

BRAKING SYSTEM FOR MICROGENERATION WIND TURBINES

Phase 3 Report

The logo for MACH INNOVATIONS is a dark green, circular emblem with a scalloped edge. Inside the circle, the word "MACH" is positioned above "INNOVATIONS". The letter "A" in "MACH" is replaced by a small white triangle. The text is rendered in a light green, sans-serif font. The logo is set against a background of several thin, light blue diagonal lines that cross the lower right portion of the cover.

MACH
INNOVATIONS

University of Alberta
MEC E 460

Dec 02, 2023

Edmonton, AB T6G 2V4
Darren Paetz
President, Renewable Energy Design Club
306-11115 80 Ave
Edmonton, AB T6G 0R4

RE: Regenerative Braking System for Microgeneration Wind Turbine – Phase 3 Deliverables

Dear Mr. Paetz,






MACH Innovations is pleased to present our Phase 3 Report on designing a braking system for your microgeneration wind turbine. The report includes:

- Conceptual overview of our final design
- Detailed design analysis
- Design compliance matrix
- Cost estimation for the project
- SolidWorks Model and Drawing package.

Upon completion of this project, a total of 762.5 hours of junior engineering work and 6 hours of senior engineering advising is spent. Resulting in a total of \$69525 for engineering costs.

It has been a pleasant journey, and MACH Innovations is looking forward to any future collaborations with you. If you have any questions or concerns regarding this project/our work, please contact Reid Mix (Mix@ualberta.ca).

Best Regards,

				
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MACH Innovations

Cc: Dr. Brian Fleck, Advisor, University of Alberta

Cc: Dr. Michael Lipsett, Course Instructor, University of Alberta

Executive Summary

MACH Innovations has agreed to design a braking system that will protect a microgeneration vertical axis wind from over speeding under gusting weather. The original scope of the project demanded a regenerative aspect, such that the energy resulting from braking was to be captured and reused. Upon further communication with the client and course instructor, the scope of the project was redirected to an emphasis on the braking aspect of the system.

Major design constraints include the cut-in and cut-out wind speed of the original brake-less turbine, which are 12.6 and 8.2 km/h respectively, as well as the damaging centripetal rotational speed of the turbine, which is 701.48 rpm and occurs at a wind speed of 18 km/h.

The Governor-Shield braking system consists of a governor system and a shielding system that enforce protection for the turbine from incoming gusts.

The governor system is designed with two moment arms of 185.5 mm in length with adjustable masses at the end. This system extends both the required time for the turbine to accelerate to steady state and to cut-out after depletion of gust by 481%, while also increasing the overall energy regeneration efficiency of the turbine by 29.67% by extending the safe-range operational time of the turbine.

The shielding system is designed with an aluminum shield orientated in a 73.7° angle to the centripetal shaft, threaded onto a flange that's mounted on the turbine's gearbox. The cone will enforce a maximum rotational speed of 701.48 rpm - applying braking with friction resulting from the governor moment arm's rotational and upward motion as it engages with the shield.

The total cost of the project is summed to be \$73395, with \$69525 allocated to engineering design cost with 762.5 hours of junior engineering work and 6 hours of senior engineering advising for all 3 phases; and \$3870 allocated to the manufacturing cost for all 9 turbines that are to be installed (\$430 individual cost).

MACH Innovations recommend future improvements to incorporate the Governor-Shield braking system design to the emergency braking system designed by the client, to ensure design viability and compatibility.

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1 Introduction

MACH Innovations was tasked by the Regenerative Energy Design Club to design a braking system for their microgeneration vertical axis wind turbine. The turbine will be installed in a location that will experience gusts of wind up to 90km/h, however the turbine itself will be in risk of damaging from violent vibration at a centripetal rotational speed of 701.48 rpm, which corresponds to an incoming wind speed of 18 km/h. The turbine itself has no external braking system installed, and the braking force generated from the generator's counter torque was tested insufficient to protect the system as tested by the client. A schematic of the original turbine is illustrated in figure 1.



Figure 1: schematic of the client turbine with no braking system.

MACH Innovation has designed the Governor-Shield braking system to fulfill the task, where a governor assembly will provide stability for vibration in transient state, while a shield assembly will enforce frictional braking for steady state over-speeding.

2 Design Concept

2.1 Shift of Scope

The project originally emphasized the regenerative aspect of the braking system – braking should not bleed off heat, and the energy from braking is to be captured for regenerative charging.

Upon discussion with the client and the course instructor, the main scope of this project has shifted to designing a braking system with emphasis on the braking aspect – that it can mechanically and physically enforce braking to protect the turbine from damage. The regenerative aspect is no longer the main objective, but it is included as an add-on challenge that the team has taken into consideration when designing the system.

The governor design was chosen for this project, the analysis and selection process can be found in the Phase 2 report.

2.2 Overview of the Design

With further analysis following phase 2, two problems were identified regarding the initial governor design when examining the steady-state properties of the system:

- System lacks a physical braking action to mechanically remove energy from the system and decelerate the turbine at max moment arm angle.
- Steady state moment of inertia increasing rapidly with increasing wind speed, governor losing its effect at very low wind speed (as low as 8 km/h)

To address these problems, two innovations are made based on the existing governor design. These innovations are conceptually explained in Sections 2.2.1 and 2.2.2, with detailed analysis shown in Section 3 of the report.

