MAE 4344 Senior Design

MD-80 Tab Actuation Project

Final Report

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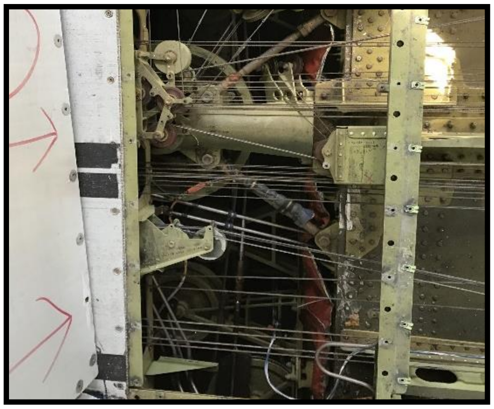
1.0 Problem Statement

The College of Engineering at Oklahoma State University owns an MD-80 aircraft. This plane is fully mechanical and is used for educational purposes by the university. Dr. James Kidd, an engineering professor at OSU, is working to integrate a flight simulator into the fuselage of the plane. This simulator would aid students' understanding of the mechanical systems and flight operations in airplanes. Going above and beyond, Dr. Kidd wants his students to be able to see the effects of their piloting in reality as well as in the simulator. The first step in this process is to connect the manually-operated aileron, elevator, and rudder tabs to the flight simulator's controls. Because these tabs are the keys to controlling the plane, seeing them in action would better cement the concepts of flying an airplane into students' minds as they operate the simulator. Currently, the tabs are controlled by a series of pulleys running from the pilot's yoke, under the fuselage flooring, through a series of pulleys and cables to the tabs. Our project consists of designing and installing a system to actuate the tabs of the MD-80 airplane.

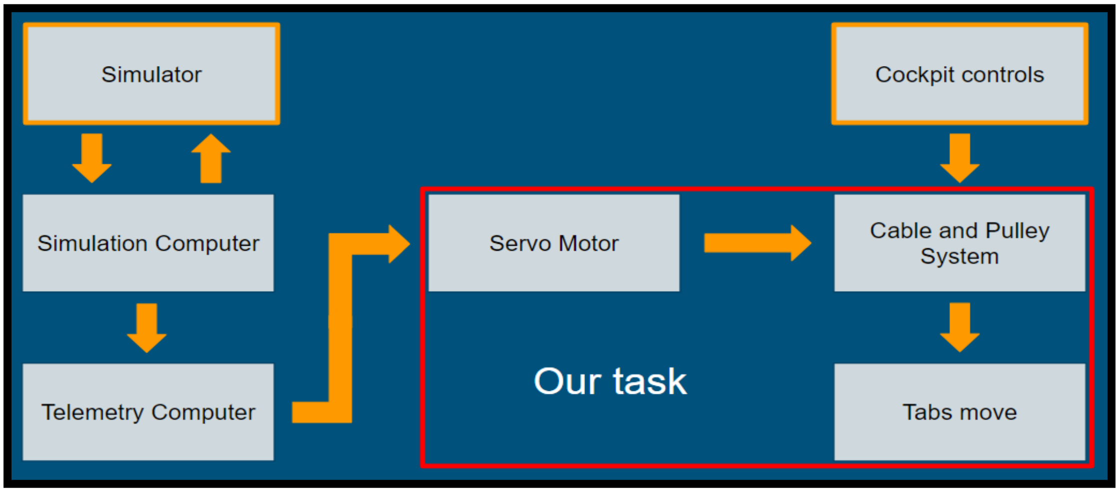
We have designed a system to actuate the aileron tabs, elevator tabs, and rudder tabs. The aileron tabs are located on the wings and actuated when the pilot turns the yoke. Their purpose is to begin creating a pressure difference on each side of the ailerons that eventually actuates the ailerons themselves, which steer the plane by regulating the plane's roll. Likewise, the elevator tabs are located on the tail crosspiece and help actuate the elevators themselves which regulate the plane's pitch. They are actuated when the pilot moves the yoke forward or backward. Finally, the rudder tab is located on the rear, vertical part of the tail. It is actuated via foot pedals in the cockpit. The rudder controls the plane's yaw.

We are working closely with a team of Electrical Engineering Technology seniors (the EET team) to complete our project. The EET team consists of Jonathan Fairchild, Ryan Wheatley, and Shane Lee. The EET team managed the electrical and computer side of the project while we completed the mechanical side. Dr. Kidd and Dr. Taylor oversaw our progress.



2.0 Project Requirements

Dr. Kidd, our client, supplied our project requirements, and we were able to ask him questions to clarify the requirements. Our system was required to actuate all three tab systems (aileron, elevator, and rudder tabs) in a way controlled by the flight simulator. Thus, our project had to integrate with the flight simulator. Our system also needed several safety measures to protect the users, plane, and system itself. Dr. Kidd also specified a one-second movement time from neutral to extreme positions for each set of tabs and that the pilot’s steering and autopilot be negligibly affected by our solution.



2.1 Project Deliverables

Our project deliverables included: a system that meets the above requirements and all documentation of our work and design rationale for the project. The documentation consisted of CAD drawings, design rationale, a user manual, all calculations, and the project budget.

3.0 Plan of Attack

Our plan of attack for our project followed the sequence: define requirements, brainstorm, analyze ideas, choose design and implement, fabricate and install the chosen design, then test and evaluate the final product. Of course, steps one, two, and three were an iterative process. As we brainstormed, we returned to ask Dr. Kidd clarifying questions about our project requirements. And as we analyzed ideas, we discovered weaknesses with our ideas and returned to the brainstorming phase to address those weaknesses. Thus, we generally followed the plan of attack but we constantly brainstormed and

analyzed our ideas in order to find solutions to the issues that surfaced as we moved forward in our design. Some examples of the issues that surfaced: undesirable motor backdrive, important safety features, and change in installation location of the system.

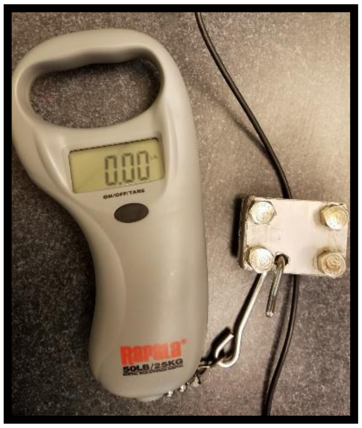
4.0 Description of Work

4.1 Determining Mounting Location

Due to the requirement that the pilot's steering was to remain unaltered, we considered three locations to mount our system: directly to the autopilot, inside the fuselage, and underneath it in the luggage bay. Ultimately we decided to mount our system in the luggage bay, which is located directly underneath center aisle of the fuselage. After discussing the idea of connecting directly to or near to the autopilot with Dr. Kidd, he decided that he wanted the autopilot to remain unaltered as well. Additionally, our only reasonable option for mounting the system in the fuselage would have been to install it in the middle of the aisle. We decided against this because it would be a potential tripping hazard to people walking through the main cabin, and it would be hazardously close to the fuel tank. It would also be aesthetically challenging to hide it next to the simulator. By mounting the motors and pulleys in the luggage bay, the system will be hidden from sight and out of the way of people moving about the cabin. Thus, the luggage bay was our best option for the system's location. Moreover, there is plenty of room in the luggage bay, it is relatively close to the simulator for ease of wiring, and it is easily accessible. This makes it the ideal spot for our system.

