$

$k = 1.693$

$F_2 = 0.679$

$LT_M = -3.35$ in-lb

$M = -2.78$ in-lb (Moment occurs in opposite direction)

Total tensile stress $\sigma_T = \sigma_M + \sigma_P$

Stress from Bending moment $\sigma_M = \frac{My}{I}$ where $y = 0.1005$

Stress from pure tension $\sigma_P = \frac{P}{A}$

$$\sigma_M = \frac{(2.78\ in\text{-}lb)(0.1005\ in)}{8.01 \times 10^{-5}\ in^4} = 3{,}481.2\ psi$$

$$\sigma_P = \frac{6.9\ lb}{0.0317\ in^2} = 217\ psi$$

$\sigma_T = 3{,}698$ psi

$$MS = \frac{\sigma_{ult,tens}}{\sigma_T} - 1 = \frac{60{,}000\ psi}{3{,}698\ psi} - 1$$

MS = 15.2

Calculation of Shear stress (Assume 9g load is worst-case)

$$\tau = \frac{W}{A} = \frac{8.4 \text{ lbf}}{0.0317 \text{ in}^2}$$

$$\tau = 263.8 \text{ psi}$$

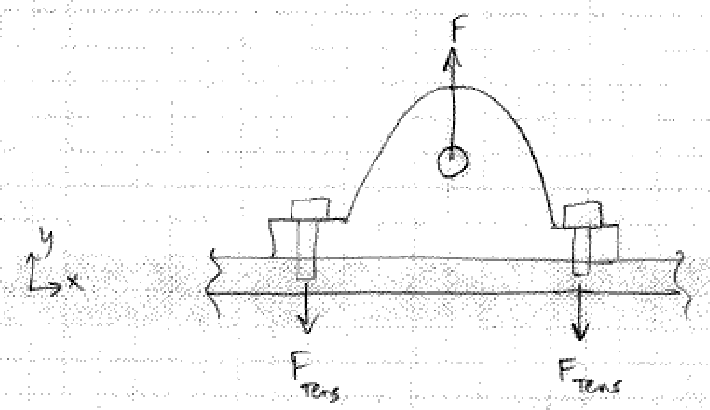
$\tau_{allowable}$ = 60% of bolt tensile strength

$$\tau_{all} = 36,000 \text{ psi}$$

$$MS = \frac{\tau_{allow}}{\tau_{max}} - 1 = \frac{36,000 \text{ psi}}{263.8 \text{ psi}} - 1$$

$$\boxed{MS = 135.5}$$

Tensile Force in Bolts C due to Vertical Loading



$$\uparrow \sum F_y = 0 = F - N F_{Tens} \qquad N = 4$$

(Force includes FS = 2)

$$F_{Tens} = \frac{F}{N}$$

Vertical, Up $\quad F = (1.86 \text{ lb})(2 g\text{'s})(2) = 7.44 \text{ lbf}$

$$F_{Tens} = \frac{7.44 \text{ lbf}}{4} = 1.86 \text{ lbf}$$

Vertical, Down $\quad F = (1.86 \text{ lb})(6 g\text{'s})(2) = 22.32 \text{ lbf}$

$$F_{Tens} = \frac{22.32 \text{ lbf}}{4} = 5.58 \text{ lbf}$$

Max F_{Tens} = 5.58 lbf

$$\sigma = \frac{F_{Tens}}{A} = \frac{5,58 \text{ lbf}}{0.0317 \text{ in}^2}$$

$$\sigma = 175.85 \text{ psi}$$

$$MS = \frac{\sigma_{allow}}{\sigma_{max}} - 1$$

$$MS = \frac{60,000 \text{ psi}}{175.85 \text{ psi}} - 1$$

$$\boxed{MS = 340.2}$$

Bearing Stress (Assume entire applied load goes through only 1 bolt)

