BOAT STABILIZATION (ANTI ROCKING) SYSTEM

by

Clark Friesen

Konur Nicholson

Lucas Estabrook

A report presented to the

British Columbia Institute of Technology

In partial fulfilment of the requirement for the degree of

Bachelor of Engineering (Mechanical)

Faculty Advisor: Greg King – BASc, MBA, PEng

Program Head: Johan Fourie – PhD (EngSci), Peng

Burnaby, British Columbia, Canada, 2018

We hereby declare that we are the sole authors of this report.

Signature(s)

We further authorize the British Columbia Institute of Technology to distribute digitally, or printed paper, copies of this report, in total or in part, at the request of other institutions or individuals for the purpose of scholarly activity.

Signature(s)

Abstract

While on a ship of any size, it is desirable to have a stable deck to ensure maximum safety and enjoyment for passengers. Ships have normally relied upon the design of their hulls for stability. However, even with a superior hull design, ships are incapable of completely mitigating such rolling motion. To reduce rolling motion further, an additional stabilization system must be implemented. This report documents the development of such a stabilization system in response to the request for proposal (RFP) received from WaterWorks Co. on October 17, 2017.

The objective of the project was to produce a fully-functional, scale-prototype of a system that could decrease the roll of a 12ft long ship by at least 50%.

Current stabilization methods were investigated and evaluated in terms of the performance requirements specified in the RFP. A gyroscopic stabilization system was then selected as the superior method of stabilization and detailed design proceeded.

In order to determine the stabilization torque required and size the flywheel located inside the gyroscope, the team performed theoretical calculations based on mathematical models of the boats that were to be stabilized.

A functional prototype was then manufactured featuring a steel flywheel and shaft enclosed in an aluminum cast-housing with waterjet-cut housing caps. The housing is located within an extruded t-slot frame, and the flywheel is driven by a 12V DC motor.

Several tests were then performed on the finished prototype to evaluate the overall effectiveness of the system. The system reduced roll by approximately 50%.

Future work includes manufacturing a full scale prototype, and implementing an active control system to drive the precession motion.

Acknowledgments

The project group would like to thank the following people who helped to make this project possible.

Thank you Greg King for proposing the project, giving us insight into possible problems with our design at different stages, and helping us come up with solutions.

Thank you Brian Ennis, Johan Fourie, Adrian Fengler, Dave Lewis, Eugene Duruisseau, and Greg King for insightful information and assistance regarding the various manufacturing processes used to build the prototype.

Thank you Vahid Askari for your help in determining the stresses acting on our design.

Special thanks to Curtis From for donating a preprogrammed Arduino board to the project for the use as a motor speed controller.

Table of Contents

List of Tables

List of Figures

1. Introduction

Traditionally, the only factor in a boat's stability was the design of the ship’s hull. While this has been satisfactory for centuries, rich boat patrons are always looking for ways to further improve the comfort and luxuries of their boating experience, which has given birth to a market of externally-mounted stability systems. However, these systems are mainly designed for boats longer than 20 feet.

1.1. Project Objectives

The goal of this project is to design a stabilization system that will reduce the roll of a small boat by 50%. The boat is about 12 feet in length. It is assumed that the boat is in calm water and thus never exceeds a roll angle of ±10 degrees.

A scale-prototype will be manufactured, and testing will be performed to determine the system’s effectiveness.

2. Detailed Description of the Current Status

2.1. The Problem to Solve

During a boating trip, waves produce large amounts of torque upon the vessel causing large rolling action of up to 10 degrees. This is detrimental to the boating experience and comfort of the passengers. A scale-prototype of a stabilization system that will reduce a small ship's roll by 50% is desired. The best method of stabilization must be selected, and then a detailed design must be completed, followed by manufacturing and testing of a prototype.

2.2. Project Hypothesis

While there are multiple commercial products available for larger vessels to stabilize roll, after evaluating the possibilities, as described in Chapter 4.2, it was predicted that the most effective solution for small, luxury vessels would be the use of a gyroscope that produces a torque countering the roll of the ship.

A simplified mathematical model of a small ship was created. Ocean waves exert an exciting moment on a boat's hull. This causes it to roll. As seen in Figure 2-1 and Figure 2-2, as the angle of roll increases, the exciting moment from the waves increases, and thus the torque necessary to stop the rolling motion increases in a similar fashion.

The model predicted that to reduce the roll of a 12 foot long boat with a beam width of 61 inches the stabilization system would require a maximum stabilization torque of approximately 450 N·m, as shown in Figure 2-2. This value is based on the boat and wave properties used for inputs, as seen in Appendix C.

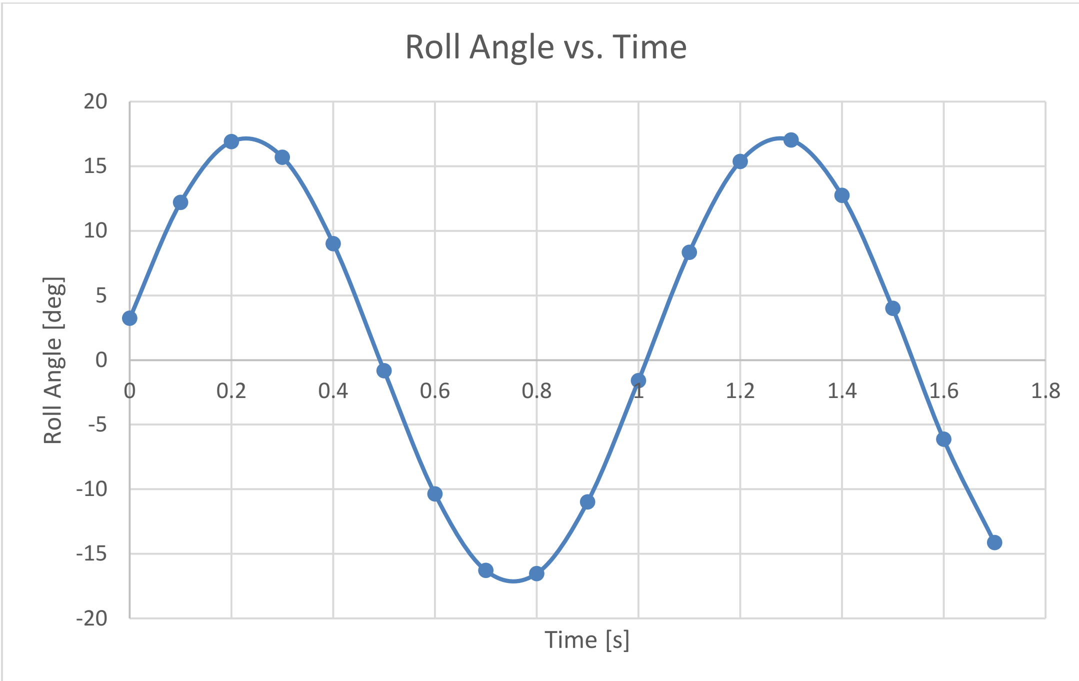


Figure 2-1 – Roll Angle of Boat vs. Time Based on Waves

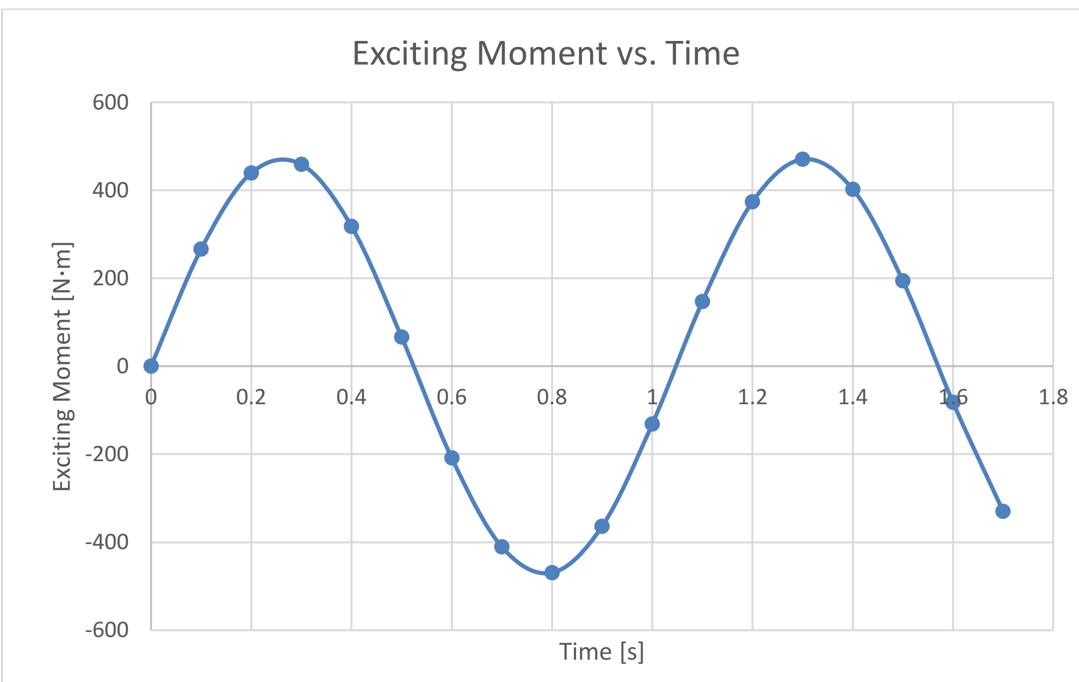


Figure 2-2 – Exciting Moment vs. Time

If the period of roll is assumed to be two seconds, then the required angular momentum produced by the flywheel must be approximatley 115 N·m·s.

For a flywheel operating at 8000rpm and designed with a web and flange configuration, as seen in Figure 2-3, the diameter would need to be almost one foot in order to achieve the required angular momentum.

Figure 2-3 - Theoretical Flywheel Section View

Therefore, for the purpose of this project, a scale-prototype will be produced featuring a flywheel with a diameter of 4 inches, a flange thickness of half an inch, and a web thickness of a quarter inch. Table 2.1 shows the stabilization torque this flywheel is predicted to produce, for various operating speeds.

Table 2.1 - Theoretical Torque Output at Different Angular Velocities

Flywheel Angular Velocity (RPM)	Stabilization Torque (N·m)
2000	2.428
4000	4.857
6000	7.285
8000	9.713

3. Theoretical Background

3.1. Ship Coordinates

As seen in Figure 3-1, boats have up to six degrees of freedom. The boat stabilization system in this project only focuses on reducing roll.

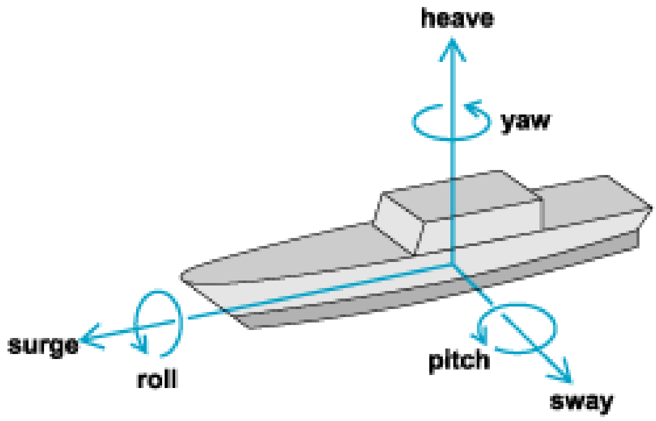


Figure 3-1 - Degrees of Freedom for a Ship

3.2. Modelling Boat Motion

In reality, a boat's motion is very complex to model, in some cases requiring "a set of six coupled differential equations" which still "rely on simplified assumptions." [1, p. 500] However, for this project, only the rolling motion needs to be analyzed, which allows further simplifications to be made.

For small roll angles of ±10 degrees, a boat's rolling motion can be approximated by:

$$a\ddot{\phi} + b\dot{\phi} + c\phi = d \tag{3-1}$$

Where a, b, and c are proportionality factors, and d is the external roll excitation. [1, p. 501]

For a ship rolling in beam seas, the external roll excitation is governed by [1, p. 506]:

$$d = g \cdot \Delta \cdot GM \cdot \pi \cdot \left(\frac{H_w}{L_w}\right) \sin(\omega \cdot t) \tag{3-2}$$

Where

$$g = gravitational\ constant$$
$$GM = metacentric\ height$$
$$\Delta = displacement\ mass$$
$$H_w = height\ of\ wave$$
$$L_w = length\ of\ wave$$
$$\omega = wave\ frequency$$
$$t = time$$

In order to estimate the torque required to stabilize a boat, it was assumed that if the stabilization system can produce the same amount of torque as the exciting moment produced by the waves acting on the boat's hull, then the system would effectively cancel out the rolling motion. Thus by inserting appropriate values for the parameters into Equation 3-2, the required stabilizing torque can be estimated.

4. Description of the Project Activity and Equipment

4.1. Concept Research

Patent research was performed to determine possible methods of boat stabilization. Each of the possibilities was then compared based on a variety of criteria, as seen in Figure 4-4, to determine which would be most effective at minimizing roll.

4.1.1. Flopper Stopper

The Flopper Stopper is a plate made with thin sheets of metal that is placed into the water. When the waves flow over the flopper stopper, viscous forces resist the rolling motion. Currently, there are not many providers of such a solution however patent research lead to **Patent No. FR2769578A1:** *Plate Stabilizer for Boat at Anchor or Adrift* seen in Figure 4-1.

While the upside of the flopper stopper is its lightweight and inexpensive construction, it can be easily damaged as it sits outside the boat under the water, and thus needs to be removed from the water manually before the boat can start to move again.

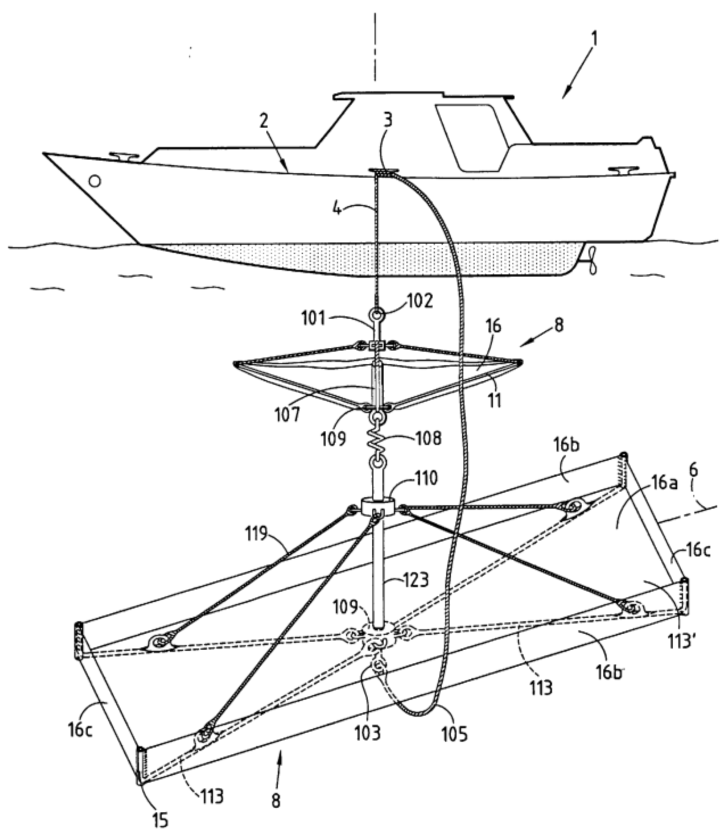


Figure 4-1 - Plate Stabilizer for Boat at Anchor or Adrift

4.1.2. External Fins

External fins have been used to aid in the stabilization of boats for a large period of time. These fins are mounted to the outside of the boat, as seen in Figure 4-2, and are either passive or active depending on the level of sophistication used to mount and control the fins.