2.2.1 Frictional Aluminum Shield

A cone-shaped aluminum outer shield was added to the system as a frictional brake that can extract energy from the turbine. The shield essentially functions as a backup braking system for the governor, should the governor be accelerated to its maximum steady state under continuous high-speed wind.

Mounting of the shield is done with a set of flanges screwed onto the turbine's gearbox, where the shield will be machined into a bee-hived shape and have its bottom screwed onto the flange with threads and nuts. A piece of metal is sandwiched between the shield and flange for a tighter fit with thread and nuts. Figure 2 below shows a diagram of the braking system mounting on the turbine.

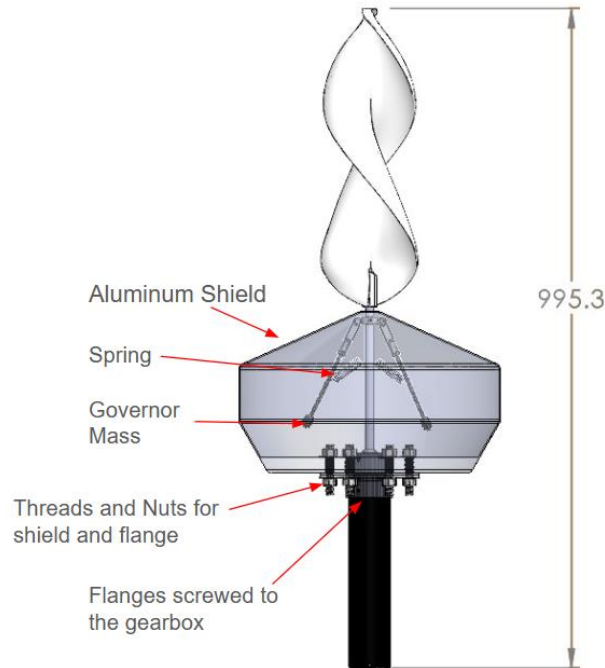


Figure 2: Diagram of the complete assembly, units in mm

Table 1 below highlights the key criterion associated with shield design, as well as a description that details the importance of each criterion.

Table 1: Shield design criterion.

Key Shield Design Criteria	Description
Shield Orientation	<ul style="list-style-type: none"> - Shield is orientated at 73.7° from the turbine shaft. - Enables friction braking between shield and moment arm, after arm reached 76° angle. - Enforcing an estimated maximum rotational speed of 700 rpm, which is directly under the system's damaging rotational speed.
Governor Geometry	<ul style="list-style-type: none"> - Easy modification of governor mass displacements along the moment arm – alter angle of engagement for higher rotational speed.
Selection of Material	<ul style="list-style-type: none"> - Selection of shield material focused on coefficient of friction and material mass. - Hardness and yield tensile strength were the initial focus in material selection but was removed from priority with further analysis, where it was found that the involved frictional force in the braking process to be of small magnitudes (100 N at 40 km/h wind).

2.2.2 Spring on the Moment Arm

A spring was added to linearize the rate at which the steady-state moment arm angle elevates with increasing wind speed. Allowing for a longer operational range for the turbine without engaging with the shield – minimizing the energy lost due to frictional braking. This effect is depicted in figure 3 below: the shield will engage at 8 km/h wind with the initial springless design to enforce braking, whereas with the attachment of spring, it will not engage until the system is experiencing wind of 18 km/h.

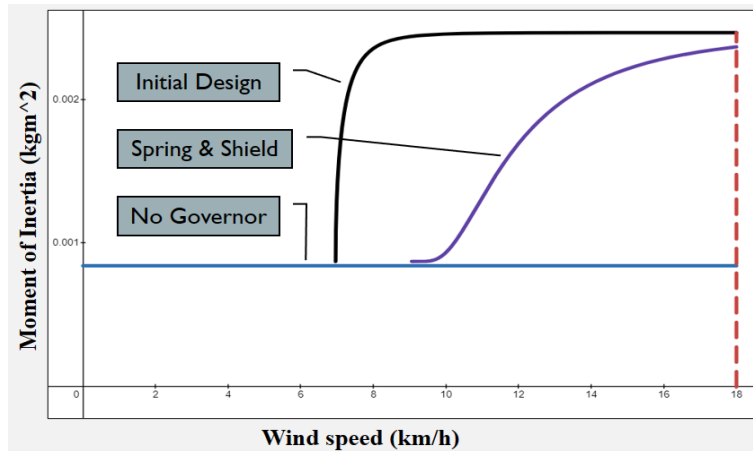


Figure 3: Steady state Moment of Inertia relationship with wind speed of different system

2.3 Governor Operation Flowchart

Figure 4 below depicts the general procedure followed by the braking system for operation, including key parameters such as cut-in and cut-out speed in shaft rpm, and system behaviors at different stages.