C-channel thickness $t_1 = 0.125$ in

Pillow block thickness $t_2 = 0.625$ in

Bolt diameter (min) $d = 0.201$ in

Minimum bearing Area occurs in C-channel

$$A = t_1 * d = 0.0251 \text{ in}^2$$

Max shear Load $F_{shear} = 33.5$ lbf

Max bearing stress $\sigma_{max} = \frac{F_{shear}}{A} = \frac{33.5 \text{ lbf}}{0.0251 \text{ in}^2}$

$$\sigma_{max} = 1,332.5 \text{ psi}$$

$$\sigma_{allow} = 38,000 \text{ psi}$$

$$MS = \frac{\sigma_{allow}}{\sigma_{max}} - 1$$

$$\boxed{MS = 27.5}$$

8.3. Analysis of Frame Structure Components

8.3.1. Corner Bracket Analysis

A picture of the aluminum corner bracket is provided in Figure 6. Because of the complex geometry of the corner bracket, ProEngineer/ProMechanica (referred to as Mechanica) was used to conduct a basic stress analysis. A single bracket was analyzed using the load of the entire frame structure. The corner bracket analyzed is shown in Figure 18. The analysis shows a positive margin, which provides a conservative analysis because in reality one corner bracket will likely not be taking the entire load of the frame structure.

Within Mechanica, a “Total Load at Point” was applied from the center of mass location (as the point) to all four bolt interface surfaces of the corner bracket. Figure 25 shows the 4 bolt interface surfaces that were used as surfaces to which the load at point was applied for the analysis. The bottom surface (one of the surfaces in contact with the c-channel frame) was used as a fixed boundary condition and assumed that it would not move inside the c-channel. The total load applied was in the X direction, and the forward load case of 9g’s was used. Thus, the applied load was equal to the weight of the entire frame structure multiplied by 18 (9g’s times factor of safety of 2). Because the corner brackets are in each corner, the 2g lateral load cases would result in lower stresses on the corner brackets. This was verified by an additional Mechanica analysis.

The aft load case of 3g’s was also applied to the corner bracket to ensure the stress was not higher under that load condition than the forward load case. The max stress determined in the Mechanica analysis was found to be lower than the forward load case, so the 9g’s forward load case was the “worst case” load condition analyzed, and thus used to determine the minimum margin of safety for the corner bracket.

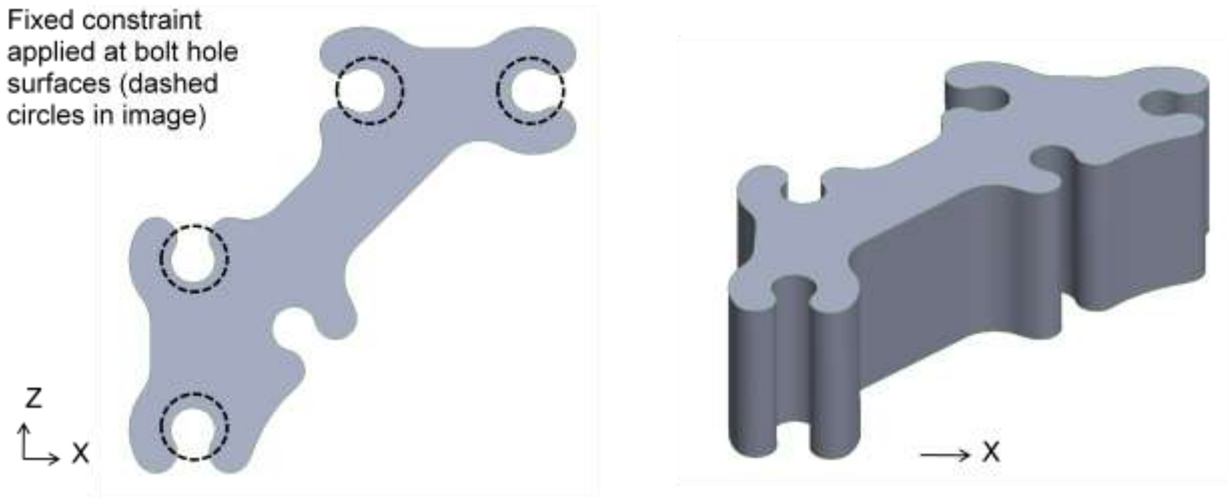


Figure 25: Corner bracket constraints used in Mechanica Analysis

The magnitude of the max principle stress determined by the ProEngineer ProMechanica analysis was found to be 25.5 ksi. As shown in the stress plots in Figure 26, this maximum stress is a small localized region, a stress concentration on the edge of one of the bolt hole surfaces. However, this maximum value was still used to determine the margin of safety as a conservative case.