While these fins are fairly effective at reducing the roll, they also introduce certain challenges, such as impeding the boats maneuverability, and being susceptible to damage from ocean debris. Also, as they are permanently mounted to the outside of the boat, repairs and modifications can only be done by removing the entire boat from the water.

Figure 4-2 - Externally Mounted Actuating Fin [2]

4.1.3. Gyroscope

Gyroscopic stabilization systems work by spinning an object with a large mass moment of inertia, usually a flywheel, at a certain speed, as designated by the boat's requirements. When the boat rolls, due to gyroscope physics, the spinning mass precesses. This precession motion then creates a torque that opposes the rolling motion. More details regarding gyroscope physics can be found in Appendix D.

The mass being spun can be anything from a solid disk to a liquid. For example, Figure 4-3 shows Patent No. US7458329B2 Hydro-gyro Ship Stabilizer, which spins water at high speeds to damp the roll of a boat. [3]

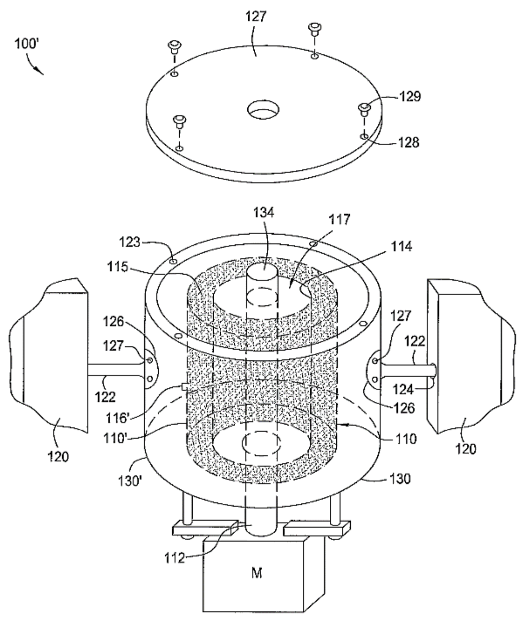


FIG. 3

Figure 4-3 - Patent No. US7458329B2 Hydro-gyro Ship Stabilizer [4]

4.1.4. Passive or Active Anti-Roll Tanks

Passive and active anti-roll tanks feature a contained liquid mass which is allowed to slosh back and forth. The tank is designed so that the sloshing motion creates an opposing force due to the fluid's inertia. This force dampens the rolling motion. More sophisticated active tank systems may also use pumps to force the liquid from one side of the tank to the other to increase the opposing forces and allow more precise timing.

4.1.5. Passive or Active Mass Dampers

Similarly to anti-roll tanks, mass dampers work by having a mass delayed by its own inertia, or forced to back and forth by a control system to create forces that oppose the rolling motion. This system is found mainly on much larger ships, such as cruise liners. Similar systems are also used in buildings to dampen out vibrations due to earthquakes.

4.2. Concept Selection

Using a decision matrix, as shown in Figure 4-4, the concepts described in chapter 4.1 were evaluated in terms of their ability to meet the performance requirements. The results of the decision matrix revealed that the flopper stopper was the superior method of stabilization. However, the project team chose to pursue a gyroscope instead, as flopper stoppers need to be taken in and out of the water during use, a task that interferes with the luxury feel of the boats the system is being designed for.

Category Weighting (1-10 = neutral)	Scale 1-5, 5 means best performance	Gyroscope	flopper stopper	Submerged Fins	Passive Anti-Roll Tank	Active Anti-Roll Tank	Passive Mass Damper	Active Mass Damper
4	Weight	3	5	3	1	1	2	2
7	Drag	4	5	1	3	3	3	3
6	Cost	1	5	1	4	3	3	2
8	Size	4	5	5	2	1	2	1
10	Damping Effectiveness							
4	Power Requirements	3	5	1	4	3	5	3
5	Efficiency							
5	Noise	2	5	4	5	3	5	3
8	intererence with ship living spaces	4	5	5	2	2	2	2
3	Easy to install	3	5	1	4	3	3	2
8	Easy to maintain	4	5	1	5	4	4	3
8	Reliable in Marine Environment	5	2	1	4	4	4	4
4	Minimal vibration	3	5	3	5	4	4	3
8	Minimal boat modification required	4	5	1	3	3	3	3
2	Tunable (once installed)	5	1	5	1	3	1	3
8	Compact	4	5	3	2	1	2	1
7	Smooth / comfortable response	5	3	2	3	4	3	4
10	Effect on boat stability (1 means makes unstable)	5	5	5	1	1	4	4
6	Range of frequencies it works with	5	4	5	2	3	2	3
	Total	414	478	296	311	277	328	290

Figure 4-4 - Concept Selection Decision Matrix

4.3. Detailed Design

The following section describes how the size of the flywheel was determined.

4.3.1. Gyroscope Torque Calculations

A 3D-model of a small ship was created in SolidWorks in order to determine appropriate parameters for Equation 3-2 and for other equations from [1] that were used in the mathematical model. Once the required stabilization torque for the small ship was calculated, the required size of the flywheel was determined to be about one foot in diameter, and six inches wide. This was done by relating the stabilizing torque to the angular momentum, and thus to the size, shape, and operating speed of the flywheel, through the governing gyroscope equations found in [5].

Due to time and manufacturing constraints concerning the housing for the flywheel, the design was scaled down to the largest size that could still be manufactured using the available processes, and within the allotted time frame and budget. The final flywheel was sized at four inches in diameter and two inches wide, as shown in the shop drawing in Appendix E.

4.3.2. Flywheel Stress Calculations

Since analytical equations for a web and flange geometry could not be found, initial estimates for the flywheel stresses were based on the governing equations found in [6].

Figure 4-5 shows that for a flywheel shaped as a hollow cylinder spinning at 8000 RPM, the stresses are well below the yield strength of steel (approximately 250MPa).

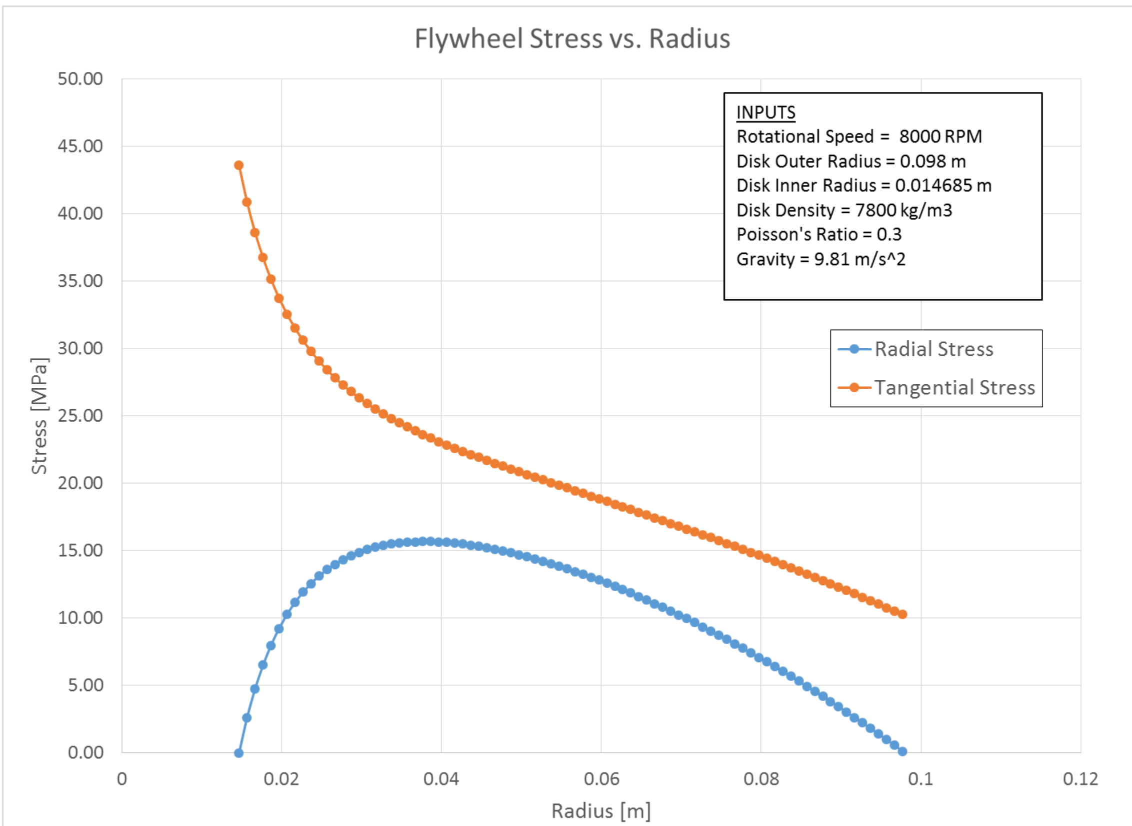


Figure 4-5 – Flywheel Stress vs Radius

4.4. Manufacturing

The following section describes the manufacturing procedures used during the production of the various components of the gyroscope stabilizer.

4.4.1. Flywheel and Shaft

To keep the flywheel as balanced as possible, it was made as a single piece by turning down a 4-½ inch diameter stock round bar. After the surface was trued on the lathe, a 1-$^{5}/_{32}$ inch hole was bored into the material to allow for a tight fit between the shaft and the flywheel, as seen in Figure 4-6.

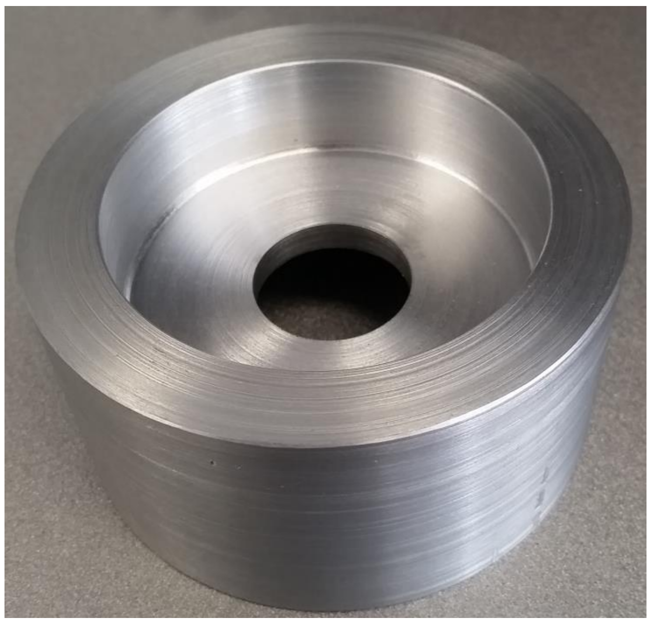


Figure 4-6 - Flywheel

The shaft was produced in similar fashion to the flywheel by turning a 1-¼ inch steel rod on the lathe. As seen in Figure 4-7, five steps of various diameters were included in shaft design to provide shoulders for the bearings, support the flywheel, as well as connect the shaft to the motor,

First, the different diameters were roughed out to 20 thousandths of an inch oversized. Half of them were turned from one side of the shaft, then the shaft was flipped around to allow turning of the rest of the diameters. The shaft was then re-mounted in the lathe, this time from both ends, and the diameters finished to the specifications. This ensured all the diameters would be as concentric as possible to reduce the chance of vibrations.

Once the flywheel and shaft were machined, it was found that the fit between them was a few thousandths of an inch too loose due to a manufacturing error. Because of time constraints, rather than reproduce the shaft or flywheel, the shaft was given a knurled surface where the flywheel would sit. This procedure increased the diameter of the shaft enough to achieve the intended tight fit between the two parts. The assembly was then aligned and refinished on the lathe to ensure proper balancing. The mounted shaft and flywheel can be seen in Figure 4-8.

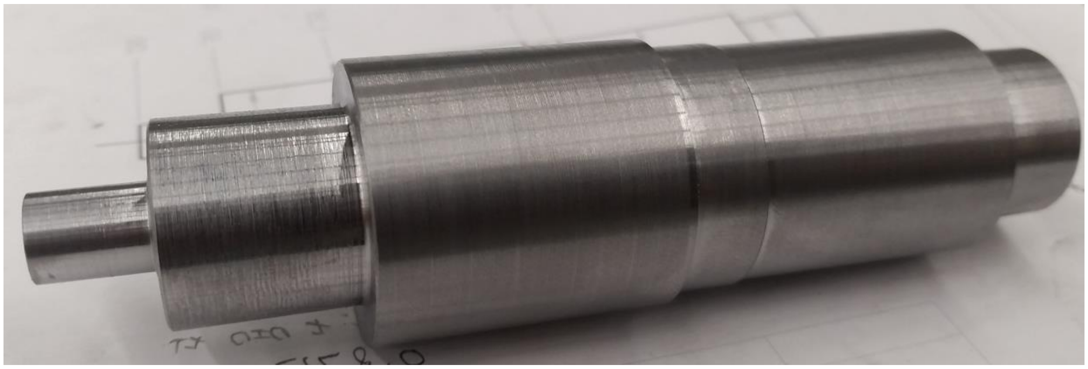


Figure 4-7 – Shaft

Figure 4-8 - Shaft Mounted in Flywheel

4.4.2. Housing

Since only one prototype was being built, it was determined that the best manufacturing method for the housing was lost-foam mold sand-casting. However, since two housing halves are required, and since the likelihood of achieving a perfect casting the first time was low, a 3D- printed negative of the housing, as seen in Figure 4-9, was produced to allow the creation of multiple polyurethane foam molds. One of these foam molds can be in Figure 4-10.

When the molten aluminum is poured into the sand casting with the foam mold inside, the foam vaporizes, form the aluminum housing as seen in Figure 4-10. This allowed for a quick and repeatable casting process.

Once castings of sufficient quality were achieved, all mating surfaces on the housing were trued on the milling machine, the bearing holes were bored out to the correct size, and bolt holes were drilled, as shown in Figure 4-11.

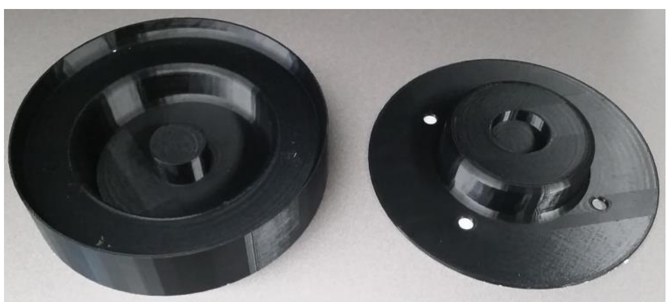


Figure 4-9 - 3D Printed Mold Negative

Figure 4-10 - Aluminum Casting (Left) and Polyurethane Mold (Right)

Figure 4-11 - Final Machined Aluminum Casting

4.4.3. Bearing Locating Caps

The bearing locating caps exist to ensure the bearings in the housing do not move axially at any time during the gyroscopes operation. The initial mounting plates for the caps were produced using a waterjet cutter, which cut the two circular parts, seen in Figure 4-12, out of a quarter inch thick aluminum plate. The parts were then powder coated for additional protection from the elements, and for aesthetic reasons.