4.2 Measuring Forces

To find the required force to move the aileron, elevator, and rudder cables, we designed a system consisting of a small ratchet strap, clamp, and a digital scale. The scale used was an electronic



fishing scale and it was attached to an aluminum clamp. The clamp was fashioned in the same manner as the clamps that our system will use to connect to the plane's cables (see below for details) in order to protect the plane's cables. We also measured the total distance that each cable moved in each direction using a tape measure and masking tape. Our results are tabulated below.

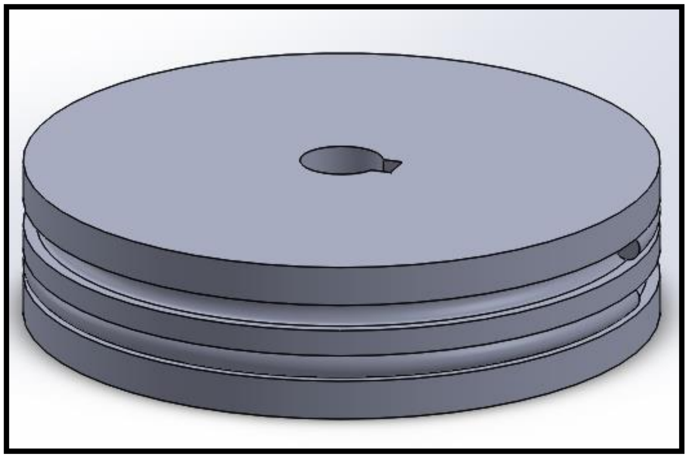
Item	Cable Connection	Force Required (lbs)	Cable Travel Forward (in)	Cable Travel Backward (in)	Total Cable Travel (in)
Aileron Tabs	7-10	30	3.625	3.5	7.125
Rudder Tabs	1-2	75	2.0	2.5	4.5
Elevator Tabs	3-6	55	4.0	3.5	7.5

4.3 Selecting Motors

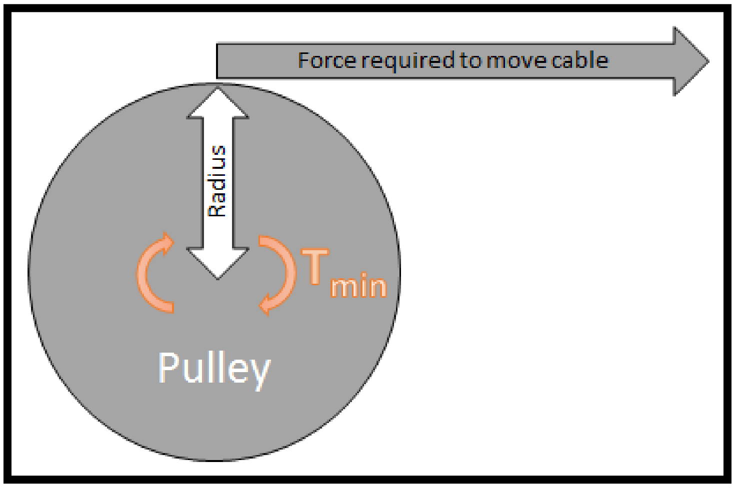
Once we found the forces required to move the cables, we were able to select our motors. The EET team suggested a brand of motor, AndyMark, that comes with the control module mounted to the motor and is also easy for them to code. The best motor for our purposes was the AndyMark am-2924. This motor provides an adequate amount of force to move the cables. At first, we decided to use the same motor for all three applications for simplicity. Then, we realized backdrive would be an issue and changed to a smaller motor for the aileron tabs (see below for details). AndyMark also offers a mounting bracket and encoder cable for the motor making it easier for both teams. The motors were mounted utilizing the bracket that was purchased along with the motors; it was patterned to match the housing on the motors.

4.4 Designing the Pulleys

We looked at several different types of pulleys and decided to use a two-grooved pulley with solid webbing and a borehole diameter of 10mm. The borehole diameter constraint is based on the shaft size of the motor we selected. We decided to use a two-grooved pulley in order to allow for easy installation and maintenance of our actuation cables that will be clamped to the plane's cables. We considered using a three-grooved pulley and using the center groove to guide the airplane cable, but decided it was not necessary and would be more expensive than a two-grooved one.



After searching manufacturers' websites for standardized pulleys, we encountered the problem that most industrial pulley bores are measured in fractions of an inch, while our motor's output shaft is measured in centimeters. Thus, because our team had the skill set and equipment necessary, we decided it would be cheaper and more effective to purchase aluminum and then machine the pulleys ourselves to the exact dimensions required. This was an easy way to maintain the units from our measurements and still fit the pulley exactly. We have included all the necessary drawings in our flash drive, so that someone may machine an additional pulley if needed.



In order to size the exact pulley dimensions required for each respective cable and motor, we made an Excel spreadsheet. The sheet calculated the corresponding minimum torque required and maximum cable displacement afforded to move a cable given a particulate outer diameter and required force. As can be seen in the basic modeled diagram of the pulley and cable, the calculations were completed using a simple moment calculation about the center of the pulley. In our calculations, a 1.5 safety factor was used. Since the maximum forces were different for each of the tabs, (the rudder tab required 75lbs of force, the elevator tabs required 55 lbs, and the aileron tabs only required 30lbs) three separate charts were created. Additionally, for each potential pulley diameter, the maximum distance the cable could travel from neutral was also calculated by finding half of the pulley's circumference. Half of the pulley's circumference was determined to be the maximum distance the cable could be pulled in either direction based on our design of using a set screw to secure the cables to the two separate grooves in the pulley. A sample chart of the described cable calculations can be found at the end of this report (page 17).

Using the constraints found from measuring the forces and distances that each cable needs to be able to move from neutral, it was determined that a pulley with an outer diameter of 3.75 inches would suffice. With a half circumference of 5.89 inches, this meets all distance requirements for each cable. As can be seen in the chart below, the torque requirements are all below the maximum torque that the motor we selected can supply.