Max stress (Mechanica analysis), σmax (psi)	Allowable stress, σy (psi)	Margin of Safety
		= σy/σmax - 1
25,500	60,000	1.4

The minimum margin of safety calculated for the bolts and the corner bracket of this experiment was a positive margin of approximately 1.4, with conservative assumptions given the actual configuration of the experiment structure.

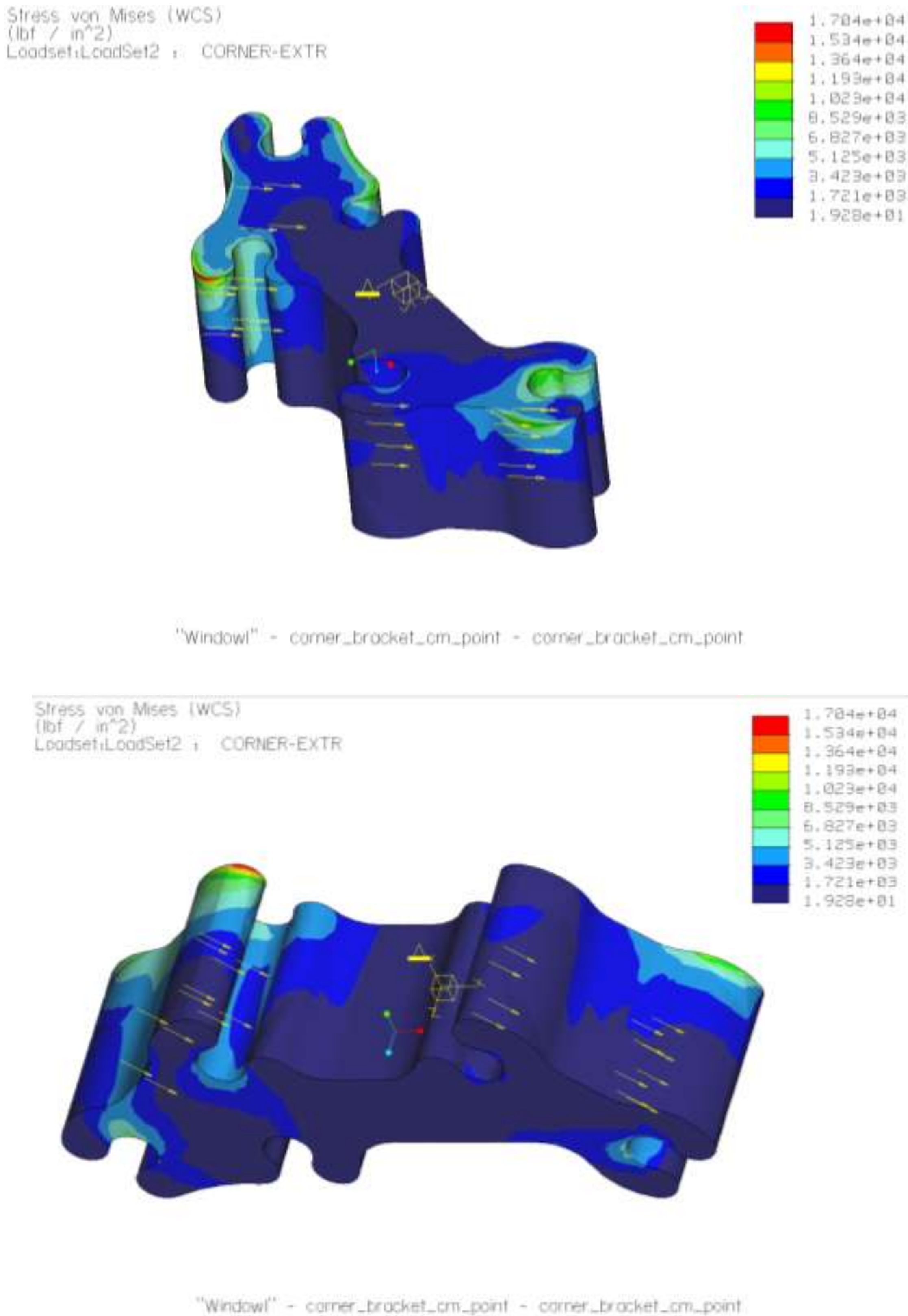


Figure 26: Mechanica Stress Plot for Corner Bracket

8.4. Pull Tests of Pendulum Rod and Pendulum Components

Several pull tests were conducted to ensure the pendulum rod and pendulum would be secure during the anticipated load cases. Table 5 shows all of the tests conducted for the corresponding maximum anticipated load cases. For all loads less than 12.5 pounds, the WDSS was used to apply the load if possible. The WDSS contains a force sensor, so the output force was read as the loads were applied.

Table 5: Pull Tests Conducted for Maximum Anticipated Load Cases

Test Components	Pull Weight (lb)	Direction
Pendulum rod will not translate axially	4.5	Lateral (axial along pendulum rod)
Bearing block will not translate axially	9.3	Lateral (axial along pendulum rod)
Pendulum string will not break	12.0	Down, forward, aft, or up (3g's during parabolas)
Standoffs to connect rigid rod pendulum will not break	12.0	Down, forward, aft, or up (3g's during parabolas)

To ensure the pendulum rod will not translate axially inside the pillow blocks, an axial load of 5 pounds was applied to the pendulum rod. The applied force accounts for the bearing block, the pendulum rod, and the collars restraining the pillow blocks (total weight of 1.12 lb) multiplied by 4 (2g's lateral loading with a factor of safety of 2). The application of this force, using the WDSS, is shown in Figure 27.