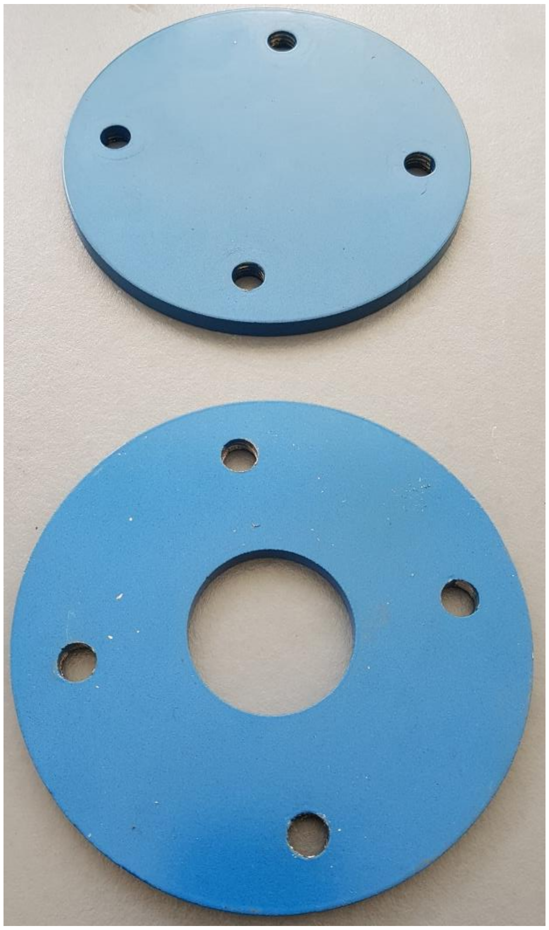


Figure 4-12 - Bottom Bearing Cap (Top) and Top Bearing Cap (Bottom)

4.4.1. Motor Mounting Bracket

The motor mounting bracket was cut on the waterjet cutter out of $^1/_{16}$ inch sheet steel. The mounting bracket was then bent into shape and powder coated to prevent rusting. The final motor mounting bracket can be seen in Figure 4-13.

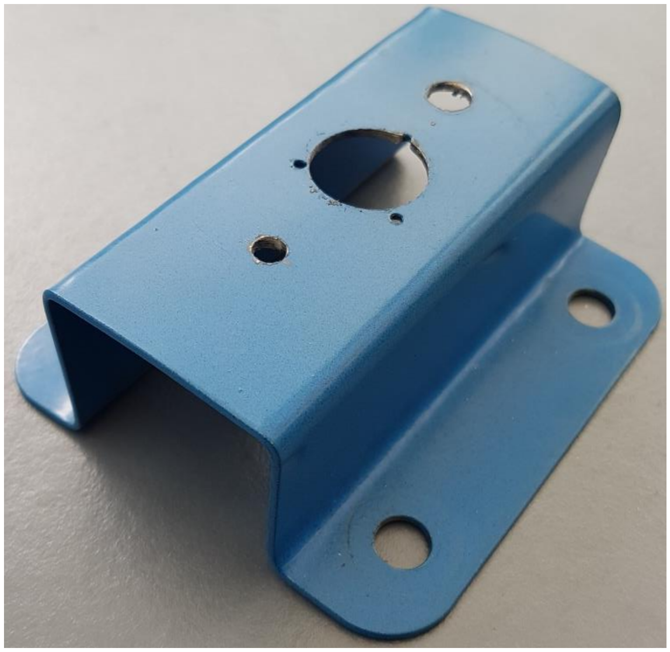


Figure 4-13 - Motor Mounting Bracket

4.4.2. Precession Brackets

The precession brackets were built out of two separate pieces; one piece of ¼ inch thick, two inch by two inch angle iron, and one piece of ¾ inch HR steel rod. The angle iron was first cut on the band saw to length then taken to the drill press to produce the two $^{3}/_{8}{}^{th}$ inch holes for bolting them to the casing, and one ¾ inch hole for the steel rod to sit in. The steel rod was turned on the lathe and then cut to length. One of the rods was hollowed out to allow a path for motor wiring. The rods were then welded to the angle iron before being sandblasted and powder coated to prevent rusting. The final brackets can be seen in Figure 4-14.

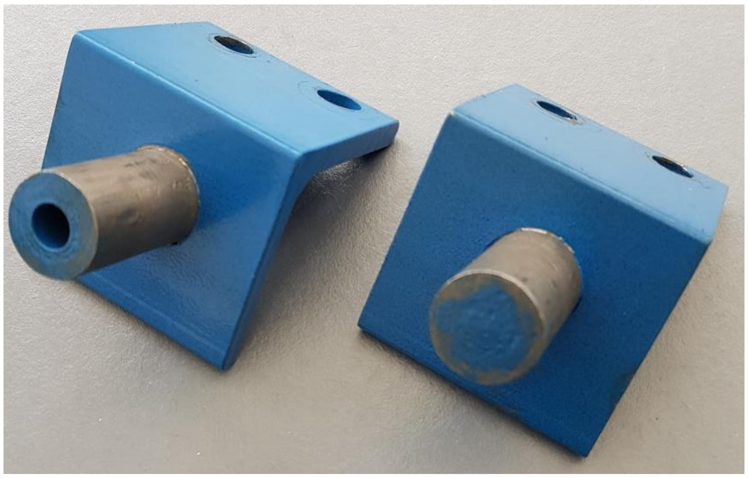


Figure 4-14 - Precession Brackets

4.4.3. Gyroscope Frame

The frame for the gyroscope was built out of one inch by one inch aluminum t-slot for the supporting structures, and then insulated using ¼ inch thick Lexan plastic for the larger sections of the frame, and ¾ inch thick Plexiglas to mount the precession bearings in. The aluminum t-slot was cut on a cold saw to the necessary lengths then had ¼ inch holes drilled into them to allow for hidden fasteners to be used. The Lexan was cut on a panel saw to the required dimensions and then had small tabs cut out of the corners to bypass the hidden screws. The Plexiglas was cut to the required lengths using a table saw and then a router was used to remove material around the edges so that it would slot into the t-slot aluminum, as seen in Figure 4-15. The Plexiglas then had a hole bored out using a milling machine to fit the bearings into. The final construction of the frame can be seen in Figure 4-16.

Figure 4-15 - Plexiglas Shoulder Bearing Mount

Figure 4-16 - Gyroscope Container

4.5. Assembly

In the final assembly, the shaft and flywheel are contained within the aluminum cast housing, which is located inside the t-slot frame via the mounting brackets, as seen in Figure 4-17. The final constructed assembly can be seen in Figure 4-18.

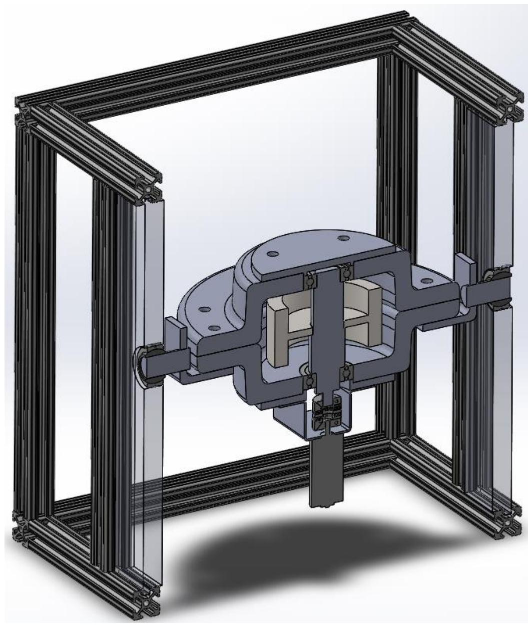


Figure 4-17 - Section View of Final Assembly

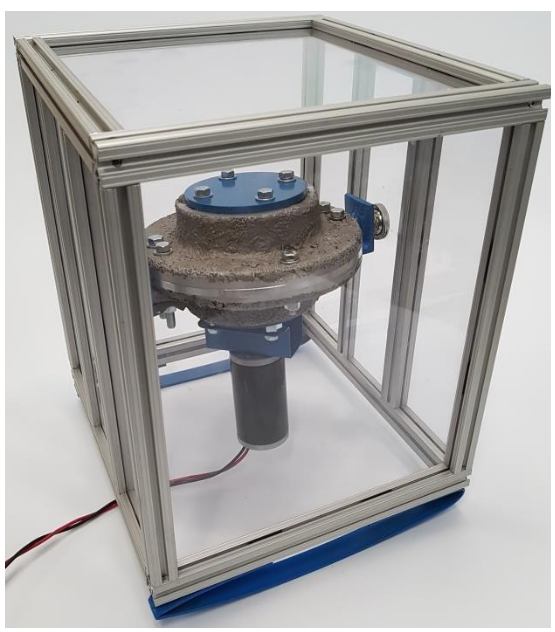


Figure 4-18 - Final Assembly of Gyroscope

4.6. Testing Procedures

To test the gyroscope's damping capabilities, several tests were performed. Arch-shaped pieces of bent steel were mounted on the bottom of the frame, shown in Figure 4-18, to allow it to rock back and forth, simulating the rolling motion of a boat at sea.

The first test involved tilting the assembly to an angle of approximately 10 degrees and then releasing it. This was performed with the gyroscope turned off and then again with the gyroscope turned on. The angle of the assembly over time was collected using an accelerometer.

For the second test, the assembly was placed on top of a piece of plywood, and then subjected to an approximately constant oscillation motion by lifting and lowering the plywood to simulate a wave. The gyroscope was left off for around five seconds then turned on for around five seconds. The roll angle of assembly was then collected with an accelerometer.

5. Discussion of Results

The following section looks at the data collected during testing and discusses the implications of the results as well as the difficulties encountered during testing.

5.1. Natural Decay Test

For the first test, the frame was tilted to a measured angle of approximately 10 degrees and then released with the gyroscope turned off and then with the gyroscope turned on. Figure 5-1 shows that when the gyroscope is active, the time for the rocking motion to decay is reduced from approximately eight seconds to four seconds.

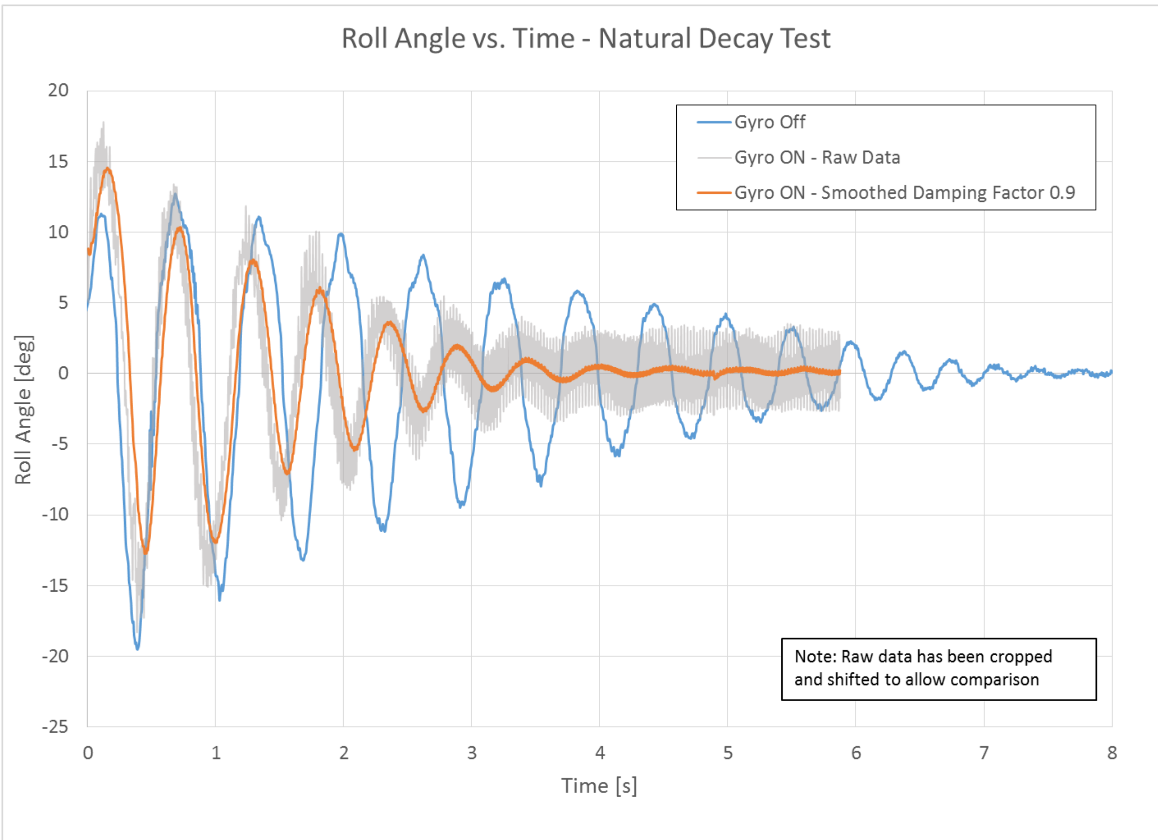


Figure 5-1 - Roll Angle vs. Time - Natural Decay Test

5.2. Constant Periodic Forcing Test

For the second test, the frame was subjected to a constant periodic force. Figure 5-2 shows that when the gyroscope is activated, the roll angle is reduced by approximately 50%.

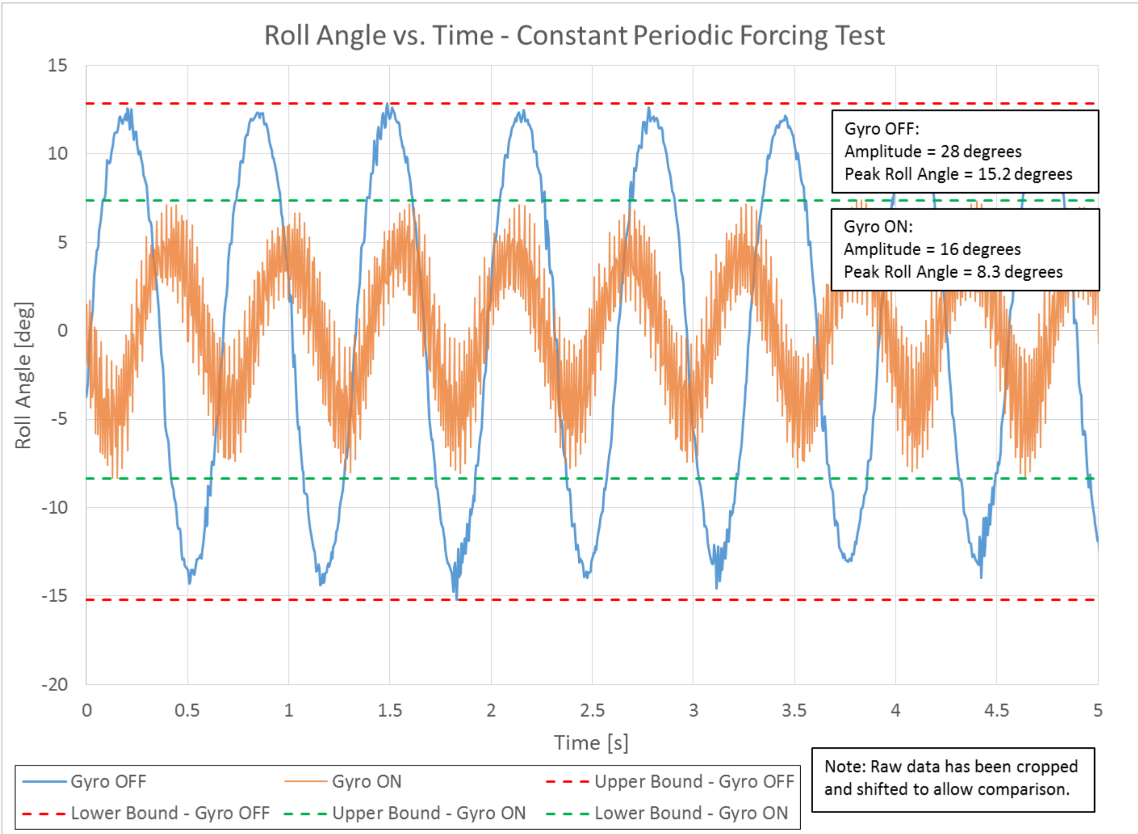


Figure 5-2 – Roll Angle vs. Time - Constant Periodic Forcing Test

5.3. Implications of Results

Since due to time constraints a mechanically repetitive test rig was not able to be constructed, precise values for how effective the system is cannot be stated at this time. However, the results shown in Figure 5-1 and Figure 5-2 are still very promising, giving a rough estimate of the system's effectiveness, and showing that the gyroscope is an effective means of stabilization that is worth developing further.