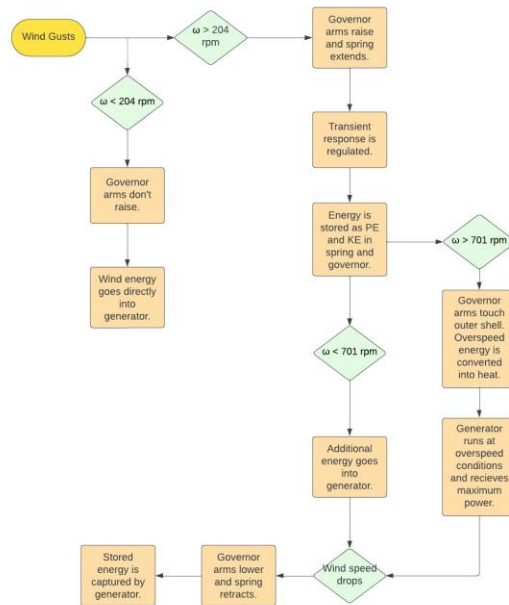


Figure 4: Governor Operation Flowchart

2.4 Design Considerations

No legal regulation applies to the project. Design considerations foremost considered the project specification as the primary design requirement. After the primary design requirements are met, secondary objectives are considered as a refinement of the design. Table 2 below shows a detailed description of the design considerations taken by the team and the design’s solution to these considerations.

Table 2: Design considerations, priorities, descriptions, and solutions.

Consideration	Priority	Description	Solution
Functional aspects	Primary Requirements	The system can deliver proper braking to turbine	<ul style="list-style-type: none"> - Governor providing stability in transient state with increasing moment of inertia. - Shield enforcing frictional braking during steady state motion of turbine to eliminate vibration failure due to overspeed operation.
	Secondary Objective	Maximize energy regeneration	<ul style="list-style-type: none"> - Governor assembly stores momentum of rotation with moment arms and the masses will continue the turbine rotation after wind has depleted. - Governor geometry (arm length, mass weight, mounting position, spring mounting) and spring constant designed to maximize energy recovery.
Manufacturing aspects	Primary Requirement	Fitting within \$1000 budget limit	- Machining involves simple rolling and welding only
	Secondary Objective	Ease of manufacturing – simplicity in assembling	- Assembly parts are mostly purchasable off shelf, and in packages of great quantity for multiple assemblies
Environmental and sustainability	Primary Requirements	Continuous operation for two years	- Assembly parts are 100% metal, no plastic or non-parts – longer operational lifetime
	Secondary Objective	Minimizing environmental impact – designing for longevity	- Assembly wear is involved predominantly with the governor rotating about the shield and the turbine shaft.

			Both motions were analyzed to involve negligible fatigue to the parts itself, therefore failure of the system is mainly associated with corrosion with outdoor environment, which, the 6061-T6 general purpose aluminum is corrosion resistant.
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3 Detailed Design Analysis

3.1 Critical Design Analysis

The design analysis was founded on the main assumption that the damaging windspeed cannot be changed by the governor brake system. The governor can extend the time the turbine takes to reach the damaging rotational velocity, but it cannot prevent it from reaching this speed by adjusting the moment of inertia alone. Which is why the friction system is included in the design.

This realization is important because it allows the design team to prioritize the energy storage potential of the system, and the reduction of transient effects, to allow the brake system to be as regenerative as possible. Along with this assumption, the design team left initial values for the arm length, spring placement, mass values, and spring stiffness, as variables such as geometric, FBD, and θ - ω relations could be made. These values were back-calculated to result in optimal energy storage for the governor once each of the models was fully designed. The flowchart below shows the order in which relations were obtained so that a logical flow of the analysis can be visualized by the reader.

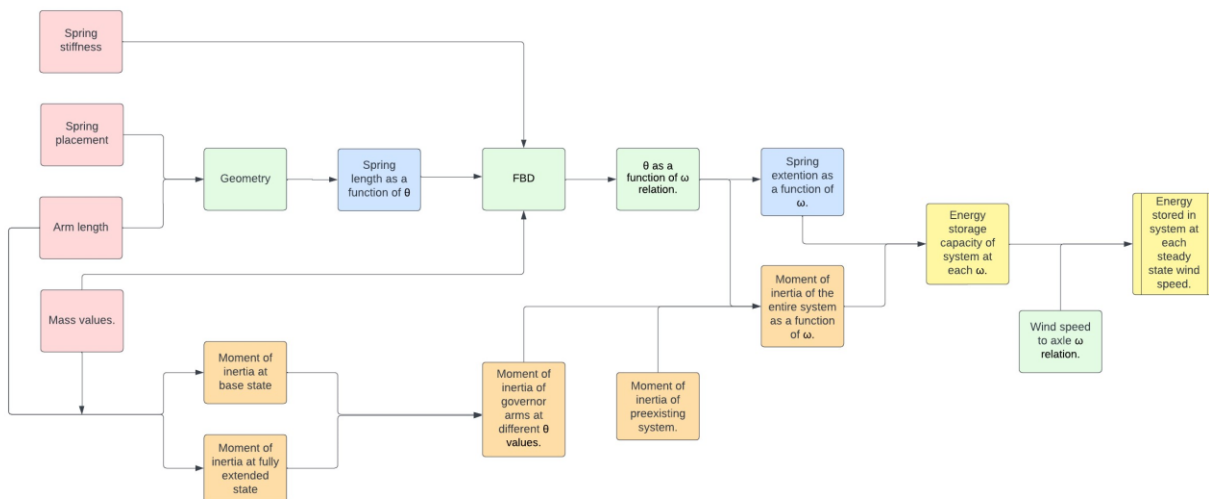


Figure 5: Design Analysis Flowchart

The moment of inertia calculations start by approximating the shape of the governor arm and masses, with shapes that already have a moment of inertia relations for an axis of rotation. The

arm is approximated by a cylinder and the masses are approximated by a cylinder with a hole running through its length. The equations for these shapes were sourced from Raymond Serway.¹ With the inclusion of variable lengths and widths, the moment of inertia of the arm and masses was determined at full extension and rest, with the use of the parallel axis theorem.