To ensure the bearing block will not translate axially, a total load of 9.5 pounds was applied axially (in the lateral direction). This force is based on the weight of the bearing block multiplied by 4 (2g's lateral times factor of safety of 2). The application of this load is shown in Figure 28.

Pull tests for the string pendulum and the rigid pendulum are shown in Figure 29 and Figure 30, respectively. The applied load for each test was 12 pounds, derived from the maximum pendulum weight of 2 pounds multiplied by 3g's (during parabolas) times a factor of safety of 2.

The hardware did not fail under any of the applied forces. Therefore, all pull tests showed that the hardware should be safe under maximum anticipated loading conditions.

Figure 27: Application of Lateral (Axial) Force on Pendulum Rod

Figure 28: Application of Lateral Force on Bearing Block

Figure 29: Pull Test for String Pendulum

Figure 30: Pull Test for Rigid Pendulum

9. Electrical Analysis and Verification

Aircraft power is required for some of the electronics for this experiment. The team will provide a power strip that will plug into the airplane extension cord. The power strip will serve as the electrical "kill switch" and will be secured external to the glove box in such a way that it is easily accessible but where it should not easily be kicked or touched during flight.

The electronic equipment used in this experiment is listed in Table 3. The WDSS is battery operated. A diagram showing the electrical components and connections is shown in the following figure.