5.4. Difficulties Encountered

The main difficulties encountered with testing the gyroscope was the lack of time to produce a mechanically repetitive test rig, as well as vibration issues that made capturing clean data difficult.

Since the constant periodic forcing was generated by one team member moving the end of a piece of plywood manually and attempting to produce a constant motion, the frequency of the forcing motion is unknown. While the team members moving the plywood did their best to match the natural frequency of the assembly, an electronically controlled forcing rig would allow fine tune adjustments to be made, and thus allow a more extensive analysis to be performed.

Another difficulty was that when the gyroscope was turned on, the accelerometer used to take readings would pick up the vibrations, making the data more difficult to interpret. This was a huge problem during initial tests. It was soon discovered that the motor and shaft were very misaligned and causing unnecessary vibrations. Once the misalignment was fixed, vibrations were reduced to a level that allowed reasonably clean data to be collected.

6. Conclusion

To achieve the final product of a working boat stabilizer, there were many steps that had to be completed sequentially. The project began with identifying the objective, which was to design and build a scale-prototype of a system that would reduce the rocking motion of a small boat at rest by 50%.

Next, the team evaluated numerous concepts and determined which would be most effective at meeting the objective using a decision matrix. The gyroscope was chosen as the superior method of stabilization.

Each team member brainstormed numerous ways of manufacturing and assembling the gyroscope, taking into account available manufacturing processes, materials, time available to manufacture the various components, as well as cost.

A working prototype was produced, and testing was performed. The results of initial tests demonstrated the gyroscope's ability to decrease roll by approximately 50%.

6.1. Future Work

Future work for the gyroscope stabilization system comes down to four main categories:

1. Testing
2. Controlling
3. Design Improvements
4. Manufacturing Improvements

For our gyroscopic stabilization system, testing was performed without a repeatable, mechanical forcing system. Therefore, future work includes developing an automated test rig to improve the accuracy of the data collected. The rig would also be capable of measuring the stabilization torque produced by the system.

The gyroscopic stabilization system currently does not use any control systems that can predict the movement of the boat which would further improve the effectiveness of the system. Therefore, to further improve the system's effectiveness, a control system should be produced that can predict the motion of the boat and drive the precession motion of the gyroscope accordingly.

The current design is also not as space efficient as it could be. Large sections of the container are empty space which could be used for increased flywheel size. Therefore, the efficiency of the housing and flywheel shape could be improved to reduce the empty space within the frame and increase the system's performance.

The motor mounting bracket could be redesigned for more precise locating of the motor shaft, which would eliminate the need for manual adjustments and guarantee proper alignment. As well, the casting process could be refined to achieve a better surface finish.

6.2. Lessons Learned

Many lessons were learned during the duration of the project. Some of these lessons resulted in changes that could be implemented immediately, whereas other lessons resulted in desired changes that will have to be implemented at a later date.

The molds for the housings were designed to the final dimensions of the SolidWorks model. However, the amount of material that needed to be removed to achieve reasonable flat matting surfaces was underestimated, and thus after machining, the housings did not fully contain the shaft. Therefore, to compensate for the lost material and ensure that the shaft would fit within the housing, a ring, as seen in Figure 6-1, was manufactured out of ¼ inch thick aluminum, and was placed between the housing mating surfaces. In the future, the team will be sure to design casting molds oversized to compensate for the lost material due to machining.

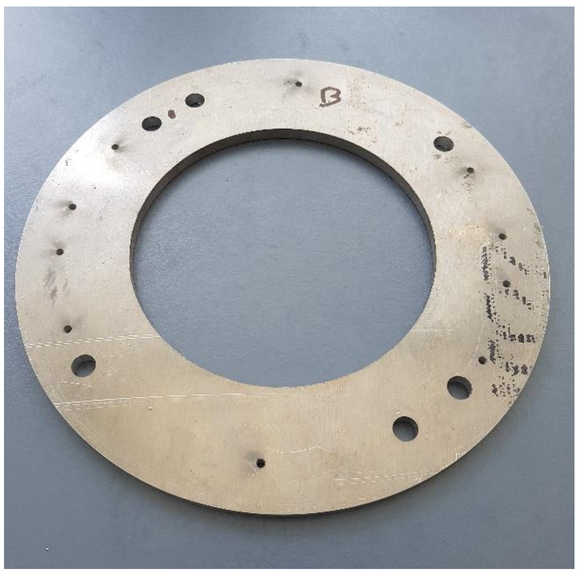


Figure 6-1 - Aluminum Spacer Ring

While the motor mounting bracket was relatively easy to bend into shape, it was discovered that when assembling it to the motor, imperfections in the bends and mounting holes caused the misalignment of the motor shaft, which resulted in unnecessary vibrations.

The reason for this misalignment was that the motor mount was originally made for a smaller motor but needed to be modified for a larger motor when it was found the smaller motor was undersized. So while the original mounting holes had been cut with the water-jet, the new mounting holes were drilled on the drill press, and the tolerances were out just enough to cause the flexible coupling to bind when rotating.

This problem was mitigated by re-drilling the mounting holes larger such that the bracket can be shifted to precisely align the motor and shaft. As well, shims were placed under the motor to improve its angular alignment.

Working through this misalignment problem gave the team a better sense for how much precision rotating parts need in order to operate smoothly, and how much time can be saved if a part is designed to eliminate the need for manual adjustment.

The final lesson learned was that the team must be always be prepared to be adaptable to unforeseen circumstances. The original motor selected to drive the flywheel ended up being drastically undersized due to misjudgment when calculating the required torque, and thus it began overheating during initial tests. With the help of Jason Brett, a significantly larger motor was found to drive the flywheel. This required some modifications to the motor mounting bracket and the flexible coupling,

7. Bibliography

[1] A. Molland, Ed., THe Maritime Engineering Reference Book: A Guide to Ship Design, Construction, and Operation, Hungary: Butterworth-Heinemann, 2008.

[2] [Online]. Available: http://www.yachtforums.com/attachments/stabilizer-trim-tab-combo-jpg.48712/.

[3] T. J. Nedwed, "Hydrogyro Ship Stabilizer and Method for Stabilizing a Vessel". Patent US7458329B2, 2 December 2008.

[4] [Online]. Available: https://patentimages.storage.googleapis.com/US7458329B2/US07458329-20081202-D00003.png.

[5] P. Steinmann, "Whitepaper 1403: How Gyros Create Stabilizing Torque," 2014. [Online]. Available: http://veemgyro.com/wp-content/uploads/2017/06/White_Paper_1403-How_Gyros_Create_Stabilizing-Torque.pdf.

[6] R. Beardmore, "Rotating Cylinders," [Online]. Available: http://www.roymech.co.uk/Useful_Tables/Mechanics/Rotating_cylinders.html. [Accessed 11 February 2018].

Appendix A. **Request for Proposal**

Request for Proposal

Boat Stabilization System

October 17, 2017

Issued by: WaterWorks Co.

Introduction and Background

WaterWorks, a leader in modern marine technology, is seeking candidates to submit proposals for the development of a lightweight and portable boat stabilization system. This system will be designed specifically for use with WaterWorks' recently developed line of luxury yachts.

Current boat stabilization systems utilize technologies such as fins which hang over the gunnel or gyroscopes placed within the boat's hull. While these technologies achieve stabilization, they are often cumbersome and expensive to install.

Project Description

The end product will meet the following objectives:

- Reduce rocking motion of yachts that are at rest to within one degree
- Be light enough to be installed by a single person
- Operate autonomously once installed and calibrated
- Comply with current marine safety regulations

Project Scope and Deliverables

The selected candidate will be responsible for a developing a complete design as well as manufacturing a functional prototype to be presented at WaterWorks' Annual Marine Technology Showcase on May 21st, 2018.

The stabilization system must be compatible with WaterWorks' recently developed line of medium sized luxury yachts which range from 35' to 45'.

Submission Requirements

Proposals must be submitted via email to proposal@WaterWorks.com by October 31st, 2017.

The following items must be addressed in the proposal:

- Organization description and key personnel
- Project deliverables
- Milestone schedule
- Work breakdown structure
- Project schedule
- Project budget breakdown

RFP Timeline

Proposal submissions due	October 31st, 2017
Top bidders selected/unsuccessful candidates notified	November 7th, 2017
Start of negotiations	November 8th , 2017
Contract Award/unsuccessful candidates notified	November 22nd, 2017

Budget

WaterWorks has designated $25,000 towards this project. Bidders may propose an alternate budget should they think it is justifiable.

Evaluation Factors

The contract will be awarded to the candidate whose proposal best meets the following criteria:

- Proposed design meets or exceeds all project objectives on time and on budget
- Candidate demonstrates a high level of technical expertise and familiarity with the marine industry
- Submission contains all required documents

Outcome and Performance Standards

To ensure that the project progresses steadily as described in the project proposal, a WaterWorks representative will perform a bi-weekly site analysis of the company awarded the project. The company will be required to submit a brief progress report to the representative which includes milestones achieved and any change requests. Furthermore, the representative will assess the work environment and determine whether the project is meeting technical and safety requirements. If either aspect is not met, WaterWorks will alert the contracted company of changes that must be made in order to ensure compliance. If the non-compliances continue, termination of the contract may be considered.

Contact Information

WaterWorks Co.

1233 Technology Avenue, Vancouver, CA

604-604-6046

proposal@WaterWorks.com

Appendix B. Project Management Documentation

This appendix contains the documents used during project management.

B.1. Milestone Schedule

Milestone	Date
Six Concept Designs Generated	November 21, 2017
Final Concept Selected	November 28, 2017
Detailed Design Completed	January 18, 2018
3D Model Completed	February 1, 2018
Shop Drawings Completed	February 8, 2018
Scale Prototype Completed	March 30, 2018
Testing and Analysis Completed	April 15, 2018
Project Completed	May 25, 2018

B.2. **Technical Requirements**

Criteria for Performance Approval:

- Weight
- Cost
- Size
- Damping Effectiveness
- Power Requirements
- Noise

Functional Requirements:

- Easy to install
- Autonomous operation
- Quiet
- Easy to maintain
- Reliable in harsh marine environment
- Minimal vibration
- Minimal boat modification required
- Compatible with medium sized yachts (20-30ft)

Performance Requirements:

- Reduce roll by at least 50%
- Smooth / comfortable response

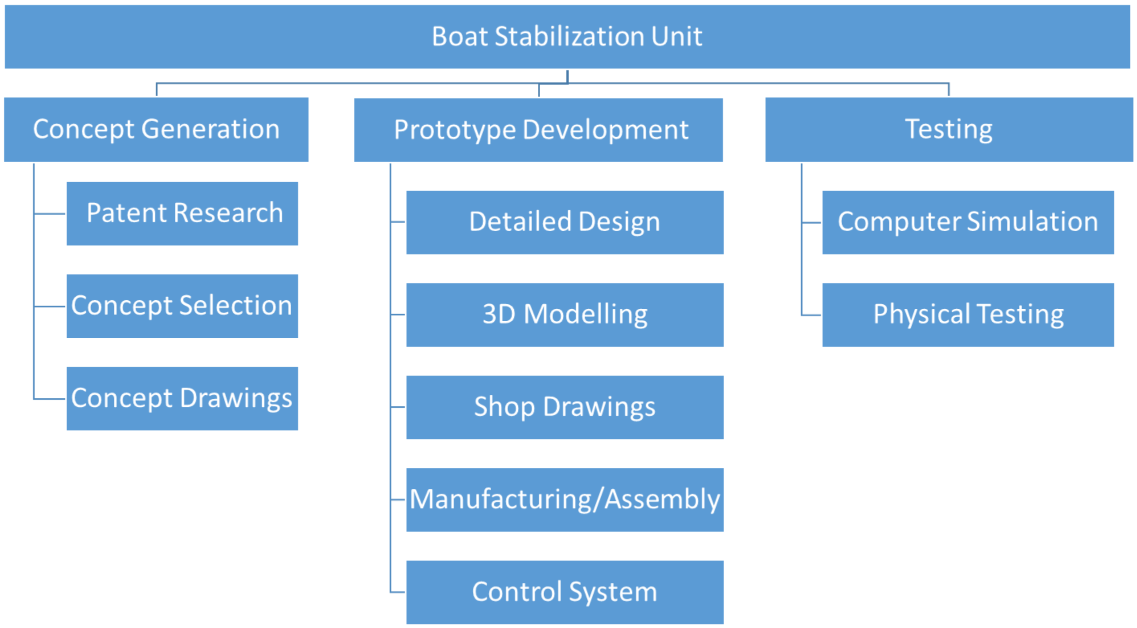
Other Requirements:

- Conforms to marine safety standards

Limits and Exclusions:

- Controls roll only
- Only designing for boats at rest
- Only designing for medium sized boats
- Tests will only look at anti-roll effectiveness