By projecting the magnitude of the arm's moment of inertia at the 0° and 90° states, for every angle in between, the moment of inertia of the governor for every θ was determined. The moment of inertia of the pre-existing turbine system was determined from the solid model provided by the client. By combining these two moments of inertia, the moment of inertia of the entire system for every θ is known. See Appendix J of the report for the full equation.

Since the arm length, spring placement, spring stiffness, mass values, and other dimensions were left as variables, the geometric nature of the system could be defined and FBDs could be made. These directly led to the development of spring length as a function of θ and θ as a function of ω . Angular velocity of the axle became the independent variable in the analysis, and therefore the moment of inertia of the system and the spring extension value both became functions of ω .

When the turbine rotates, some of the wind energy is stored as:

$$PE_{Spring} = \frac{1}{2} k * \Delta l^2$$

$$KE_{Turbine} = \frac{1}{2} I_{Turb} * \omega^2$$

$$KE_{Gov} = \frac{1}{2} * I_{Gov} * \omega^2$$

$$PE_{Gov} = mgh$$

Since these are each a function of ω , the energy storage of the system could be determined for all ω .

The last step was to correlate the velocity of the wind to the angular rotation of the axle. This was achieved by looking through the client's wind tunnel data, to obtain the axial rotational speed a function of wind speed - $\omega(V_{wind})$.

Due to the main assumption that for steady state conditions, the angular velocity of the turbine is independent of the moment of inertia of the system; therefore, for every steady-state windspeed there exists a corresponding rotational velocity that is unchanged by the increase in moment of inertia of the system. Which allowed the design team to obtain the energy stored within the system as a function of windspeed, given that the wind blows long enough for the turbine to

reach steady state speed. Figures 6, 7 and 8 depict a more graphical view for the findings, showing the change in moment of inertia, individual storage and total storage capacity in response to wind speed respectively.