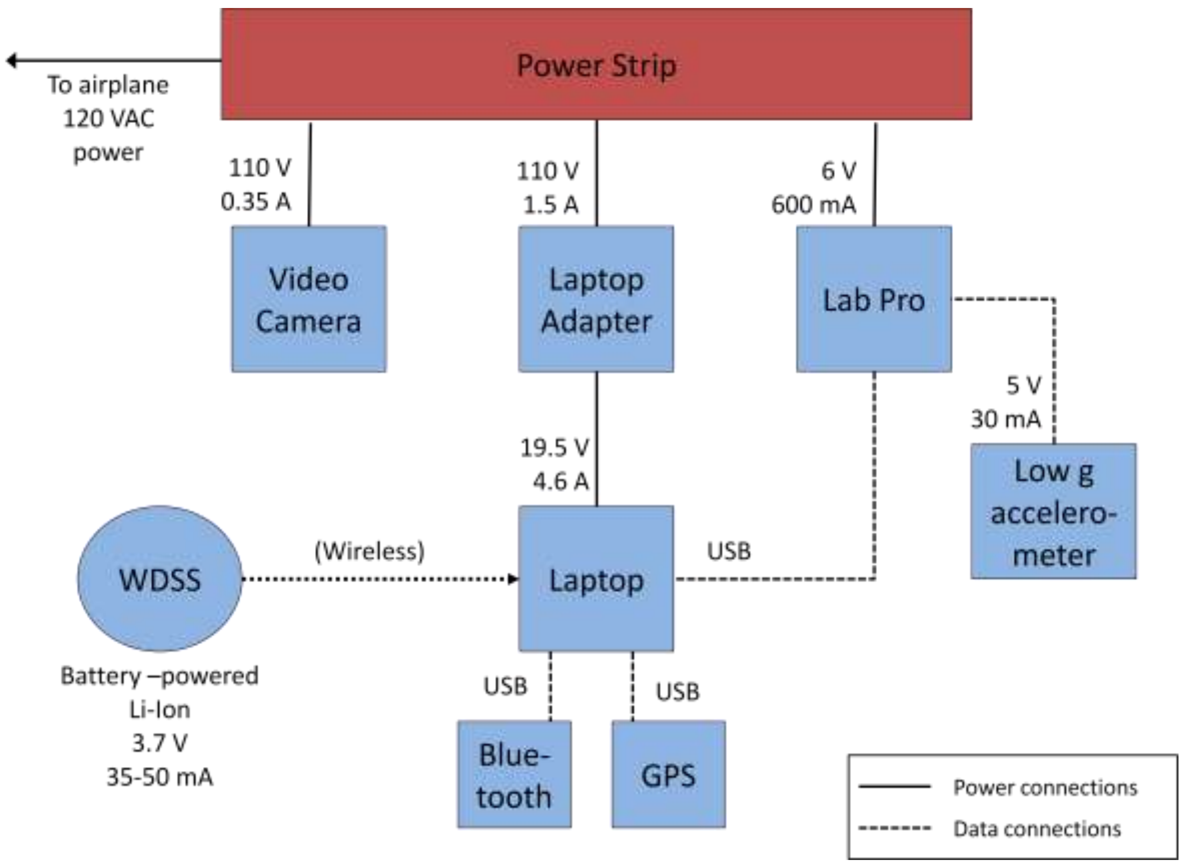


Figure 31: Electrical power Schematic

Table 6: Electrical load table

Power Source Details	Load Analysis
Power Cord A	
Voltage: 120 VAC, 60Hz	Dell Inspiron Laptop 1.5 amps
Wire Gauge: 12	Vernier Labpro 0.01 amps
Max Outlet Current: 20 amps	Total Current Draw: 1.01 amps

As previously specified, the video camera and laptop will be mounted on opposite sides of the glove box. Cords will be secured with Velcro and/or tape as required.

The Sony HandCam is being replaced by a battery powered Cisco FlipCam which is powered by a 3.7 V Li-Ion Battery.

10. Pressure Systems

This experiment does not contain a pressure vessel/system.

11. Laser Certification

This experiment does not use any laser systems.

12. Parabola Details and Crew Assistance

The majority of the data for this experiment will be collected during the microgravity parabolas. The expected 28 microgravity parabolas plus the lunar and Martian gravity parabolas will be sufficient for the successful completion of the experiment.