Cable	Required Force (lbs)	Minimum Torque Required with 3.75” pulley (ft-lb)
Aileron Tabs	30	7.03
Elevator Tabs	55	12.89
Rudder Tabs	75	17.58

It is important to note that this required torque included a safety factor of 1.5.

In order to maintain consistency through simplicity, we decided to use the same 3.75 inch pulley for each set of cables, even though the aileron and elevator tabs could actually employ a larger pulley due to a lower required force.

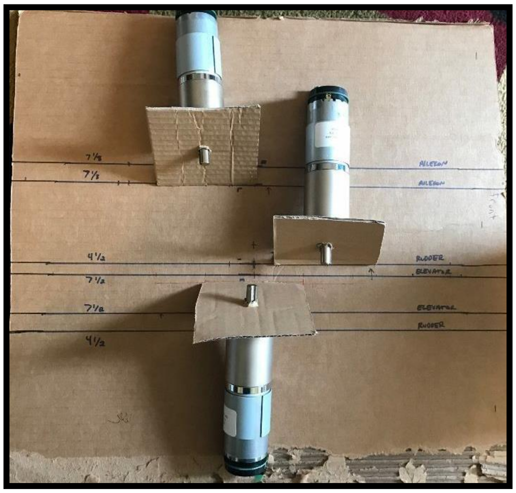
4.5 Minimizing Backdrive

Backdrive is the force required to move a motor when the motor is powered off. This was an important factor in our design due to the requirement that the pilot’s steering remain unaffected. Thus, in order to minimize the backdrive of our system on the pilot’s steering, we oversized the pulleys and used two different types of motors. For our pulley diameter, we calculated that our chosen motors could drive a 2.75 inch diameter pulley with a 1.5 factor of safety. However, with the AndyMark am-2924, the backdrive is 3.5 ft-lb which would almost double the force the pilot would have to exert to move the aileron tabs. This was unacceptable. So we enlarged the pulley diameter to 3.75 inches and downsized the motor to the AndyMark am-2971 which has a backdrive of 1.3 ft-lb. This decreased the backdrive from 30 ft-lb to 8.3 ft-lb. This was deemed an acceptable backdrive for the aileron tabs by our client.

4.6 Designing Safety Mechanisms

To keep the system as safe as possible, we designed multiple safety mechanisms. These mechanisms will be in place to not only protect the new system that we are implementing but also the existing system of the plane. Our goal was to make the motors the weakest point of the system which will ensure that we will not damage the airplane. The first safety mechanism will be a software safety device. The EET team has the ability to regulate the current to the motors and if the motors reach a threshold current then the software will stop the motor from turning any further. The second safety mechanism will be an electrical breaker; this breaker is similar to the software safety device in that it will regulate the current of the motor and will shut it off if the current is too large. The final safety mechanism is a mechanical stopper. This device consists of two pins protruding about 1 inch out from the pulley. Each pin will hit a separate stopper pin mounted just below the pulley and will not allow the motor to move the cable past a certain point in either direction. This will prohibit the cable from being overly stressed by transferring all of the stress to the pullet pins and stopper pin. The pulley pin and stopper pin were both calculated to have more than adequate strength as sized to 0.25 inch diameters (See calculations at the end of this report).

4.7 Cardboard Model



Since the wires are close together inside of the luggage bay and it is difficult to accurately measure dimensions, Dr. Kidd suggested that we make a cardboard model of our system. So we cleaned up the ceiling tarps in the luggage bay to make the space for our system accessible. Then we used spare cardboard from Lowe's to make a cardboard model of our bracket that will fit perfectly in the actual location where it will be installed in the luggage bay.

4.8 Ordering Materials

With our motors and pulley sizes finalized we began getting purchase orders together for our client. We placed all orders through Dr. Kidd with his approval. First, we ordered motors and brackets from Andy Mark's website. Then, we ordered the aluminum circles for our pulleys from Stillwater Steel, and the delrin from McMaster Carr. Then, we ordered our bracket materials from Stillwater Steel. We also ordered spare nuts and screws for our project from Lowe's.

4.9 Machining Pulleys

We machined the pulleys ourselves due to their unique nature. The 10mm borehole and 4mm keyway were difficult to find online, and the two-groove nature of the pulleys with space between the grooves was unavailable online. The space between the grooves is critical to our design so that no radial forces are exerted on the cables. This would result in the cables wearing against the bushings in the luggage bay. Thus, we decided to machine our own pulleys.

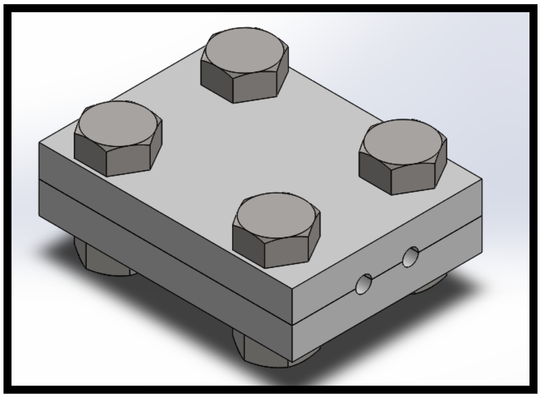
We started with laser-cut aluminum circles from Stillwater Steel. Due to the method of plasma cutting and the relative thickness (¾”) of the aluminum, the backside of the pulleys did not come out perfectly round. To fix this, we first marked the center of the pulley on the cut surface and drilled the borehole through the center of the pulley. After drilling the hole, we used a lathe to turn the pulley slightly down to achieve a more circular and better finished surface. To cut the needed 4 mm keyway into the aluminum pulley, we used a 4 mm file to ensure we did not remove too much material and thus adhered to the keyway’s tight tolerances. We also drilled and tapped a 10-24 threaded hole for our set screws which will secure the cables to the pulley.

4.10 Testing Motors and Pulleys

In order to ensure that our motors would be able to move the cables as we calculated that they should, we tested our motor-pulley design. We started in the lab where we mounted one of our larger motors on two-by-fours that were clamped to the table. We decided to first test the motor without a load, so we set the voltage to 12 V and the current very low to 0.1 A. Then we touched the wires from the voltage output to the motor. It worked, but did not spin very quickly. This was expected due to the low current.

Next, we tested the motor and pulley with a load. First, we secured a steel cable to the pulley by means of a hole and a set screw that we had machined into the pulley. Then we looped the cable through twenty pounds of weights. When we applied the 12 V input, the motor did not move. This was due to a low current output by the supply. So we lightened the weight and the motor was able to lift 3.68 lbs (a pipe wrench) with the 12 V supply and limited current. In further testing, we used a 12V battery charger the had the capability of 10, 60, and 100 amp currents. For our smaller motor, we had calculated that it should lift 100 lbs at stall torque, which occurred at 22 amps. Our design only requires the motor to pull 35 lbs of force. With the charger set to 10 amps, we secured a 45 lb load to the cable and tested the motor. At 10 amps of current, the motor performed as expected pulling the load up, but it was relatively slow. Next we turned the charger up to 60 amps to determine how much more current the motor would draw while under load. This increased our lifting rate, with the motor never drawing more than 20 amps of current. Thus, we are confident that the motors will perform as expected when they have the required input voltage and current.