B.3. Work Breakdown Structure

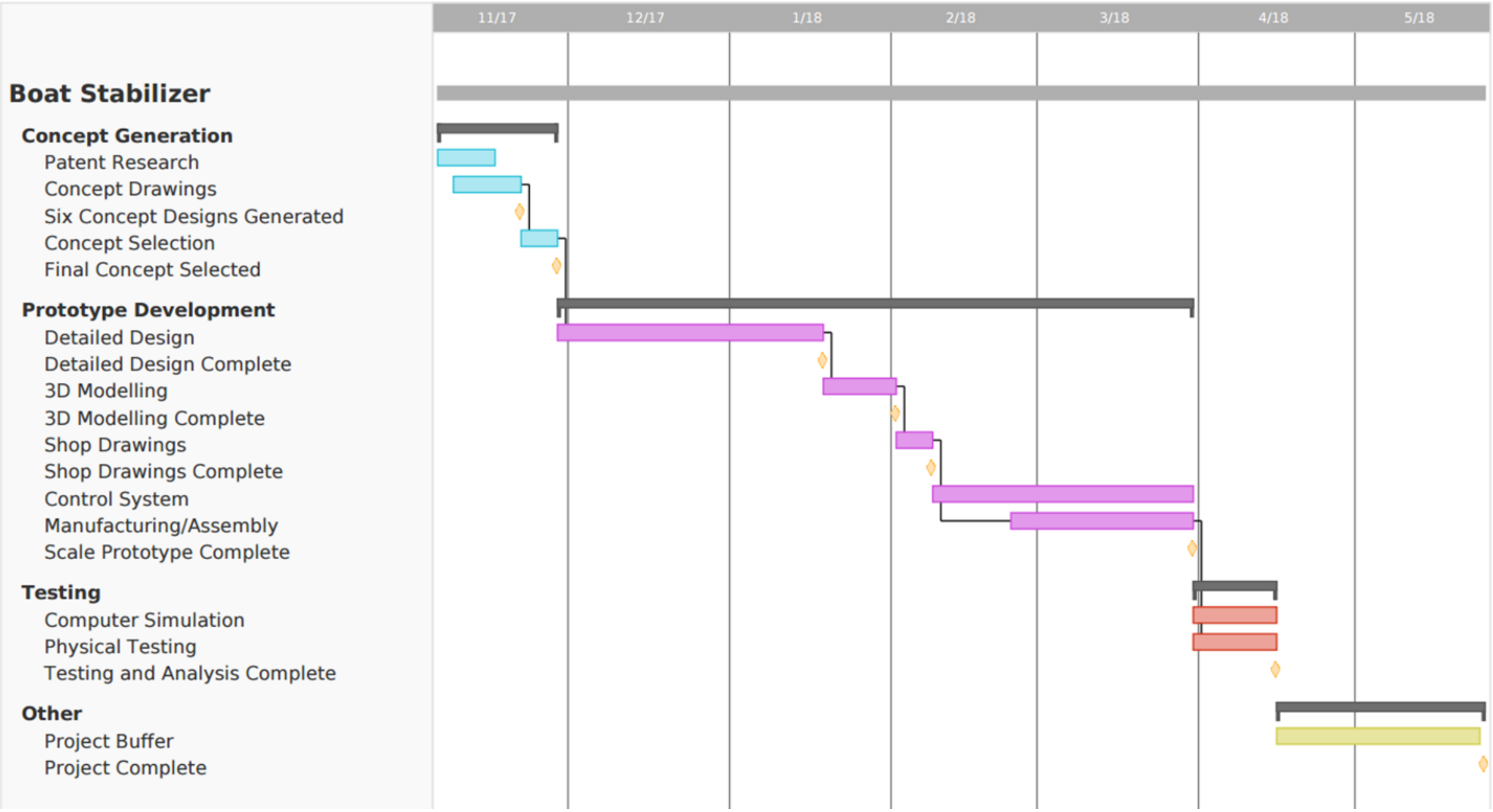


B.4. **Responsibility Assignment Matrix**

Work Items	Greg King	Clark Friesen	Konur Nicholson	Lucas Estabrook
Documentation	I	R	A	A
Concept Generation	C	A	A	R
Control Design	I	R	A	A
Control Implementation	I	R	A	A
Manufacturing	C	A	R	A
CAD Modeling	I	A	A	R
Research	I	A	A	R
Testing	I	A	R	A

R = Responsible A = Accountable C = Consult I = Inform

B.5. **Project Schedule**



Appendix C. **Boat Model Parameters**

Constants used in Theoretical Calculations

Constants	INPUTS
g [m/s²]	9.81

Boat Properties used in Theoretical Calculations

Boat Properties	INPUTS
i'_T [m]	0.272
Δ [kg]	917.000
D	0.100
GM [m]	0.100

Wave Properties used in Theoretical Calculations

Wave Properties	INPUTS
H_W [m]	0.500
L_W [m]	3.000
v_A [rad]	0.524
ω [rad/s]	6.000

Equation Parameters used in Theoretical Calculations

Equation Parameters	INPUTS
a	67.843
b	49.409
c	899.577
[illegible]	0.364
ω_o	3.641
Φ_o	0.000
V_3	0.573
η	1.648
Υ_3	0.190

Appendix D. **Design Review Package**

Boat Stabilization System

Design Review Package

Prepared For:

Johan Fourie

Greg King

Mechanical Engineering Class of 2018

Prepared By:

Clark Friesen

Konur Nicholson

Lucas Estabrook

Date: January 31st, 2018

Introduction

While at sea or on a lake boats are put into motion by the waves when at rest. The motions that a boat can be placed under are yaw, pitch, and roll, as seen in figure 1. The goal of the boat stabilization project is to create a system to reduce the roll of a ship at rest, specifically for small fishing boats.

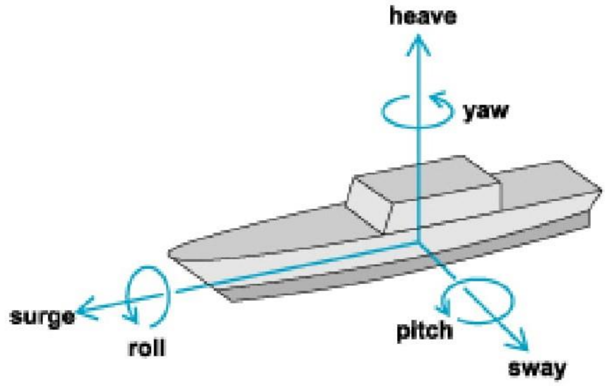


Figure 1 - yaw, pitch, and roll of a boat
Source: https://i.stack.imgur.com/odMH9.gif

Problem Statement

Boats of all sizes roll when at rest in water which makes for a less comfortable experience for occupants onboard. Currently there are many systems in the market for ships that are at least 30ft long but there are few if any solutions commercially available for ships smaller than this.

Project Objective

The objective of this project is to design a stabilization system that works with boats that are around 12 feet long. The stabilization system should decrease roll by at least 50% for ships experiencing a maximum roll of 10 degrees without the system activated. Thus the system is only designed to stabilize effectively in relatively calm conditions.

Concept Selection

Seven possible solutions to minimize the roll of a ship were considered and are outlined below.

- Gyroscopes
- Flopper stoppers
- Submerged fins
- Passive or active anti-roll tanks
- Passive or active mass dampers

As shown in Figure 2 , a decision matrix was created and, based on careful weighting of the performance objectives, the stabilization system decided upon was the gyroscope.

Category Weighting (1 – 10)	Scale 1-5, 5 means best performance	Gyroscope	flopper stopper	Submerged Fins	Passive Anti-Roll Tank	Active Anti-Roll Tank	Passive Mass Damper	Active Mass Damper
4	Weight	3	5	3	1	1	2	2
7	Drag	4	5	1	3	3	3	3
6	Cost	1	5	1	4	3	3	2
8	Size	4	5	5	2	1	2	1
10	Damping Effectiveness							
4	Power Requirements	3	5	1	4	3	5	3
5	Efficiency							
5	Noise	2	5	4	5	3	5	3
8	intererence with ship living spaces	4	5	5	2	2	2	2
3	Easy to install	3	5	1	4	3	3	2
8	Easy to maintain	4	5	1	5	4	4	3
8	Reliable in Marine Environment	5	2	1	4	4	4	4
4	Minimal vibration	3	5	3	5	4	4	3
8	Minimal boat modification required	4	5	1	3	3	3	3
2	Tunable (once installed)	5	1	5	1	3	1	3
8	Compact	4	5	3	2	1	2	1
7	Smooth / comfortable response	5	3	2	3	4	3	4
10	Effect on boat stability (1 means makes unstable)	5	5	5	1	1	4	4
6	Range of frequencies it works with	5	4	5	2	3	2	3
	Total	414	478	296	311	277	328	290

Figure 2 - Stabilization system decision matrix

Theory of Gyroscope Physics

The following is a brief explanation of how a gyroscope works:

1. *Waves cause the vessel to roll*
2. *Rolling motion combines with the spinning flywheel to create precession motion*
3. *Precession motion combines with the spinning flywheel to create stabilizing torque* [1]

Symbol	Description	Coordinate Sense	Units
ω_s	Flywheel spin rate	+ve clockwise looking down	rpm or rad.s^{-1}
ω_p or $\dot{\alpha}$	Flywheel precession rate	+ve rocking forward	deg.s^{-1} or rad.s^{-1}
α	Flywheel precession angle	+ve rocking forward	deg or rad
$\dot{\theta}$	Vessel roll rate	+ve to STBD	deg.s^{-1} or rad.s^{-1}
θ	Vessel roll angle	+ve to STBD	deg or rad
τ_{wave}	Wave Induced Rolling Torque	+ve to STBD	kNm
τ_{gyro}	Gyro torque	+ve to STBD	kNm
τ_{prec}	Precession torque	+ve rocking forward	kNm
τ_{stab}	Stabilizing torque	+ve to STBD	kNm
τ_{yaw}	Yaw torque	+ve bow to port	kNm
$\tau_{control}$	Precession Control Torque	+ve Bow up	kNm
J_{spin}	Flywheel Rotational Inertia	n/a	kg.m^2

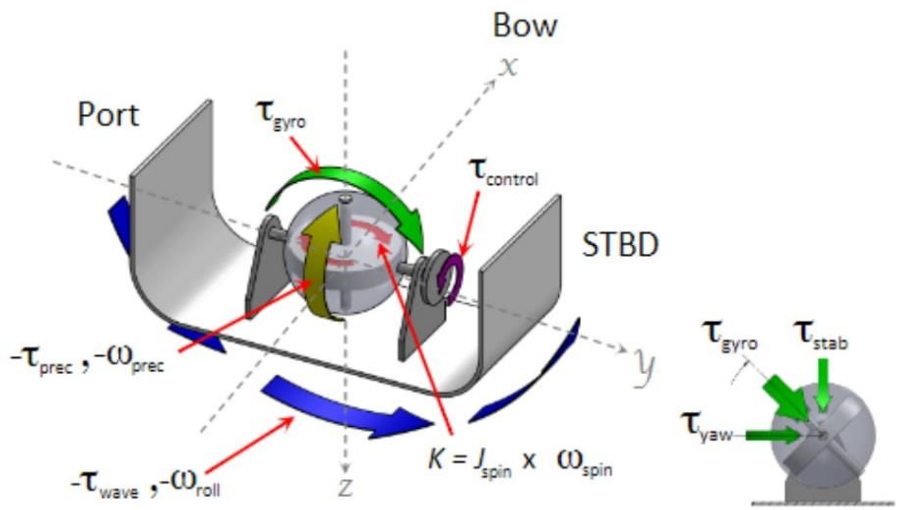


Figure 3 - Physics of a Gyroscope [1]

Competitive Analysis of Existing Products

The main competition for our system is from Seakeeper. They too produce gyroscope stabilization systems for boats with the main difference being that their systems are for boats 30 feet or longer and cost at least $28,000. Thus a niche market exists for stabilizing small fishing boats which our system is designed for.

Figure 4 - Seakeeper Stabilizer

Current Product Development Specifications

The specifications for this project were originally quite flexible. Overall our group decided that the only aspect of motion that the gyroscope will deal with in the initial design is the rolling motion of the ship. The finished model will be a full size gyroscope designed to stabilize typical 12 foot long aluminum boats.

Performance:

The performance of our gyroscope is intended to reduce the roll of a 12ft long aluminum fishing boat by 50%. It will be designed to achieve this roll reduction for calm conditions where there is a maximum roll angle of 10 degrees without the stabilizing system activated.

Weight:

The max weight of the entire system will be less than 120lbs.

Size:

The entire system must fit within a 12ft long fishing boat with a beam width of 61”.

Safety:

The gyroscope must be contained safely within its gimbal cage and mountings.

Concept Development

The current status of the design is summarized in Figure 5 below:

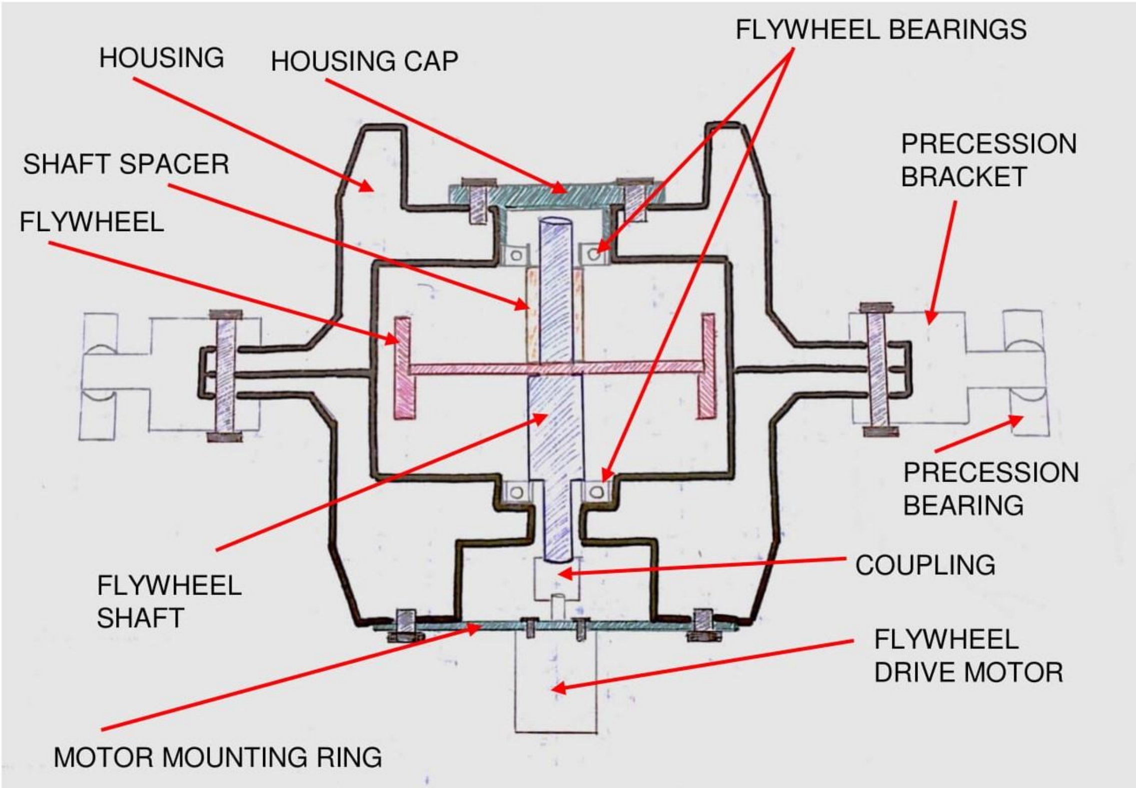


Figure 5 - Gyroscope Assembly (Frame not Shown)

Assembly Details

The following describes in more detail the individual components of the assembly shown in Figure 5.

Housing

The housing will be made of two identical castings, which will then be machined with the required holes for the flywheel bearings to sit in. It will most likely be cast from aluminum which is readily available in the BCIT shop.

Housing Cap

The housing cap consists of a ring which presses against the outer race of the flywheel bearing as shown in Figure 5. Thin spacers may need to be inserted in between the housing cap and the housing itself to ensure a proper bearing tolerance.

Flywheel

The flywheel will be constructed from two parts: an outer ring and an inner disc. The outer ring is made from a machined pipe, and the inner ring is made from plating cut to rough size on the waterjet and then precisely machined on the lathe. It is yet to be determined whether the outer ring and inner disc will be welded together or fit together by shrink-fitting.

To optimize the effectiveness of a flywheel, it is desired to have as much mass rotating at the maximum distance away from the spin axis. This minimizes the overall mass while increasing the angular momentum created by the flywheel. Based on the torque requirements of the gyroscope, the angular momentum required to stabilize a 12-foot boat is approximately 116 [N*m*s]. This value can be achieved by adjusting various flywheel properties – these include flywheel RPM, material density, web thickness and radius, flange thickness and radius, and inner hole radius (for shaft mounting).