A minimum of one parabola at lunar gravity and one parabola at Martian gravity per flight are required (Data collected for at least two parabolas total at both lunar and Martian gravity are desired).

A total of 4 different hyper gravity parabolas at less than the maximum of 1.8 g are required (to add variety in the hyper gravity data sets).

13. Institutional Review Board

This experiment does not require an institutional review board.

14. Hazard Analysis

Table 7 summarizes the hazard analysis checklist and includes Risk Assessment Codes (RAC's) based on the consequence and likelihood estimate described by the Reduced Gravity Office Hazard Analysis document. A value of "0" in the Hazard Risk Assessment Code column indicates the Hazard Source is not applicable for this experiment. As described by the RGO Hazard Analysis Document, a RAC of 4-7 is "Acceptable with controls." Any potential hazards identified for this experiment were determined to have RAC's within the acceptable range as described above (all RAC's are greater than 4).

Table 7: Hazard Analysis Checklist

Hazard Risk Assessment Code	Hazard Source	Controls/Comments
0	Flammable/combustible material, fluid (liquid, vapor, or gas)	
0	Toxic/noxious/corrosive/hot/cold material, fluid (liquid, vapor, gas)	
0	High pressure system (static or dynamic)	
0	Evacuated container (implosion)	
0	Frangible material	
0	Stress corrosion susceptible material	
7	Inadequate structural design (i.e., low safety factor)	While the analysis shows the frame to be adequately designed, components of the frame could come apart during flight/the control for this hazard is to securely torque the bolts and to provide locking features on fasteners mounting the structural frame to the attachment plate. The RGO provided glove box will also contain the components in the unlikely event of a failure due to inadequate structural design.
0	High intensity light source (including laser)	
0	Ionizing/electromagnetic radiation	
0	Rotating device	
6	Extendible/deployable/articulating experiment element (collision)	WDSS or weights attached to the pendulum may become loose during flight. The pendulum itself could potentially become loose during flight. The largest pendulum bob mass is approximately 1.1 lbs/ the control for this collision hazard is the

		RGO glove box.
0	Stowage restraint failure	
0	Stored energy device (i.e., mechanical spring under compression)	
0	Vacuum vent failure (i.e., loss of pressure/atmosphere)	
0	Heat transfer (habitable area over-temperature)	
0	Over-temperature explosive rupture (including electrical battery)	
0	High/Low touch temperature	
5	Hardware cooling/heating loss (i.e., loss of thermal control)	The laptop could overheat/the control for this hazard is to provide proper ventilation for the laptop fans by allowing air to flow around the computer during flight. The team will also monitor the laptop to ensure it does not overheat.
0	Pyrotechnic/explosive device	
0	Propulsion system (pressurized gas or liquid/solid propellant)	
0	High acoustic noise level	
0	Toxic off-gassing material	
0	Mercury/mercury compound	
0	Other JSC 11123, Section 3.8 hazardous material	
0	Organic/microbiological (pathogenic) contamination source	
6	Sharp corner/edge/protrusion/protuberance	The corners of the RGO provided glove box may be sharp/the control for this hazard will be to cover the corners of the box with padding for flight. The structural frame mounted inside the glove box may have sharp edges/corners/the control for this hazard is to file down the edges/sharp corners and cover any remaining sharp corners with padding.
0	Flammable/combustible material, fluid ignition source (i.e., short circuit; under-sized wiring/fuse/circuit breaker)	
0	High voltage (electrical shock)	
0	High static electrical discharge producer	
6	Software error or compute fault	There is a slight chance that the laptop computer could fail to operate properly. There is also the potential for the video camera or the other instrumentation to fail to operate properly. The video camera provides visual data collection and can be

		used as backup data for pendulum analysis in case of laptop software or computing fault. The instrumentation provides somewhat redundant data collection between the WDSS, low g accelerometer, and USB GPS system. The experiment was designed to have the video camera as the primary source for data collection. The control for this hazard is built into the experiment based on some redundancies in the electronic data collection.
0	Carcinogenic material	
0	Other	

15. Tool Requirements

External tools that may be required are a 7/16" wrench and a 7/16" nut driver. These tools will likely only be used as ground support equipment and should not be required on board the aircraft during the flight.