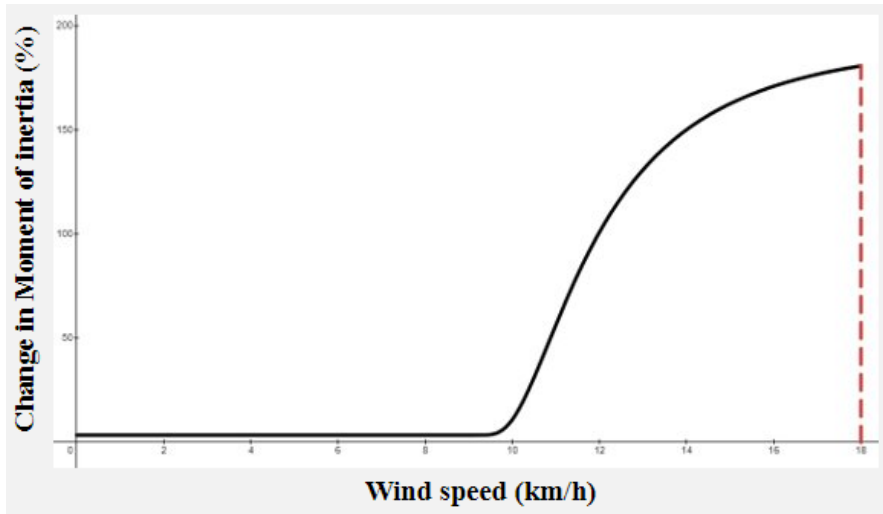


Figure 6: Change in Moment of Inertia of the System with Wind Speed

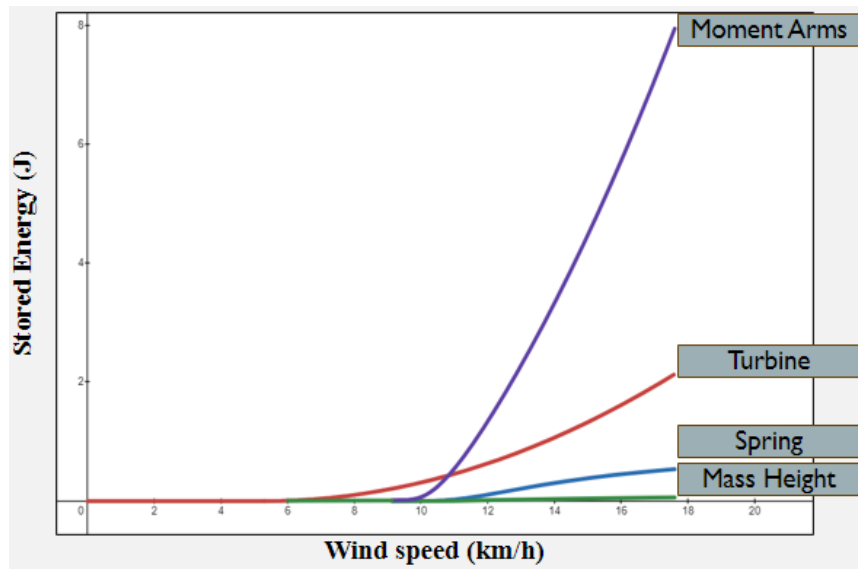


Figure 7: Stored Energy in Different Components at Varying Wind Speeds

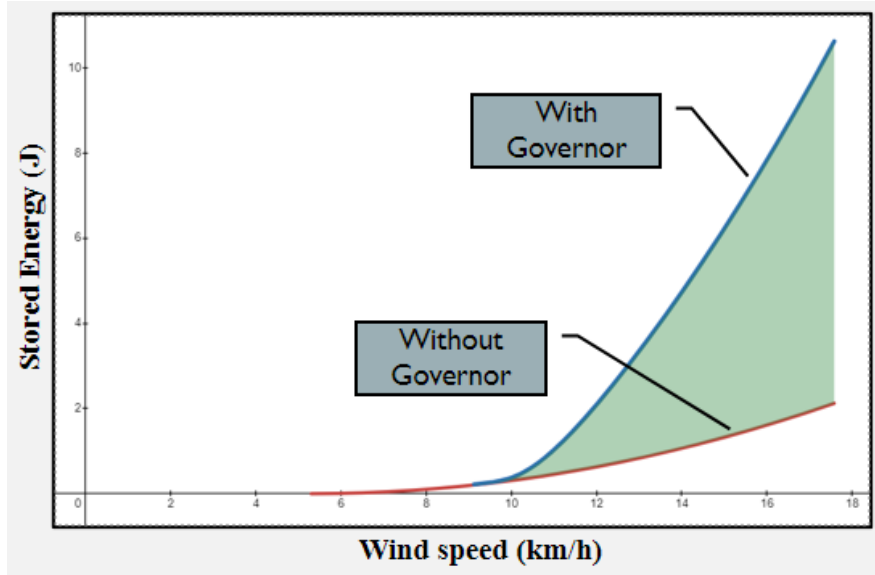


Figure 8: Total Stored Energy of System at Various Wind Speeds

The findings from this process are summarized in Table 3 below.

Table 3: Summarization of analysis result

Subject	Value
Cut in/cut out speed	12.6 km/h / 8.2 km/h
Damaging wind speed	18 km/h
Arms raising wind speed	9.5 km/h
Braking wind speed	18 km/h
Increase in $I_{Initial}$	3.5%
Increase in I_{Max}	180%
Energy Storage Capacity Increase	481%

It should be noted that the main drawback of the design is that there is no way for the governor to “lock up” and completely stop the motion of the turbine. It was designed to allow the governor to operate at overspeed conditions, and thus it does not have the ability to cease rotation if necessary.

3.2 Shield Material Analysis

The cross-sectional area of the mass engaging with the shield is approximately 0.0004 m^2 , and as depicted by figure 4 below, the frictional force associated with 90 km/h wind is approximately

500 N. At this maximum wind speed, stress exerted from friction braking is 1.25 MPa, which is extremely low compared to material yield tensile yield strengths.

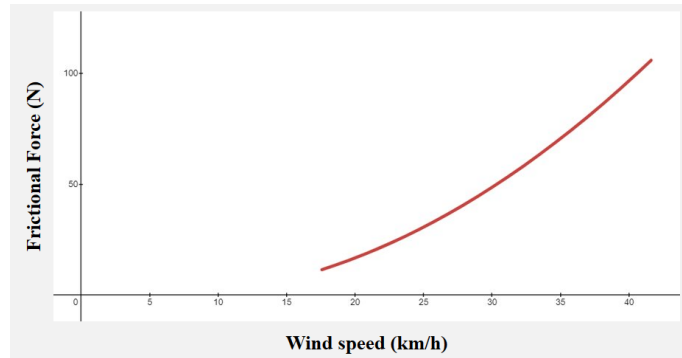


Figure 9: Magnitude of frictional force as a function of wind speed

Due to the low stress, material selection prioritizes coefficient of friction and density to maximize braking effectiveness and ease for production.

Table _ below shows a comparison of the three common sheet metal materials considered, including aluminum, brass, and galvanized steel.² With highlights on the significant properties considered in selection.

	6061-T6 Aluminum³	260 Brass OS070 Tempered⁴	ASTM A653 Galvanized Steel⁵
Yield Tensile Strength (MPa)	276	95	303
Coefficient of Friction	0.61	0.51	0.25
Hardness (HB)	75	54	110
Density (g/cc)	2.72	8.73	7.87
Cost	\$6.76 for 0.032in thickness	\$5.99 for 0.032in thickness	\$7.54 for 0.0396in thickness

Aluminum was selected as the sheet metal material to be used for the shield for having:

- Greatest coefficient of friction
- Smallest density
- A decent hardness and yield strength in comparison to the other materials
- Reasonable cost – not overly expensive

Detailed properties of each material can be found in Appendix I: Shield Material Properties

3.3 Cost Analysis

Figure 6 below shows a price breakdown for all 9 systems to be installed, summing up to a total of \$4508.2 for all 9 systems.