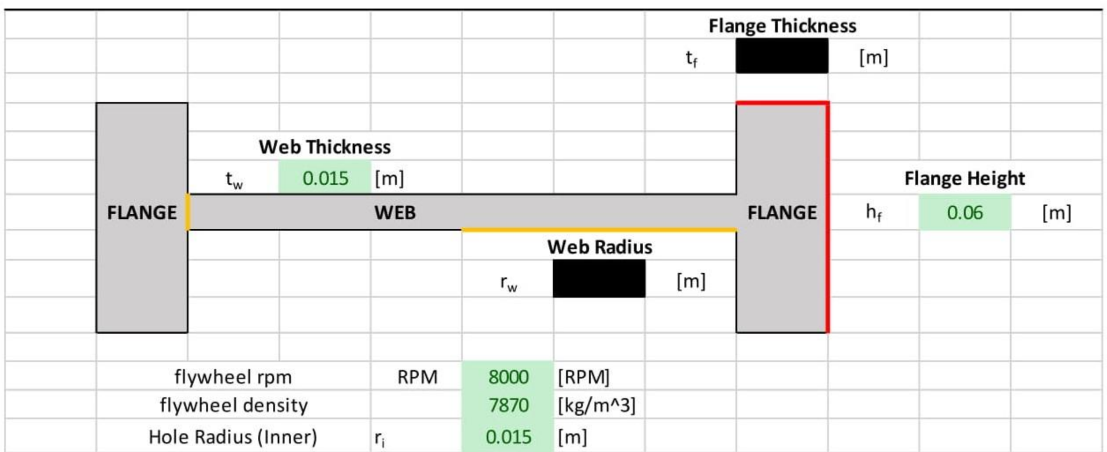


Figure 6 - Flywheel Spreadsheet Inputs

The combination of flange thickness and web radius will determine the maximum radius of the flywheel, and since it is one of our objectives to make the entire system portable, they were plotted against each other as seen in Figure 7.

	Web Radius [m]											
Flange Thickness [m]	0.1	0.105	0.11	0.115	0.12	0.125	0.13	0.135	0.14	0.145	0.15	0.155
0.005	5.145752	5.600062	6.072915	6.564311	7.07425	7.602733	8.149759	8.715328	9.29944	9.902096	10.52329	11.16304
	0.034519	0.040969	0.048272	0.056499	0.065723	0.076021	0.087473	0.100159	0.114166	0.12958	0.146492	0.164996
	0.105	0.11	0.115	0.12	0.125	0.13	0.135	0.14	0.145	0.15	0.155	0.16
	28.91824	34.3221	40.44037	47.33246	55.06013	63.68746	73.28085	83.90905	95.64313	108.5565	122.7249	138.2263
0.007	5.774739	6.258718	6.76124	7.282305	7.821914	8.380066	8.956761	9.551999	10.16578	10.79811	11.44897	12.11839
	0.041587	0.049085	0.057535	0.067012	0.077594	0.089362	0.1024	0.116794	0.132633	0.150011	0.16902	0.18976
	0.107	0.112	0.117	0.122	0.127	0.132	0.137	0.142	0.147	0.152	0.157	0.162
	34.83946	41.12132	48.20035	56.13971	65.00487	74.86364	85.78616	97.84491	111.1147	125.6726	141.5981	158.973
0.009	6.415594	6.929242	7.461433	8.012168	8.581446	9.169267	9.775631	10.40054	11.04399	11.70598	12.38652	13.0856
	0.049062	0.057648	0.067285	0.078055	0.090039	0.103323	0.117995	0.134146	0.151871	0.171264	0.192426	0.215459
	0.109	0.114	0.119	0.124	0.129	0.134	0.139	0.144	0.149	0.154	0.159	0.164
	41.10217	48.2947	56.36865	65.39092	75.43071	86.55955	98.85132	112.3822	127.2307	143.4778	161.2065	180.5025
0.011	7.068316	7.611634	8.173494	8.753898	9.352845	9.970335	10.60637	11.26095	11.93407	12.62573	13.33593	14.06468
	0.056961	0.066673	0.07754	0.089645	0.103076	0.117923	0.134278	0.152237	0.171898	0.193362	0.216732	0.242116
	0.111	0.116	0.121	0.126	0.131	0.136	0.141	0.146	0.151	0.156	0.161	0.166
	47.71929	55.85572	64.95935	75.10077	86.35291	98.79105	112.4928	127.538	144.009	161.9904	181.5691	202.8342
0.013	7.732906	8.305893	8.897423	9.507495	10.13611	10.78327	11.44897	12.13322	12.83601	13.55734	14.29722	15.05564
	0.065298	0.076177	0.088315	0.1018	0.116725	0.133182	0.151269	0.171087	0.192738	0.216326	0.241961	0.269753
	0.113	0.118	0.123	0.128	0.133	0.138	0.143	0.148	0.153	0.158	0.163	0.168
	54.70391	63.81812	73.98676	85.28416	97.78699	111.5742	126.7272	143.3296	161.4674	181.2289	202.7047	225.9879
0.015	8.409364	9.01202	9.633219	10.27296	10.93125	11.60807	12.30345	13.01736	13.74982	14.50082	15.27037	16.05846
	0.07409	0.086177	0.09963	0.114539	0.131003	0.149119	0.168989	0.190717	0.21441	0.240179	0.268136	0.298396
	0.115	0.12	0.125	0.13	0.135	0.14	0.145	0.15	0.155	0.16	0.165	0.17
	62.06941	72.19584	83.46544	95.95625	109.7487	124.9255	141.5716	159.7746	179.624	201.212	224.6329	249.9834

Figure 7 – Example of Web Radius vs Flange Thickness Spreadsheet Results for Above Inputs

For each combination of flange thickness and web radius, as well as the five green constant inputs for the flywheel shown in Figure 6, four properties were extracted as shown in Figure 8.

	Mass	[kg]
	Inertia	[kg/m^2]
	Total Radius	[m]
	Angular Momentum	[N*m*s]

Figure 8 - Outputs of the Flywheel Spreadsheet

In the angular momentum rows from the spreadsheet above, cells highlighted in blue are viable options in terms of meeting the minimum angular momentum criteria. The cells highlighted in bright yellow are the optimal choices as they meet the requirements while minimizing the overall mass and flywheel radius.

Flywheel Shaft

The flywheel shaft will most likely be machined from steel and will be approximately one inch in diameter according to preliminary calculations.

$$\sigma = \frac{32M}{\pi D^3}$$

$$D = \left(\frac{16T_{gyro}}{\pi\sigma}\right)^{\frac{1}{3}} = \left(\frac{16(450)}{\pi(250x10^6)}\right)^{\frac{1}{3}} = 0.02093m = 20.93mm = 0.824inch$$

Shaft Spacer

The spacer is used to position the bearing in the housing.

Motor Mounts

The motor will be mounted on a circular plate cut on the water jet and then mounted to the outside of the housing.

Precession Bearings

The precession bearings will be spherical plain bearings which will allow for inaccuracies in manufacturing and thus prevent having the precession axis lock. They will be press fit into the outer frame (not shown).

Frame

The frame will mount into the boat and hold the gyroscope system stable. The frame design will be finalized at a later date.

Project Schedule

Figure 9 shows the work plan for the next month. The project is currently right on schedule, with manufacturing planned to commence on February 24th.

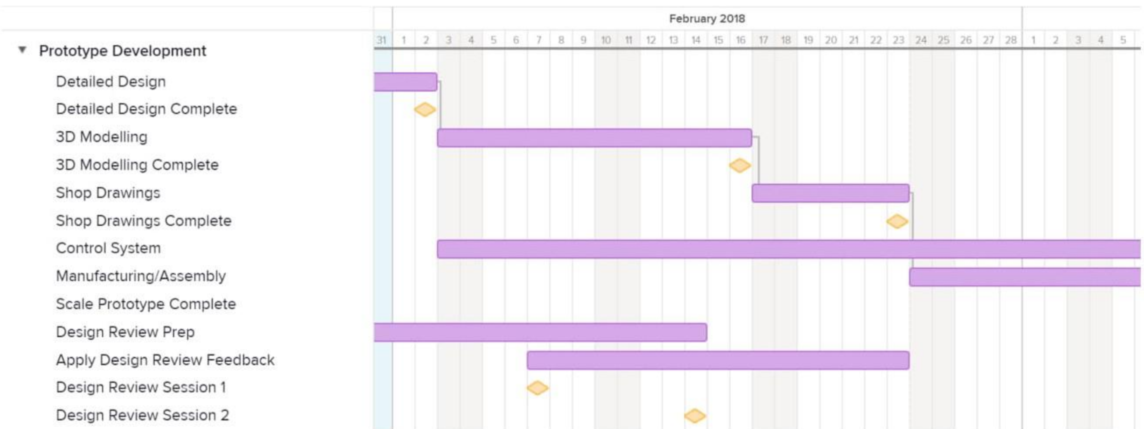


Figure 9 - Gantt Chart, Next 30 Days

Project Budget

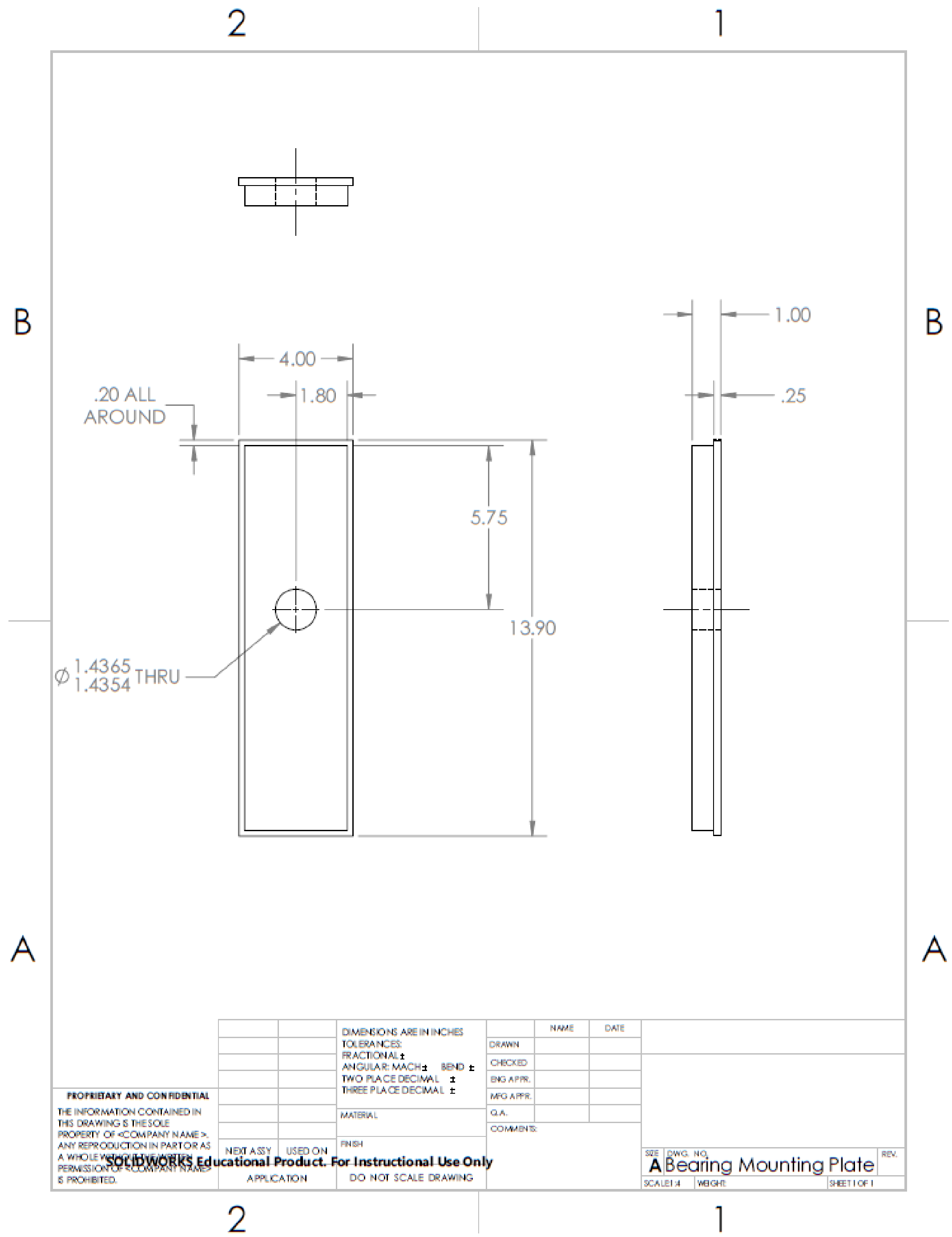
Our total budget is $300. We are aiming to keep the project costs at or below this amount by manufacturing many of the components ourselves, and by acquiring parts for free where possible. Currently no money has been spent as we are still in the design phase.