The experiment structure and other required pieces will be attached to the bottom of the glove box before loading the assembly on to the aircraft. The electronic components that will be mounted external to the RGO provided glove box will be properly stowed during takeoff and landing and will not require tools to secure them to the box for the experimentation phase of the flight.

16. Photo Requirements

One fixed camera pole is requested to mount a Sony HandyCam video camera. The video camera will be mounted on the outside of the glove box and will be used to record data for all experiments. The experiment videos will serve as a primary data collection method in conjunction with the WDSS.

One still photographer and one videographer are requested to document flight activities on both days.

17. Aircraft Loading

The experiment can be loaded onto the airplane with a forklift or lifting pallet. All pieces will be contained within an RGO glove box. The pieces will be secured onto the floor of the box, so there is no particular manipulation strategy required. The total weight of the experiment will be approximately 28 lbs (including electronics that will be stowed during takeoff and landing) in addition to the weight of the RGO horizontal glove box.

18. Ground Support Equipment

Other equipment required at Ellington field will be RGO approved tape, Velcro, and scissors (to cut Velcro pieces). A combination of tape and Velcro will be used to secure the experiment pieces to the RGO glove box.

19. Hazardous Materials

There will be no toxic, corrosive, explosive or flammable materials as part of this experiment.

20. Materials Safety Data Sheet

No hazardous materials, chemicals, or fluids are included in this experiment; therefore Materials Safety Data Sheets are not required.

21. Experiment Procedures Documentation

21.1. Equipment Shipment

The team will ship the experiment to Ellington Field.

21.2. Ground Operations

- Unpack shipped experiment pieces on work table at the hangar in Ellington Field
- Place experiment pieces inside glove box after a visual inspection
- Practice in-flight operations

21.3. Loading

- Use a forklift or lifting pallet to load glove box onto the airplane
- Stow laptop computer, video camera, LabPro sensor unit, low g accelerometer, and GPS sensor for takeoff
- Place personal items above seats for take-off

21.4. In-Flight

Experiments will be conducted according to

Table 2. Data will be taken in both microgravity and hyper gravity portions of the flight.

Flyer #1 will be responsible for changing the pendulum length and masses, setting the pendulum in motion (by hand), and ensuring the video camera is recording properly.

Flyer #2 will start and stop the laptop software for data collection as required. Flyer #2 will also be responsible for counting parabolas and informing Flyer #1 about the following experiment conditions (pendulum length and mass of pendulum bob).

- **Before parabola**:
  - Flyer # 1 will start camcorder
  - Flyer # 2 will start data collection on laptop computer
  - Flyer #1 will set pendulum in motion by hand by reaching using the gloves on the glove box
  - Flyer #1 will move the gloves out of the way from the experiment (pull gloves as close to outside edges of glove box as possible)
- **After parabola**:
  - Flyer # 2 will stop data collection on laptop computer and save data file
  - Flyer #1 will stop the pendulum motion by hand and change the mass or length of the pendulum as necessary
- **Before landing/After completing all experiments**:
  - Flyer # 1 will stop video camera and shut down for stowing
  - Flyer # 2 will ensure data collection on laptop computer then shut down the laptop for stowing
  - Flyer #1 will ensure all components inside the glove box are secured for landing
  - Flyer #2 will stow all electronics and equipment external the glove box and verify the experiment is secured for landing

The team may use any remaining parabolas for other outreach activities. Time permitting, some of the personal items listed in previous sections will be used during this portion.

21.5. Post-Flight

- Re-charge WSDD batteries, laptop computer batteries, and video camera batteries
- Back up flight experiment data onto flash drive or second computer

21.6. Off-Loading

The experiment will be removed from the airplane using a forklift or lifting pallet by the crew. The team will remove all experiment equipment from the RGO glove box and pack it for return shipment.

22. Bibliography

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