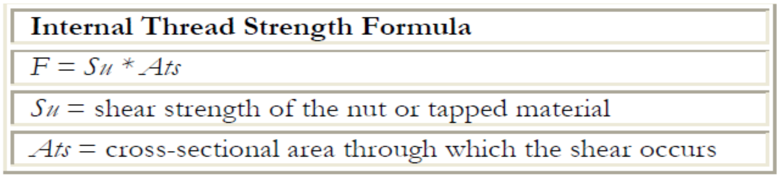
4.11 Calculating Clamp Bolt Failure



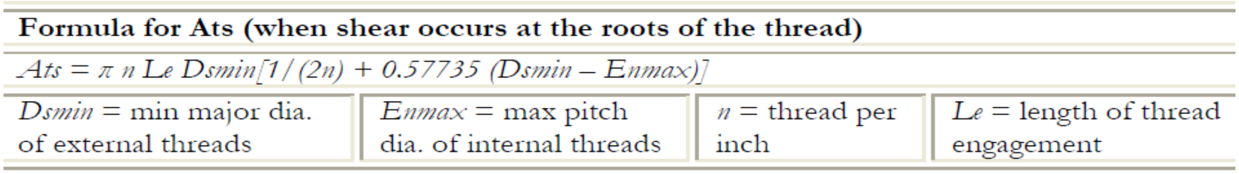
In order to connect the tab actuation cables to our pulleys, we will be using delrin clamps. These clamps will ensure a secure grip on the cables without damaging them or altering their lateral or vertical position in the bay. These clamps have four steel bolts holding them together. We decided to use steel instead of delrin bolts due to availability and strength. The only problem with this is that the steel bolts may strip the delrin threads. So, with the help of a Fastenal article, we calculated the forces required to break the bolts, strip the bolts, and strip the delrin. The results are tabulated below. According to the article, the bolts should fail in tension before any material is stripped. This is because stripping often goes undetected, whereas a bolt failure is quite noticeable. According to our results below, we decided to include a steel nut on the end of each bolt. This will ensure that the bolt will be the first to fail in tension instead of the delrin stripping.

Failure	Force to Fail (lbs)	Su of Material (kpsi)
Delrin Strips	1,200	9 (White Delrin sheet)
Bolt Breaks	1,900	60 (Grade 1 steel)
Bolt Strips	8,500	60 (Grade 1 steel)
Nut Strips	9,600	74 (Grade 2 steel)

Formulas used are from “Screw Thread Design” by Fastenal Engineering and Design Support



Internal Thread Strength Formula
$F = Su * Ats$
Su = shear strength of the nut or tapped material
Ats = cross-sectional area through which the shear occurs



Formula for Ats (when shear occurs at the roots of the thread)

$Ats = \pi\ n\ Le\ Dsmin[1/(2n) + 0.57735\ (Dsmin - Enmax)]$

$Dsmin$ = min major dia. of external threads	$Enmax$ = max pitch dia. of internal threads	n = thread per inch	Le = length of thread engagement

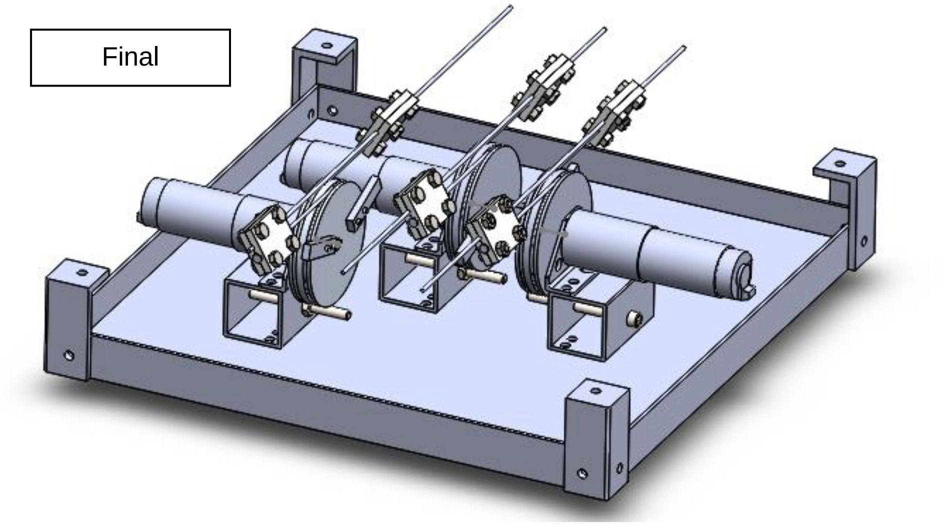
4.12 Hydraulic Investigations

Since the elevator and rudder tabs are hydraulically assisted when the plane is flying, they are affected by engine start-up. When the plane engine is started, the hydraulics for these tabs are pressurized. This aids in moving the tabs by decreasing the force required to actuate them while the plane is running. However, once the engines are turned off, this residual hydraulic pressure stays in the system for about a week. This drastically increases the forces required to move the tabs without hydraulic help. Thus, our system will not be able to function properly within a week of engine startup unless the hydraulics are bled down. Using the plane's schematics, we were able to find the hydraulic accumulators for the elevator tabs. They are located about ten feet above the ground on the starboard side of the plane at the base of the tail. However, we were unable to discover a feasible way to depressurize the hydraulics before using our system. There were no valves or easily detachable couplings in the system. So we included warnings in our user manual not to use the system within one week of engine start-up.

5.0 Key Design Decisions

Our main decisions include: installing the system in the luggage bay, using two AndyMark am-2924 motors and one AndyMark am-2971 motor, using 3.75 inch pulleys, machining the pulleys ourselves, using steel nuts on the delrin clamps, and installing various safety mechanisms. We made these decisions based on our engineering analysis of the system and Dr. Kidd's input. See above for more detail about these decisions.