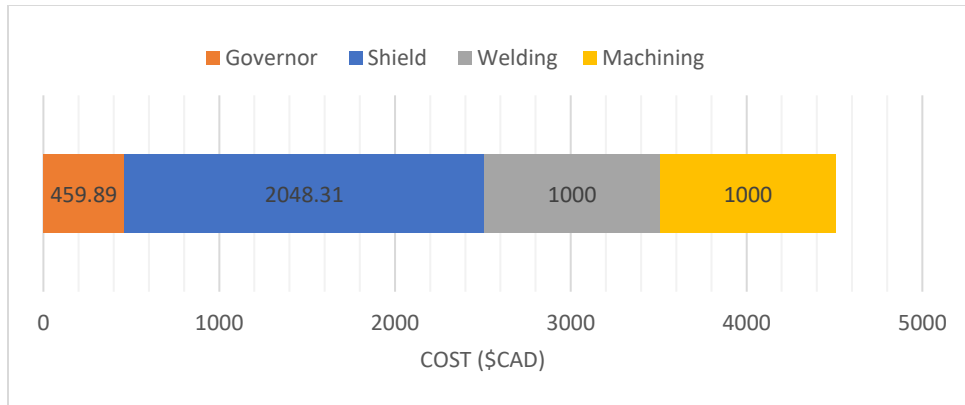


Figure 10: Total manufacturing cost breakdown, accounts for all 9 systems

Smaller parts such as hex nuts and washers come in packages of great quantity and require no additional purchase for multiple installations. One additional hour each in machining and in welding is also included, in consideration of any additional shop hours that may result from continuous operation.

Dividing the prices down gives a manufacturing cost of \$501 per braking system, which is within the \$1000 manufacturing budget limit authorized by the client. A detailed table of individual part price in both governor and shield subassemblies can be found in Appendix D: Detailed Cost Analysis.

4 Design Compliance

A design compliance matrix has been developed to ensure that MACH Innovations has met or exceeded the clients' goals. This matrix lists the various specifications that were developed with the client, and explains them, their importance, any updates made, and whether they were compliant. The matrix also has a weighting attached to each specification, from 1-5, with 1 meaning low importance, and 5 meaning high importance. No significant updates have been made to the matrix between Phase 2 and Phase 3.

Table 4: Design Compliance Matrix

Item	Specification	Description	Weighting	Regulating Authority	Updates	Compliance
<i>Braking Specifications</i>						
1.1	System must be suitable for continuous outdoor operation, duration of at 2 years.	The braking system will be installed on an outdoor wind turbine system, so resistance to outdoor elements and temperature changes is a must for reliable system operation.	5	Client		Full Compliance All materials used (Galvanized steel & aluminum) are weather resistant and can last for a minimum of 2 years
1.2	System must measure turbine speed and respond with brake action with no user input within 100ms.	The braking system is to protect the turbine from resonance and high wind speeds. To complete this, the system must be able to measure the turbine speed and respond with braking action.	5	Client		Full Compliance System is a mechanically responsive system that has zero delay time.
1.3	System should <u>increase operational time during gusting conditions, at gusts up to 90 km/h</u>	The braking system will allow the turbine to operate in a larger variety of wind speeds without damage and will therefore increase the operational energy output of the turbine.	4	Client	This section has been updated to an increase of operational time, away from an increase in operational wind speed.	Full Compliance See design analysis section for full breakdown
1.4	System should increase operating efficiency to greater than 30%	Increased efficiency is the goal of a regenerative braking system, as such, maximizing the efficiency of the system is a priority.	3	Client		Full Compliance See design analysis section for full breakdown

1.5	System should not “bleed off” braking energy as heat, energy is to be captured and stored	Regenerative braking could allow for increased operating efficiency of the turbine braking system allowing for more generation at high wind speeds.	3	Client		Partial Compliance System reduces need for braking action through energy capture, but physical heat dissipation braking action is present
1.6	System should have few or no consumable components, consumable components should last 2 years.	Consumable components require service which can be expensive to maintain and create waste.	3	Client		Full Compliance Due to low system forces, all system parts are expected to last a minimum of 2 years
1.7	System may be compact, ~200mm wide and ~300mm tall	System should not increase the footprint of the turbine but a small increase may be allowed if required for design or budgetary reasons.	2	Client		Partial Compliance 250.19mm x 414.17mm (height x width). The design is roughly the same size as existing system
1.8	System may be retrofitted into the existing wind turbine system	The braking system must be able to be integrated into the existing wind turbine system. Alterations to the existing system are allowed.	2	Client		Partial Compliance An extension of the turbine shaft is necessary for system to fit
1.9	System may include a back-up braking system capable of withstanding gusts of 150kmh	The system may include a back-up braking system which will have the ability to prevent damage to the turbine at much higher speeds.	1	Client	Client has decided to construct braking system themselves	Full Compliance Client has taken over this task.
<i>Environmental Factors</i>						
2.1	System should be environmentally friendly in its material and prototyping	The Goal of the Renewable Energy club at the U of A is to create sustainable energy through projects such as this one, meaning environmental and sustainability considerations are important.	3	Client		Full Compliance All materials used are infinitely recyclable, see environmental section for further breakdown
<i>Safety</i>						
3.1	System shall follow legal standards and regulations in material selection and prototyping	To ensure safe operation of the turbine, legal and safety standards such as the Canadian Electrical Code and the CSA Guide to Canadian Wind Turbine Codes and Standards will be followed.	4	CSA	See appendix for full list of CSA guidelines.	Full Compliance Design is in full compliance of applicable CSA guidelines