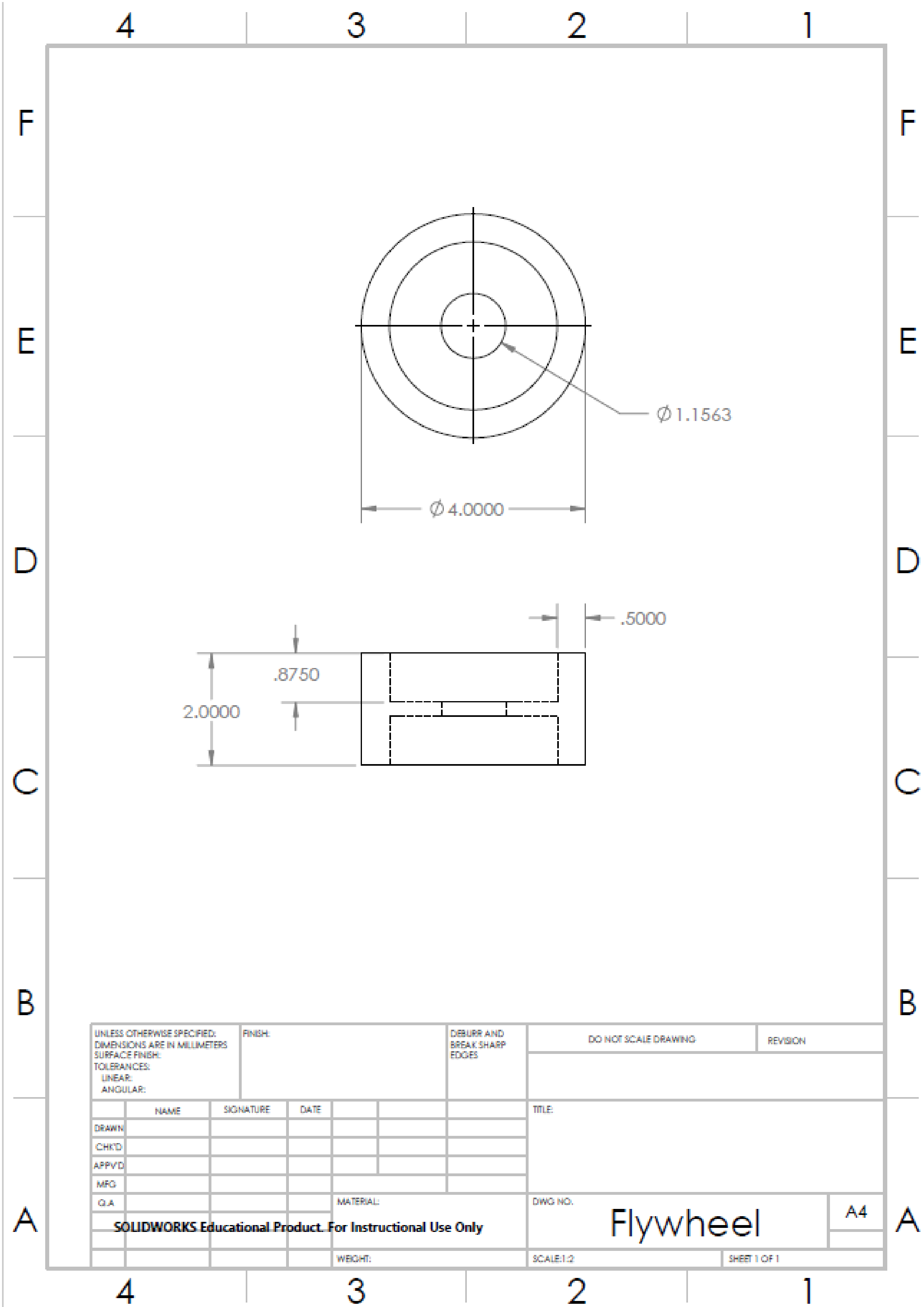
References

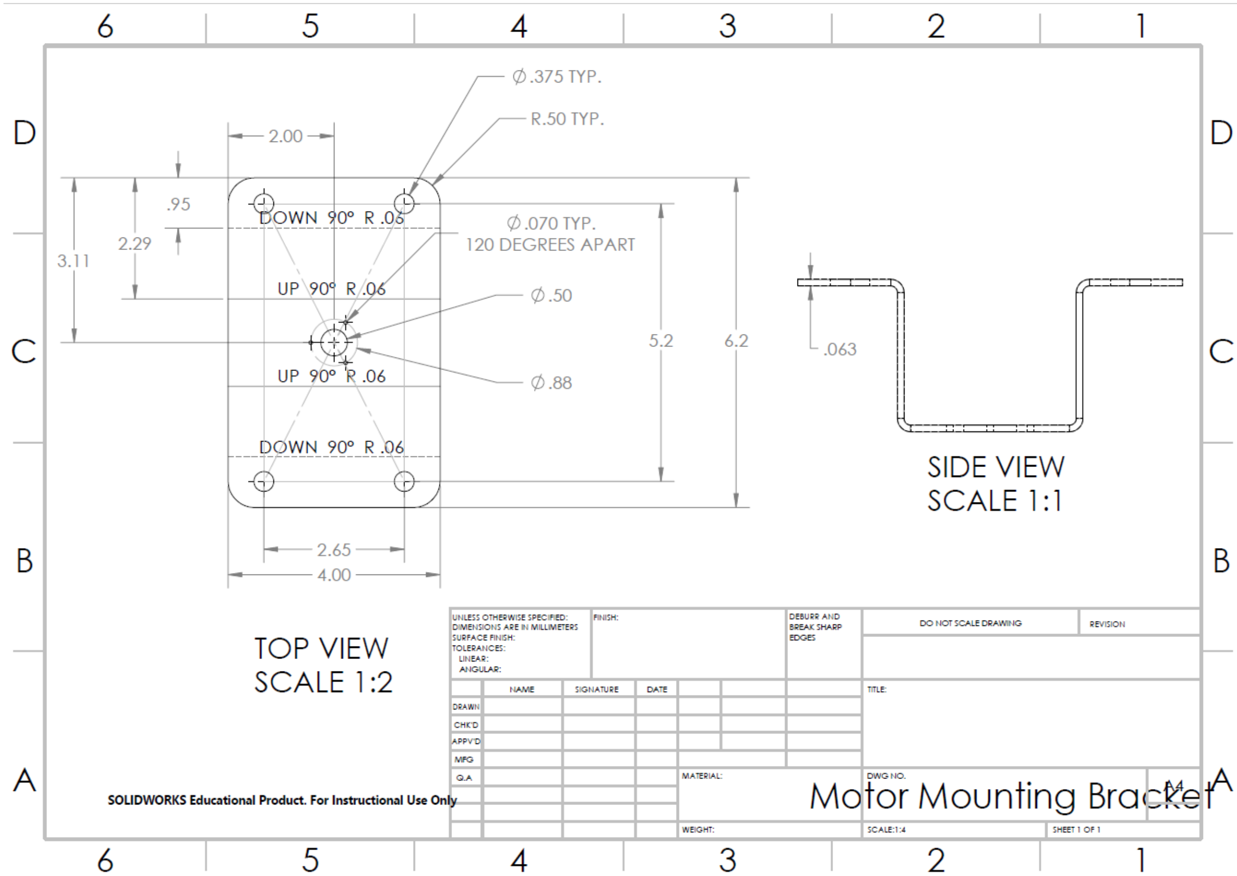
[1] P. Steinmann, "How Gyrostabilizers Work," 28 July 2016. [Online]. Available: http://veemgyro.com/how-gyrostabilizers-work/.

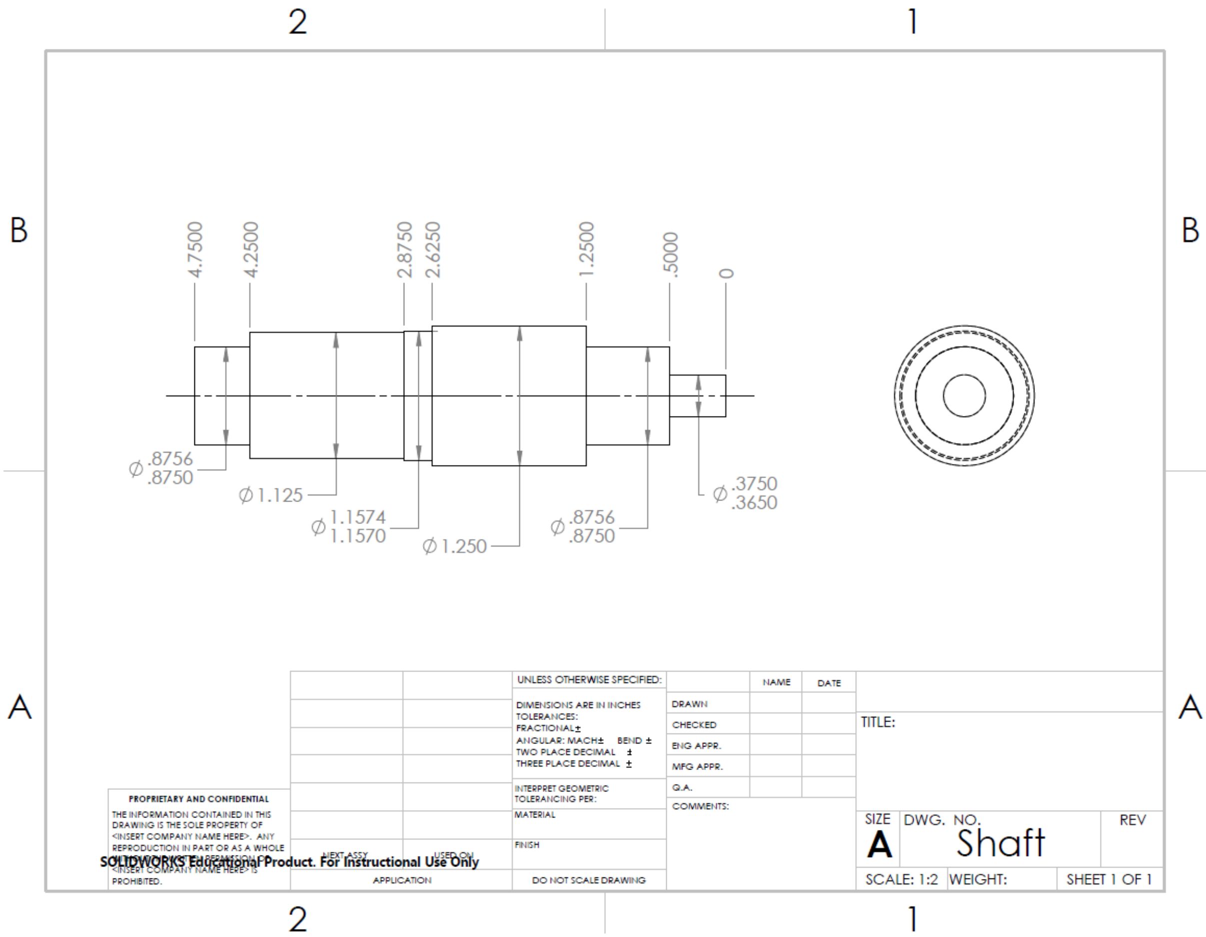
Appendix E. **Manufacturing Drawings**

The following section includes the manufacturing drawings for all parts produced.

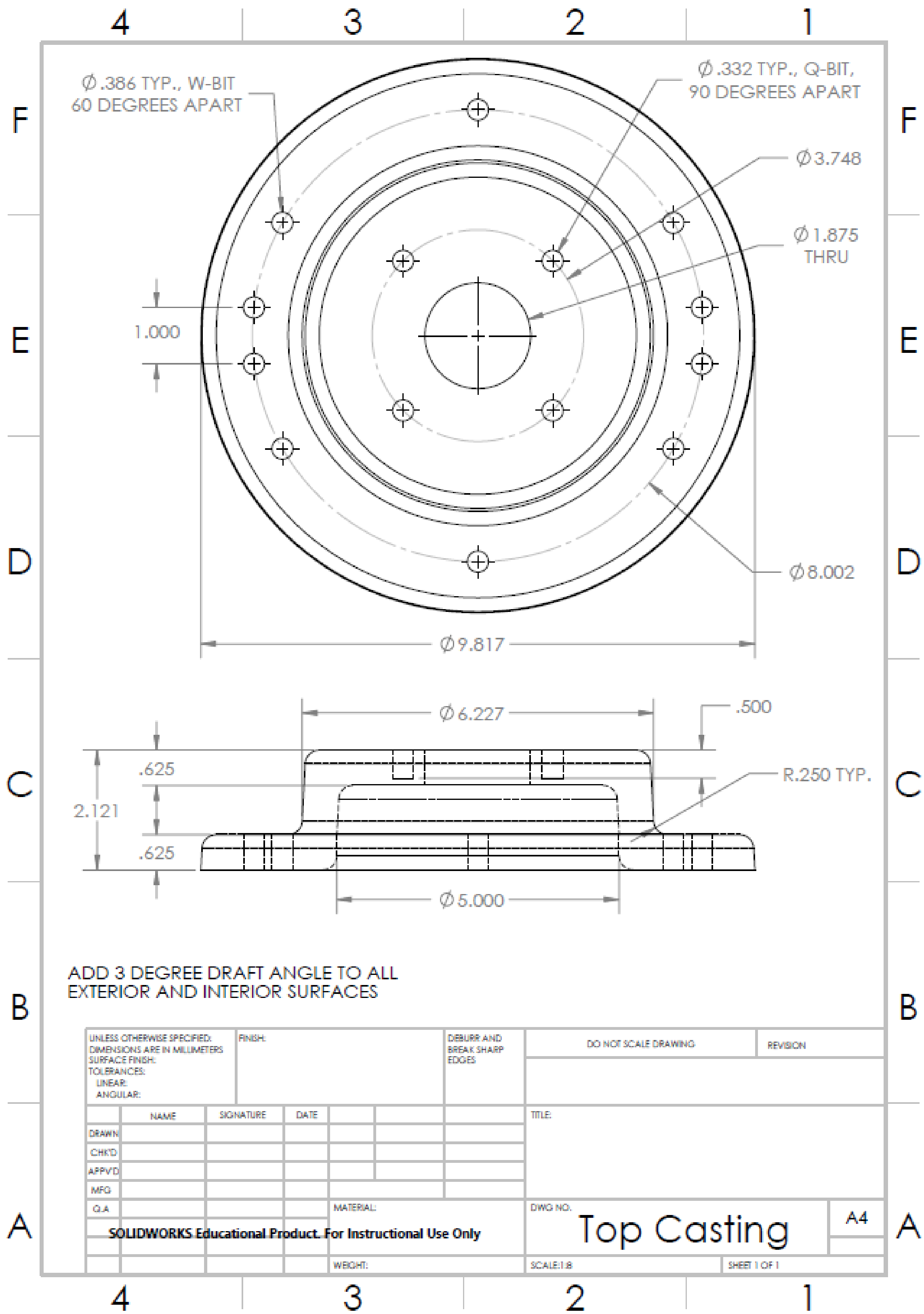


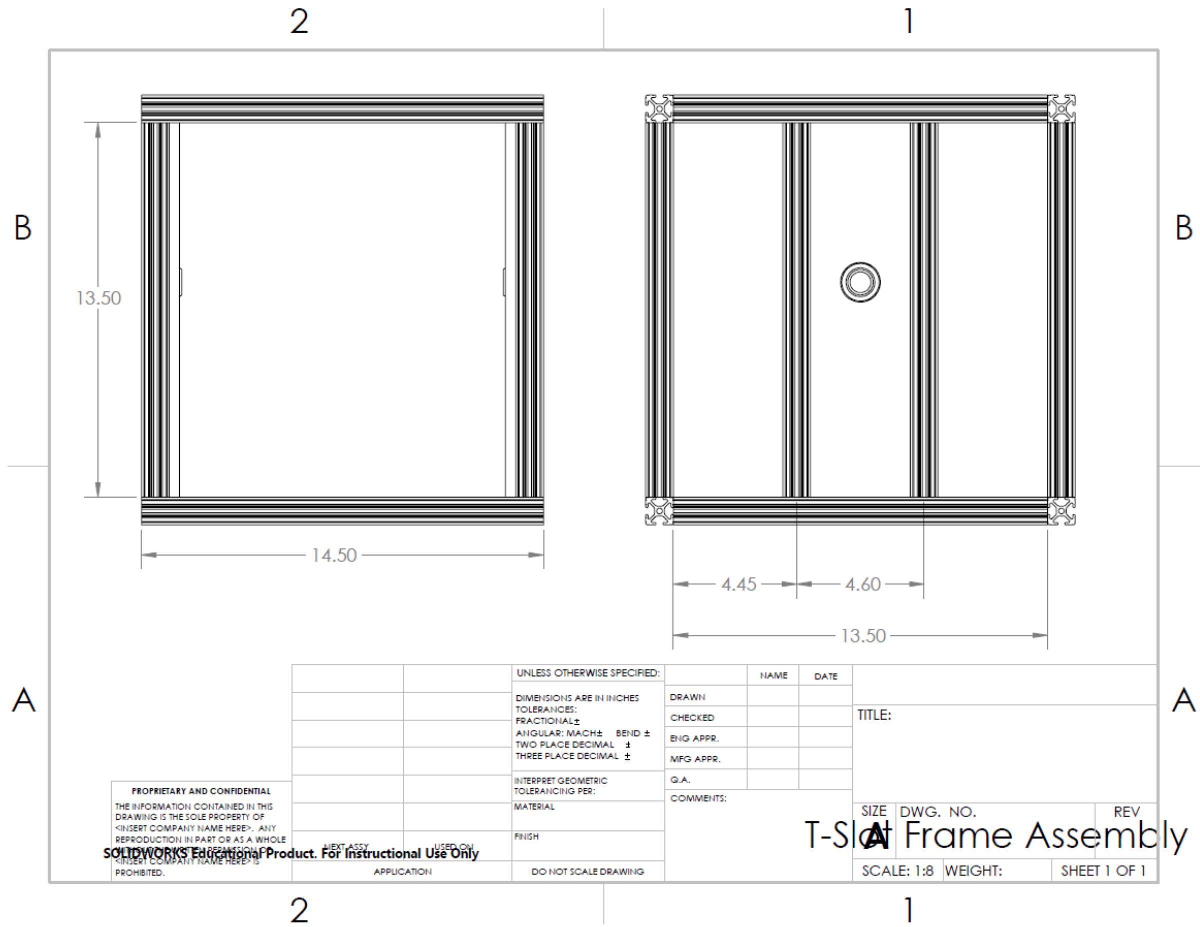

Ø 1.1563
Ø 4.0000
.5000
.8750
2.0000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
Flywheel
A4
SOLIDWORKS Educational Product. For Instructional Use Only
WEIGHT:
SCALE:1:2
SHEET 1 OF 1