6.0 Final Design Description



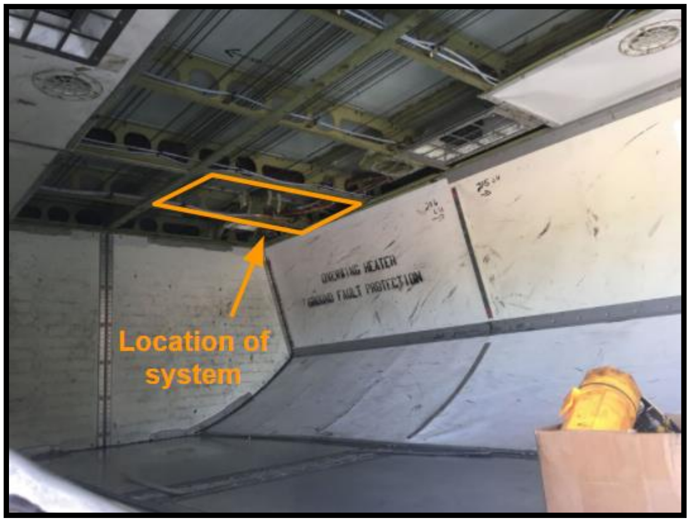
6.1 Design Highlights

As described above, our design consists of three motors that move independently to actuate the three different tabs on the airplane. The motor that moves the aileron tabs is less powerful than the other two due to the lower actuation force required for the aileron tabs. The motors are outfitted with custom pulleys to optimize cable movement and to minimize backdrive. The motors are mounted on spacers via brackets to allow uninhibited movement of the pulleys. These spacers are mounted to the frame which consists of an aluminum plate welded to aluminum angle. The aluminum angle attaches to the crossbeams of the plane for simple, nonpermanent mounting of the entire system. In addition, the pulleys have two grooves and two keyways to secure a the two cables that attach to the plane's cables via the delrin clamps. This ensures that no vertical or radial forces act on the plane's cables and that the plane's cables are not damaged in any way by our system. The safety measures of our design include: coded position stops, electrical breakers, and mechanical stops. These ensures that material stresses from malfunctions are on our system and not the plane itself.

7.0 Design Evaluation

As mentioned above, engineering calculations were performed in order to ensure that our system will not fail under critical conditions. The necessary torque for motors to pull the cables was calculated. The back drive for the motors was effectively addressed and reduced to the client's desires. The first thing to fail in the delrin clamps was calculated to be the bolt in tension when secured with a steel nut. Additionally, calculations were performed to justify the 0.25 inch diameter stopper pins. Additional details of our calculations can be found at the end of this report.