3.2	Operation of the system must not cause harm to humans operating on the system	Negating possible risk factors is a big priority to increase the safety of the turbine. Maintenance must be done to the turbine at regular intervals and the safety of humans must be considered.	4	CSA	See appendix for full list of CSA guidelines.	Full Compliance Design is not operated by people and includes a shield design to limit human interaction.
Commercial Requirements						
4.1	Cost of system may be between \$350-1000	Price ranges were given by client based on previous experiences designing and building the wind turbines the system will be attached too.	2	Client		Full Compliance Final design cost is \$430 per unit.
4.2	System may be producible in the Elko garage and MecE shop	Client currently has a system of 9 turbines installed, ease of prototyping replicas (manufacturing) should be considered.	1	Client		Partial Compliance Majority of system can be created inhouse or purchased, with only the shield manufacturing requiring outside work.

This matrix highlights that most of the clients' requests have been fulfilled or exceeded. Of the few partial compliance specifications, they are low priority to the client and efforts to ensure compliance were used to ensure that other higher priority specifications were met. Detailed calculations and understanding of product specifications can be found in the detailed design analysis section or in the appendix. See appendix for client confirmation of system requirements.

5 Project Management

5.1 Project Hours

MACH Innovations is dedicated to ensuring that the client receives detailed reports of hours worked and where the time was invested. All project phases were estimated underneath what the actual hours worked where. Figure 11 shows the difference between the estimated completion

time in each phase and the actual completion time.

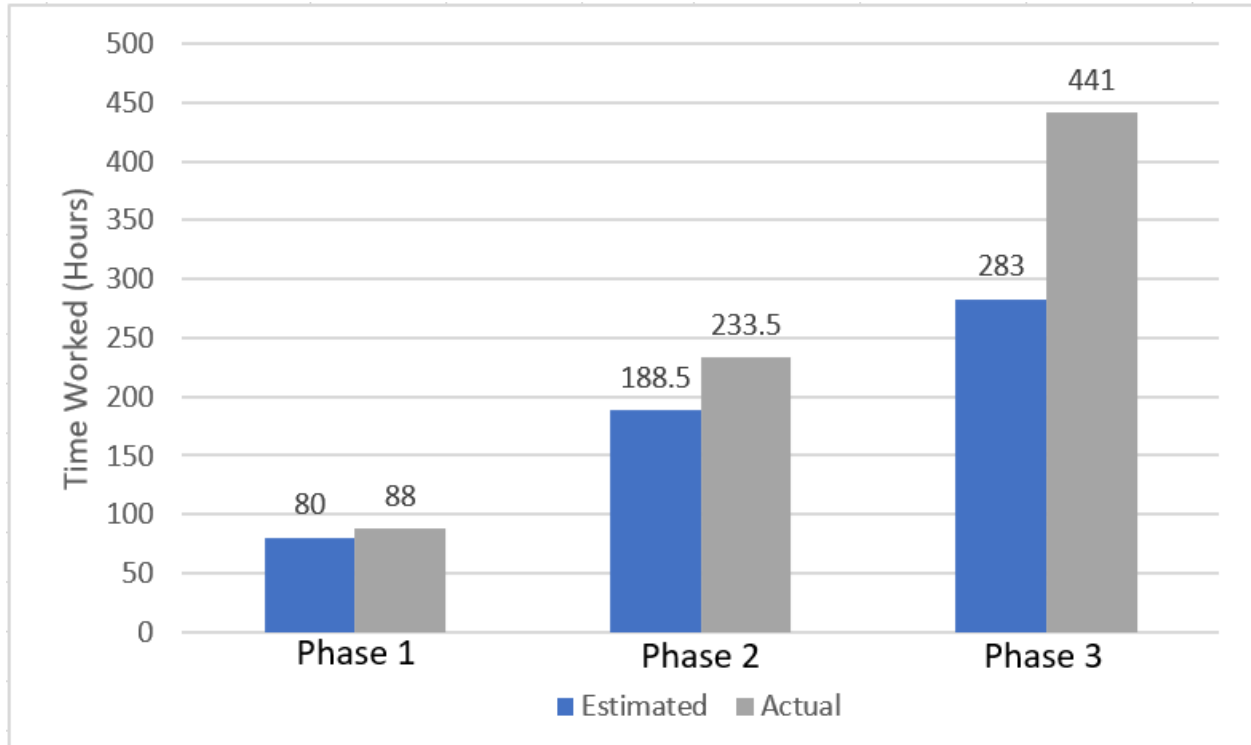


Figure 11 - Project Phase Time Comparison

Table 5 shows the specific hours worked by each individual team member, comparing the estimated hours to actual hours.