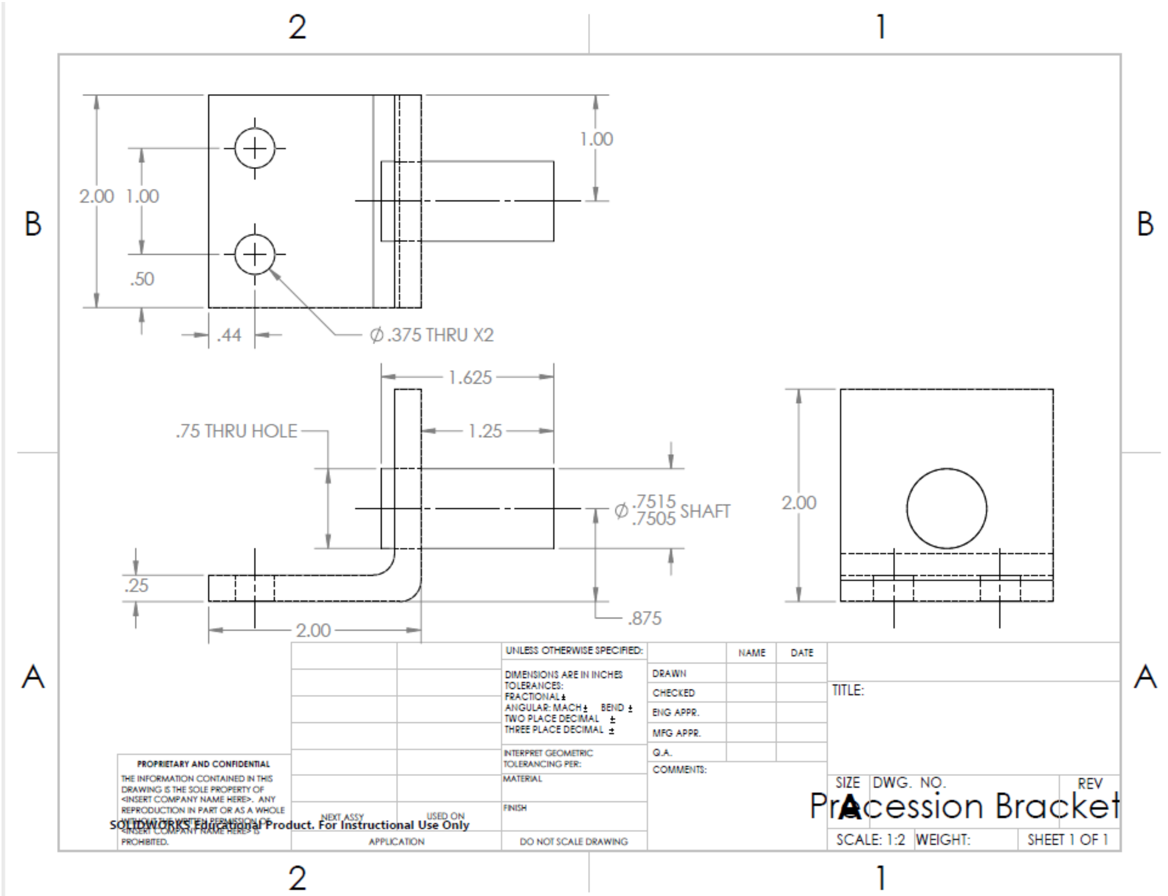

Ø.375 TYP.
R.50 TYP.
2.00
.95
2.29
3.11
DOWN 90° R .06
Ø.070 TYP.
120 DEGREES APART
UP 90° R .06
Ø.50
5.2
6.2
.063
UP 90° R .06
Ø.88
DOWN 90° R .06
2.65
4.00
SIDE VIEW
SCALE 1:1
TOP VIEW
SCALE 1:2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
Motor Mounting Bracket
A4
WEIGHT:
SCALE:1:4
SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only



2
1
B
A
4.7500
4.2500
2.8750
2.6250
1.2500
.5000
0
Ø .8756 .8750
Ø 1.125
Ø 1.1574 1.1570
Ø 1.250
Ø .8756 .8750
Ø .3750 .3650
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
Shaft
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
SOLIDWORKS Educational Product. For Instructional Use Only


Ø.386 TYP., W-BIT
60 DEGREES APART
Ø.332 TYP., Q-BIT,
90 DEGREES APART
Ø3.748
Ø1.875
THRU
1.000
Ø8.002
Ø9.817
Ø6.227
.500
.625
2.121
R.250 TYP.
.625
Ø5.000
ADD 3 DEGREE DRAFT ANGLE TO ALL
EXTERIOR AND INTERIOR SURFACES
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
TITLE:
DWG NO.
Top Casting
A4
SOLIDWORKS Educational Product. For Instructional Use Only
WEIGHT:
SCALE:1:8
SHEET 1 OF 1


13.50
14.50
4.45
4.60
13.50
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
T-Slot Frame Assembly
REV
SCALE: 1:8
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
SOLIDWORKS Educational Product. For Instructional Use Only


2.00
1.00
1.00
.50
.44
Ø .375 THRU X2
1.625
1.25
.75 THRU HOLE
Ø .7515 .7505 SHAFT
2.00
.25
2.00
.875
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
DWG. NO.
REV
A
Procession Bracket
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
SOLIDWORKS Educational Product. For Instructional Use Only

Appendix F. **Calculations**

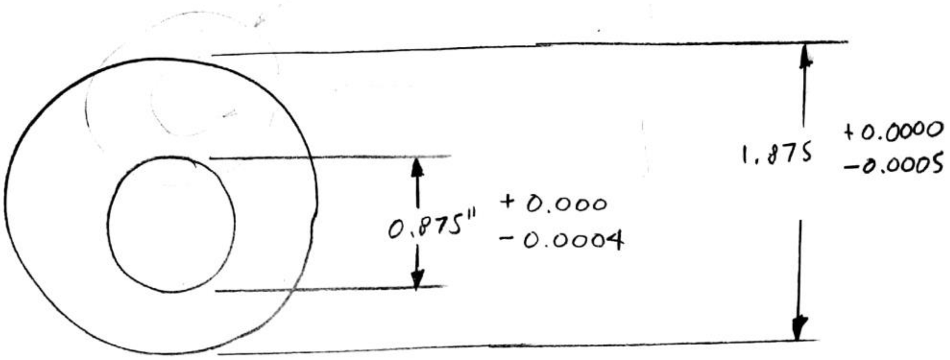
The following section includes the calculations performed to tolerance the dimensions for manufactured parts, stresses acting on various components of the system, as well as a critical speed analysis of the shaft.

F.1. **Tolerance Calculations**

MARCH 2ND 2018 CLARK FRIESEN

TOLERANCES FOR SHAFT BEARINGS PART NO. 6035SK604

TRADE NO. R14-2Z



HOLE = 0.8750"
0.8746"

WANT A TIGHT FIT

⇒ WANT LN2 FIT ⇒ LIMITS OF INTERFERENCE = 0 / 1.0 (THOUSANDTHS OF AN INCH)

MAX INT. = BIG SHAFT − SMALL HOLE

⇒ BIG SHAFT = MAX INT + SMALL HOLE
= 0.001 + 0.8746 = 0.8756

MIN INT = SMALL SHAFT − BIG HOLE

⇒ SMALL SHAFT = MIN IN + BIG HOLE
= 0 + 0.8750 = 0.8750

⇒ SHAFT Ø = 0.8756"
0.8750"
AT BEARINGS

FLYWHEEL TO SHAFT TOLERANCES

CLARK FRIESEN
2018/03/06

FLYWHEEL ID = 1"

- PRESS FIT ONTO SHAFT

⇒ FN1 FIT ⇒

FLYWHEEL ID = 1.0005" / 1.0000"

SHAFT OD = 1.0012" / 1.0008"

SHAFT TO COUPLING TOLERANCES

COUPLING I.D. = 3/8" = 0.375"

NO TOLERANCE GIVEN FOR COUPLING I.D

⇒

SHAFT O.D = 0.375" / 0.365"

PRECESSION BRACKET ROD TOLERANCE

SWIVEL BEARING I.D = 0.7515" / 0.7495"

WANT TIGHT FIT ⇒ LN1 ⇒ INTERFERENCE = .05 thousandths of an inch = 1.0

⇒ MAX INT = BIG SHAFT − SMALL HOLE

⇒ BIG SHAFT = MAX INT + SMALL HOLE = 0.001 + 0.7495 = 0.7505

MIN INT = SMALL SHAFT − BIG HOLE

⇒ SMALL SHAFT = MIN INT + BIG HOLE = 0.7515"

⇒

PRECESSION ROD Ø = 0.7515" / 0.7505"

PRECESSION BEARING MOUNTING PLATE TOLERANCE

SWIVEL BEARING O.D. = $1\frac{7}{16}$" $^{+0"}_{-0.0007"}$

O.D = 1.4375"
1.4368"

WANT PRESS FIT ⇒ CUSTOM ⇒ INTERFERENCE = 0.3 thousandths of
2.1 an inch

⇒ MAX INT = BIG SHAFT − SMALL HOLE

⇒ SMALL HOLE = BIG SHAFT − MAX INT
= 1.4375" − 0.0021" = 1.4354"

MIN INT = SMALL SHAFT − BIG HOLE

⇒ BIG HOLE = SMALL SHAFT − MIN INT
= 1.4368" − 0.0003" = 1.4365"

⇒ PRECESSION BEARING HOLES = 1.4365"
1.4354"

CLARK FRIESEN

WHERE FLYWHEEL BEARINGS MEET HOUSING

BEARING OD = 1.875" +0.0000" −0.0005"

= 1.8750"
1.8745"

IN THIS CASE THE BEARING ACTS AS THE SHAFT, HOUSING = HOLE

⇒ WANT LOOSE FIT BETWEEN BEARINGS AND HOUSING

⇒ CHOOSE LC6 FIT

⇒ CLEARANCE = 1.0 MIN (THOUSANDTHS OF AN INCH)
5.1 MAX

MAX CLR = BIGGEST HOLE − SMALLEST SHAFT

⇒ BIGGEST HOLE = MAX CLR + SMALLEST SHAFT
= 0.0051 + 1.8745"
= 1.8796"

MIN CLR = SMALLEST HOLE − BIGGEST SHAFT

⇒ SMALLEST HOLE = MIN CLR + BIGGEST SHAFT
= 0.001" + 1.875"
= 1.876"

⇒ HOUSING BEARING HOLES = 1.8796" / 1.8760"

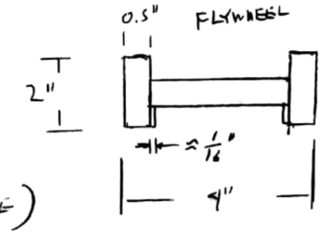
F.2. Miscellaneous Calculations

CRITICAL SPEED ANALYSIS → FLYWHEEL SHAFT

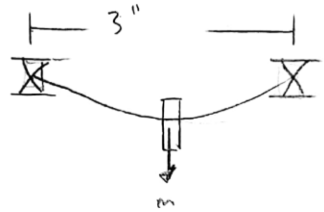
CLARK FRIESEN
FEB 21st

FLYWHEEL WITH A36 STEEL RING, 6061 INNER

$m = 1.36$ kg (from solidworks)



ASSUME SHAFT IS ORIENTED HORIZONTALLY
(EVEN THOUGH IT'S VERTICAL MOST OF THE TIME)



$$\omega_n = \sqrt{\frac{g}{\delta_{ST}}}$$

pg 284 machine design 2 notes

$$n_c = \frac{30}{\pi}\sqrt{\frac{g}{\delta_{ST}}} \quad [RPM]$$

from appendix D-2

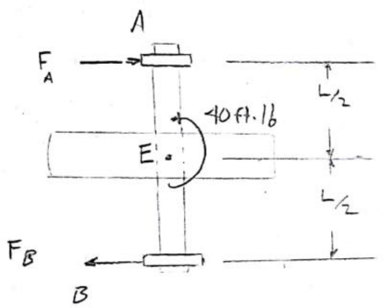
$$\delta_{ST} = \frac{PL^3}{48EI} = \frac{(1.36)(9.81)\left(3'' \times 25.4\frac{mm}{in} \times 1\frac{m}{1000mm}\right)^3}{48\,(200\times10^9\,PA)\left(\frac{\pi}{64}\right)\left(\frac{7}{8}'' \times \frac{25.4mm}{in} \times \frac{m}{1000mm}\right)^4}$$

$$\delta_{ST} = 5.134 \times 10^{-8}\ m$$

$$\Rightarrow n_c = \frac{30}{\pi}\sqrt{\frac{9.81}{5.134\times10^{-8}}} = 131999.89 \text{ rpm} \ll 10\,000 \text{ rpm}$$

⇒ CRITICAL SPEED NOT AN ISSUE.

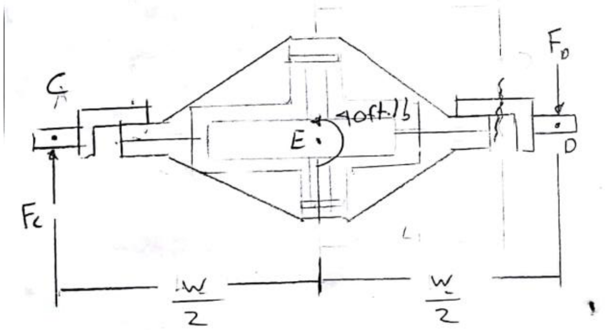
Precession bracket sizing



$$\Sigma M_B = 0 = 40\,ft{\cdot}lb - F_A L$$

$$\Rightarrow F_A = \frac{40\,ft{\cdot}lb}{L} = \frac{480\,lb{\cdot}in}{L}$$

SAY $L = 6'' \Rightarrow F_A = 80\,lb$



$$\Sigma M_C = 0 = 40\,ft{\cdot}lb - F_D W$$

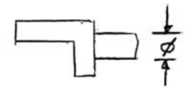
$$\Rightarrow F_D = \frac{40\,ft{\cdot}lb}{w} = \frac{480\,lb{\cdot}in}{w}$$

SAY $w = 12'' \Rightarrow F_D = 40\,lb$

$$\frac{\tau}{n} = \frac{V}{A} = \frac{V}{\pi r^2} \Rightarrow r = \sqrt{\frac{Vn}{\pi\tau}}$$

$$r = \sqrt{\frac{(40\,lb)(2)}{\pi(36000\,psi)}} = 0.0266''$$

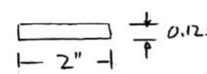
$$\Rightarrow \boxed{\phi_{MIN} = 0.053''}$$



$$\frac{\tau}{n} = \frac{V}{A} \Rightarrow A = \frac{Vn}{\pi\tau} = \frac{(60\,lb)(2)}{\pi(36000)} = 0.00106\,in^2$$

$$\boxed{A \geq 0.00106\,in^2}$$

$\Rightarrow$



$$2(0.125) = 0.25\,in^2$$

$\Rightarrow$ SAFE