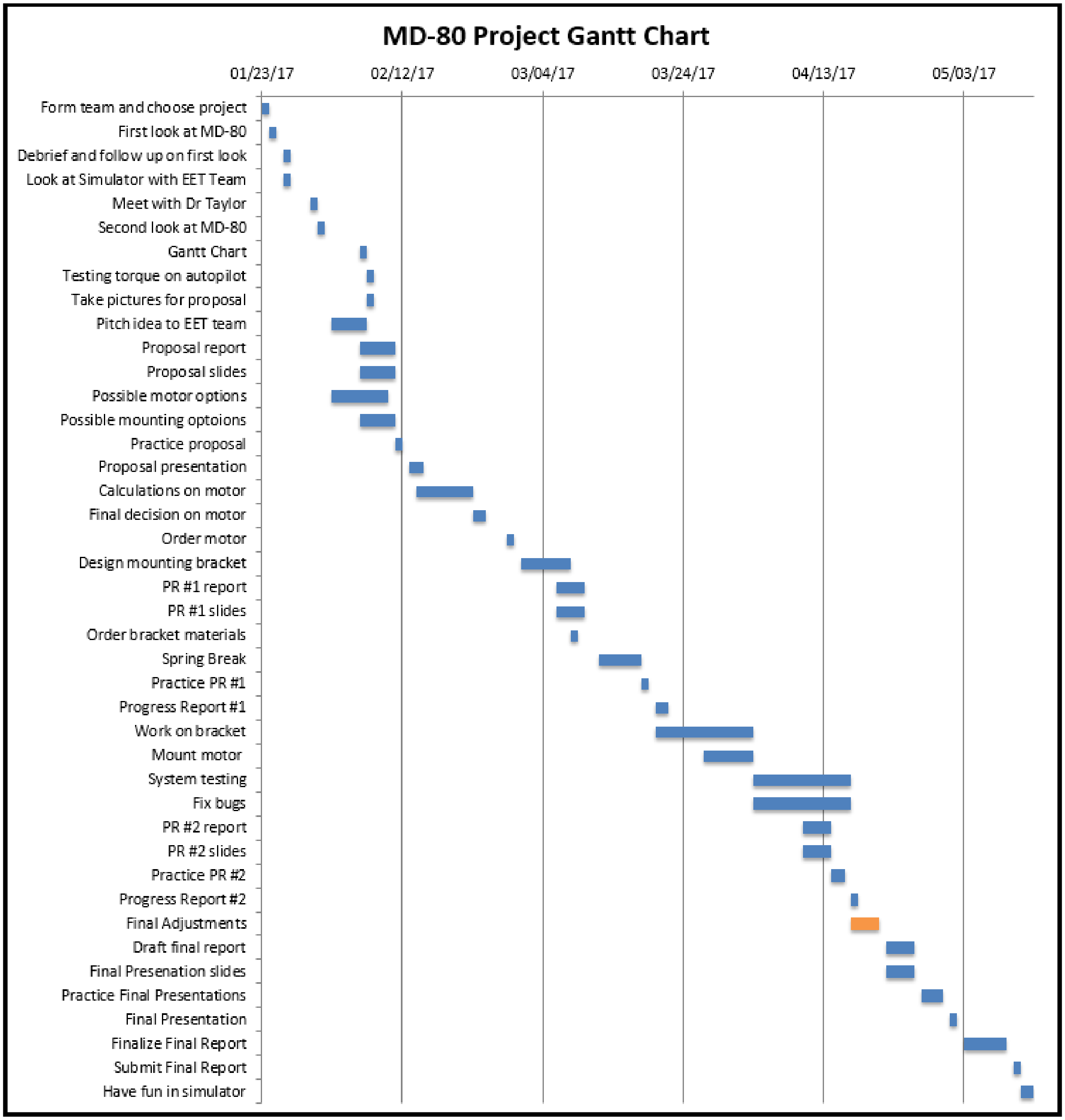
8.0 Future Work Recommendations

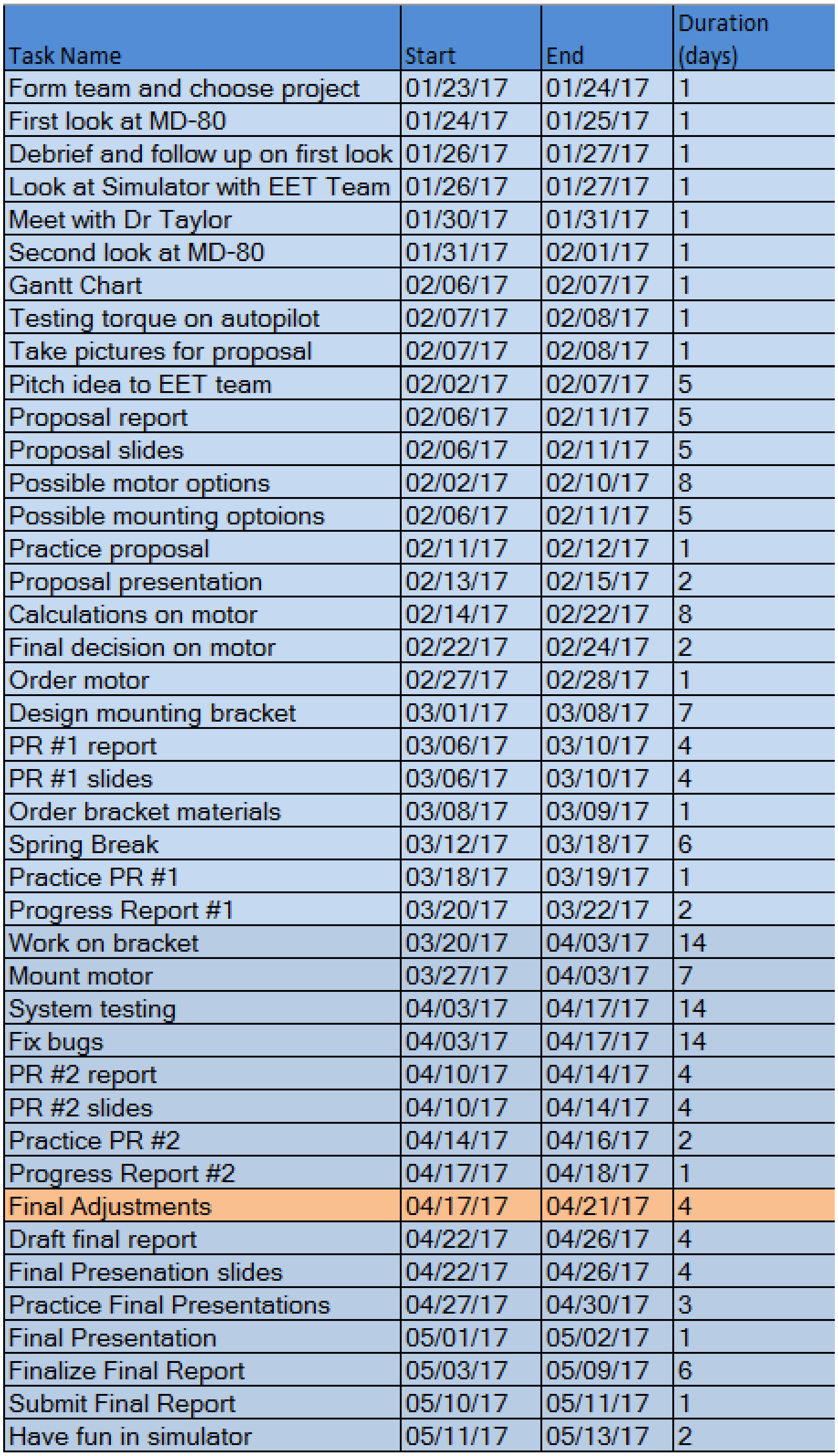


Our design has been placed in the Design & Manufacturing Laboratory. It should be installed as directed in the user manual under Dr. Kidd's guidance. The only remaining design calculations that need to be completed include the exact location of the mechanical stopper pins on the pulley. These should be set upon installation to ensure that the pulley pins run into the stopper pin (connected to the spacer below) before maximum rotation is reached. Additionally, the motors' performance based on applied current should be graphed in order to determine which electrical breaker should be installed to ensure maximum current (and consequently torque) is not reached when unneccessary. Lastly, a mechanical stop switch should be installed as a last resort on the luggage bay frame to ensure that the delrin clamps trigger the system to shut down before they ram into the frame.

9.0 Revised Gantt Chart

Color-coded Gantt Chart: blue tasks are completed, orange tasks are future tasks.





Task Name	Start	End	Duration (days)
Form team and choose project	01/23/17	01/24/17	1
First look at MD-80	01/24/17	01/25/17	1
Debrief and follow up on first look	01/26/17	01/27/17	1
Look at Simulator with EET Team	01/26/17	01/27/17	1
Meet with Dr Taylor	01/30/17	01/31/17	1
Second look at MD-80	01/31/17	02/01/17	1
Gantt Chart	02/06/17	02/07/17	1
Testing torque on autopilot	02/07/17	02/08/17	1
Take pictures for proposal	02/07/17	02/08/17	1
Pitch idea to EET team	02/02/17	02/07/17	5
Proposal report	02/06/17	02/11/17	5
Proposal slides	02/06/17	02/11/17	5
Possible motor options	02/02/17	02/10/17	8
Possible mounting optoions	02/06/17	02/11/17	5
Practice proposal	02/11/17	02/12/17	1
Proposal presentation	02/13/17	02/15/17	2
Calculations on motor	02/14/17	02/22/17	8
Final decision on motor	02/22/17	02/24/17	2
Order motor	02/27/17	02/28/17	1
Design mounting bracket	03/01/17	03/08/17	7
PR #1 report	03/06/17	03/10/17	4
PR #1 slides	03/06/17	03/10/17	4
Order bracket materials	03/08/17	03/09/17	1
Spring Break	03/12/17	03/18/17	6
Practice PR #1	03/18/17	03/19/17	1
Progress Report #1	03/20/17	03/22/17	2
Work on bracket	03/20/17	04/03/17	14
Mount motor	03/27/17	04/03/17	7
System testing	04/03/17	04/17/17	14
Fix bugs	04/03/17	04/17/17	14
PR #2 report	04/10/17	04/14/17	4
PR #2 slides	04/10/17	04/14/17	4
Practice PR #2	04/14/17	04/16/17	2
Progress Report #2	04/17/17	04/18/17	1
Final Adjustments	04/17/17	04/21/17	4
Draft final report	04/22/17	04/26/17	4
Final Presenation slides	04/22/17	04/26/17	4
Practice Final Presentations	04/27/17	04/30/17	3
Final Presentation	05/01/17	05/02/17	1
Finalize Final Report	05/03/17	05/09/17	6
Submit Final Report	05/10/17	05/11/17	1
Have fun in simulator	05/11/17	05/13/17	2

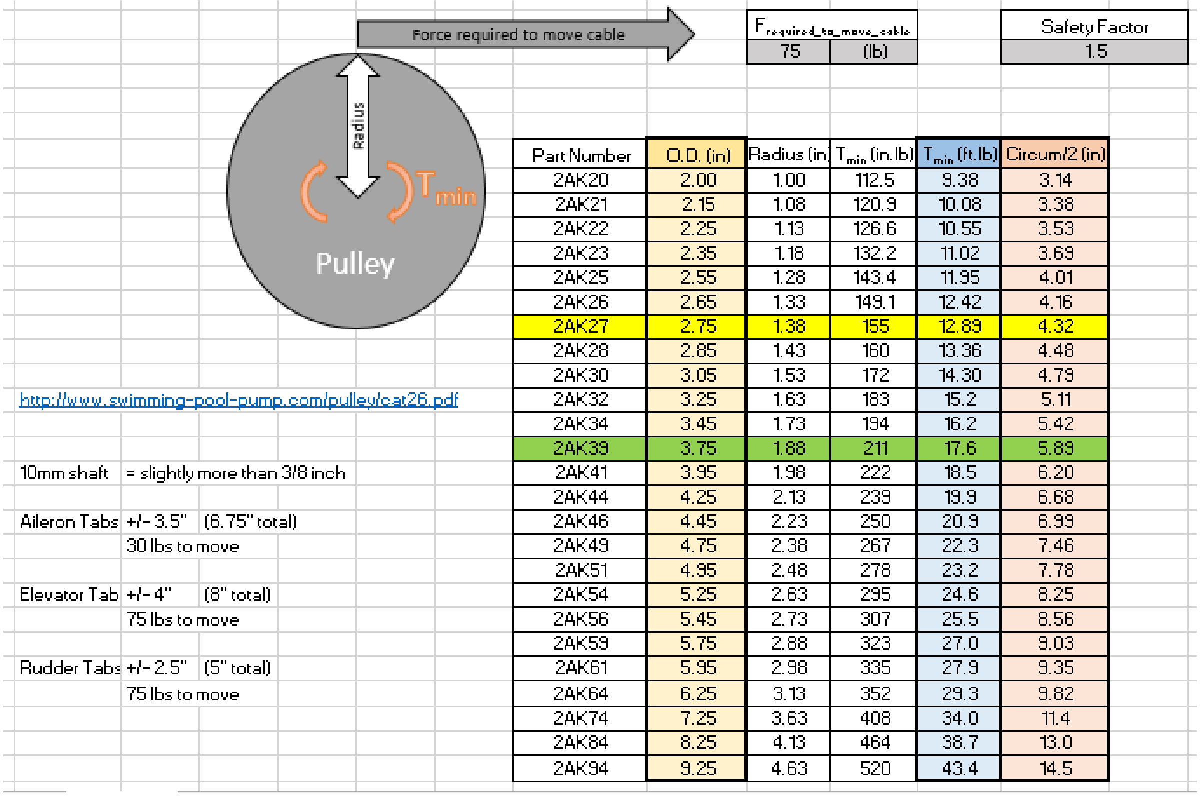
10.0 Revised Budget Table

Item	Cost
Large Motors (2)	$216
Small Motor	$104
Delrin for clamps	$24.50
Bracket materials	$150
Pulleys	$80
Miscellaneous costs	$50
Machine shop costs	$80/hour*
Estimated total	$624.50

*Team completed all of the labor.

11.0 Calculations

Minimum Motor Torque Calculation Spreadsheet



$F_{required\_to\_move\_cable}$	
75	(lb)

Safety Factor
1.5

Part Number	O.D. (in)	Radius (in)	T_{min} (in.lb)	T_{min} (ft.lb)	Circum/2 (in)
2AK20	2.00	1.00	112.5	9.38	3.14
2AK21	2.15	1.08	120.9	10.08	3.38
2AK22	2.25	1.13	126.6	10.55	3.53
2AK23	2.35	1.18	132.2	11.02	3.69
2AK25	2.55	1.28	143.4	11.95	4.01
2AK26	2.65	1.33	149.1	12.42	4.16
2AK27	2.75	1.38	155	12.89	4.32
2AK28	2.85	1.43	160	13.36	4.48
2AK30	3.05	1.53	172	14.30	4.79
2AK32	3.25	1.63	183	15.2	5.11
2AK34	3.45	1.73	194	16.2	5.42
2AK39	3.75	1.88	211	17.6	5.89
2AK41	3.95	1.98	222	18.5	6.20
2AK44	4.25	2.13	239	19.9	6.68
2AK46	4.45	2.23	250	20.9	6.99
2AK49	4.75	2.38	267	22.3	7.46
2AK51	4.95	2.48	278	23.2	7.78
2AK54	5.25	2.63	295	24.6	8.25
2AK56	5.45	2.73	307	25.5	8.56
2AK59	5.75	2.88	323	27.0	9.03
2AK61	5.95	2.98	335	27.9	9.35
2AK64	6.25	3.13	352	29.3	9.82
2AK74	7.25	3.63	408	34.0	11.4
2AK84	8.25	4.13	464	38.7	13.0
2AK94	9.25	4.63	520	43.4	14.5

http://www.swimming-pool-pump.com/pulley/cat26.pdf

10mm shaft = slightly more than 3/8 inch

Aileron Tabs +/- 3.5" (6.75" total)
30 lbs to move

Elevator Tab +/- 4" (8" total)
75 lbs to move

Rudder Tabs +/- 2.5" (5" total)
75 lbs to move

Bracket Reaction Force Calculations

(Large motor) $T_{max} = 33\ \text{ft} \cdot lb = 396\ in \cdot lb$
(Small motor) $T_{max} = 16\ \text{ft} \cdot lb = 192\ in \cdot lb$

$$\Sigma F_y: 0 = 2(R_y) - W$$

$$R_y = \frac{W}{2} = \frac{(2\ lbs)}{2} = 1\ lb$$

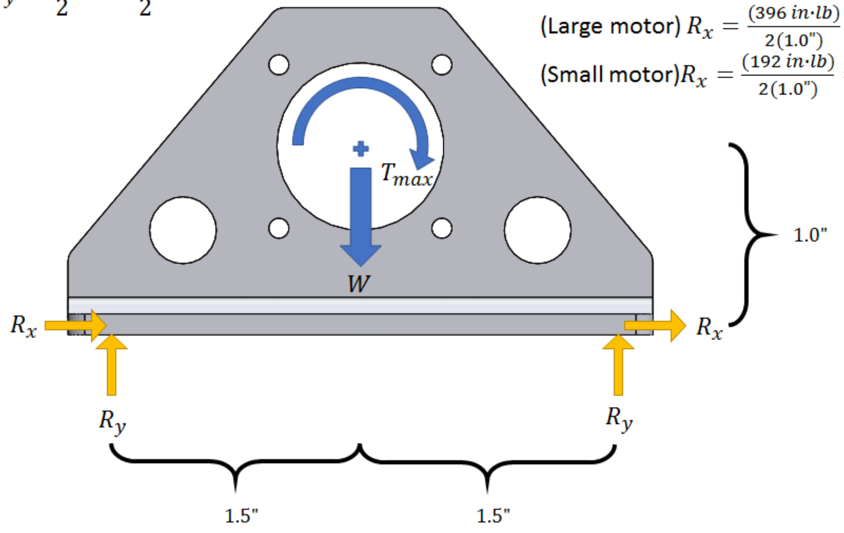
$$\Sigma M: T_{max} = R_y(1.5'') - R_y(1.5'') + R_x(1.0'') + R_x(1.0'')$$

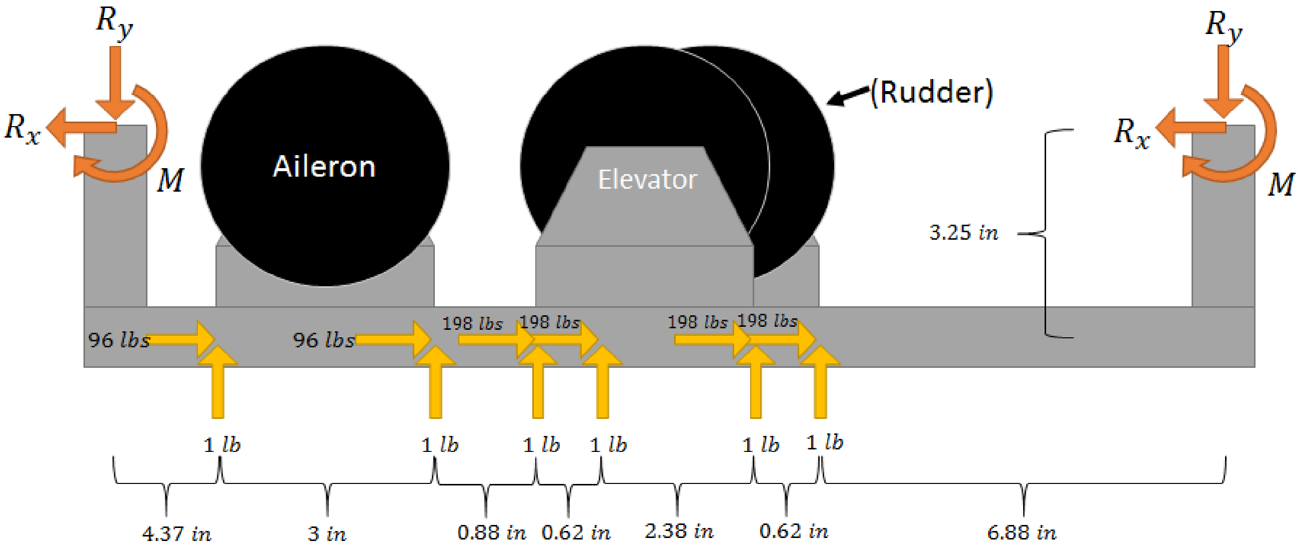
$$T_{max} = R_x(1.0) + R_x(1.0) = 2(1.0'')R_x$$

$$R_x = \frac{T_{max}}{2(1.0'')}$$

(Large motor) $R_x = \frac{(396\ in \cdot lb)}{2(1.0'')} = 198\ lbs$

(Small motor) $R_x = \frac{(192\ in \cdot lb)}{2(1.0'')} = 96\ lbs$



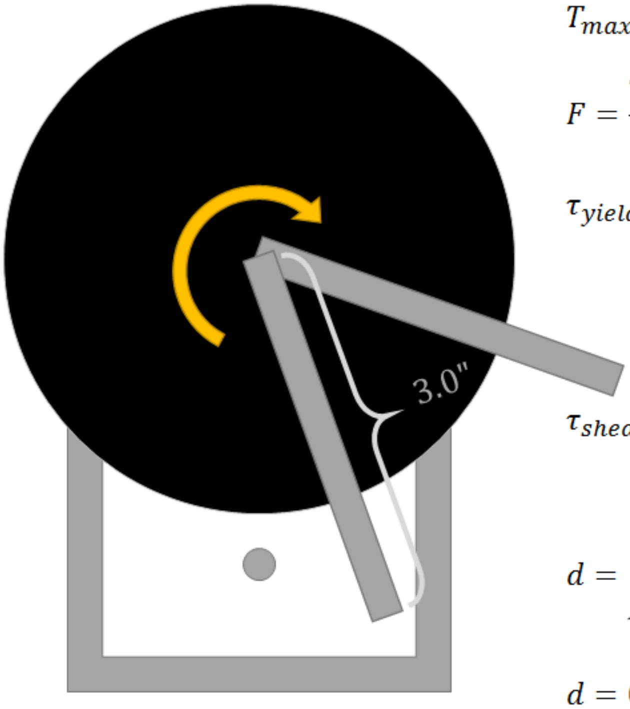


$$\Sigma F_x:\ 4(R_x) = 2(96\ lbs) + 4(198\ lbs)$$
$$R_x = 246\ lbs$$

$$\Sigma F_y:\ 4(R_y) = 6(1\ lb)$$
$$R_y = 1.5\ lbs$$

$$\Sigma M:\ M + 2(1.5\ lbs \cdot 18.75'') = (1\ lb \cdot 4.37'') + (1\ lb \cdot 7.37'') + (1\ lb \cdot 8.25'') + (1\ lb \cdot 8.87'') + (1\ lb \cdot 11.25'') + (1\ lb \cdot 11.87'') + 2(96\ lbs \cdot 3.25'') + 4(198\ lb \cdot 3.25'')$$
$$M = 3193.73\ in \cdot lbs = 266.14\ ft \cdot lbs$$

Mechanical Stopper Pin Shear Stress Calculations



$$T_{max} = 33\ ft \cdot lbs = 396\ in \cdot lbs$$

$$F = \frac{T_{max}}{r} = \frac{396\ in \cdot lbs}{3.0\ in} = 132\ lbs$$

$$\tau_{yield\_aluminum} = 40{,}000\ psi$$

$$\tau_{shear} = \frac{SafetyFactor \cdot F}{A} = \frac{SafetyFactor \cdot F}{\frac{\pi d^2}{4}}$$

$$d = \sqrt{\frac{SafetyFactor \cdot F}{\frac{\pi}{4} \cdot \tau_{yield}}} = \sqrt{\frac{3 \cdot (132\ lbs)}{\frac{\pi}{4} \cdot (40{,}000\ psi)}}$$

$$d = 0.1123\ in$$

$\therefore\ d = 0.25\ in$ will definitely be large enough to stop pulley at maximum torque.