Table 5 - Team Member Hour's Worked

<i>Team Member</i>	<i>Estimated Hours Worked</i>	<i>Actual Hours Worked</i>
<i>Reid Mix</i>	100.4	148.7
<i>Ahra Ko</i>	120.4	147.7
<i>Nathan Correia</i>	103.4	166.7
<i>Justin Van Engelen</i>	114.4	152.7
<i>Bowei Huang</i>	113.4	146.7
Total	552	762.5

5.2 Gantt Chart

The Gantt chart in the appendix has been updated to reflect the actual time invested. A concise Gantt chart has been included in this section to highlight where work was completed about the project timeline. This shows that the project was rear-loaded in terms of design work and deliverables.

Table 6: Compressed view of the team's Gantt chart

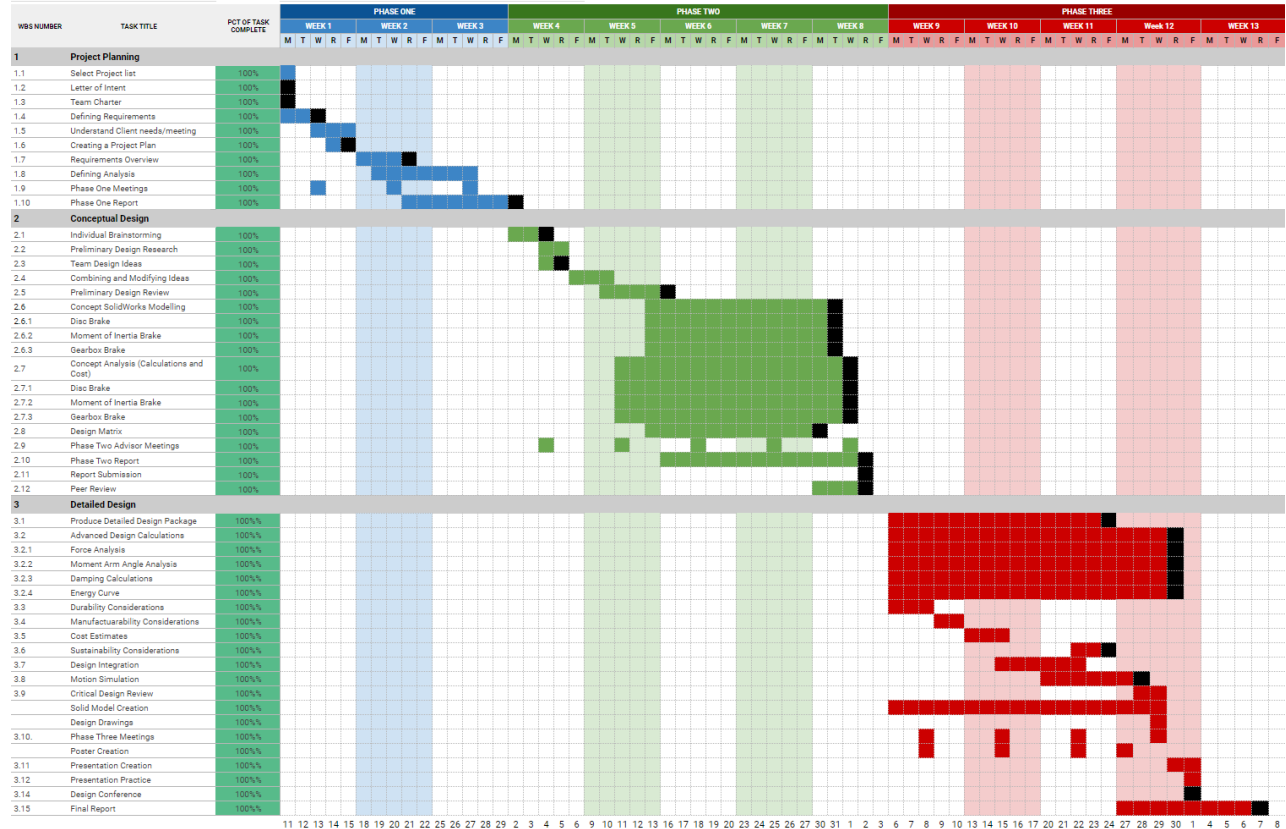


Figure 12 - Concise Gantt Chart

Overall, the project has deviated from both estimated time to completion and in structure of project development. The project became very rear loaded in terms of design work and completion of deliverables, away from the ideal design path of front-loaded design work. Future efforts will be made to ensure earlier design work along with using this project as a reference when estimating hours to completion for different aspects of the project.

5.3 Engineering Cost Hour Cost

Below is a table listing the hours per phase and the associated cost for junior and senior engineering hours.

Table 7 - Cost Breakdown of Engineering Hours

Phase	Junior Engineer Hours	Junior Engineer Cost (\$90/hr)	Senior Engineer Hours	Senior Engineer Cost (\$150/hr)	Total Cost

I	88	\$7920	1.5	\$225	\$8145
II	223.5	\$20,115	2.5	\$375	\$20,490
III	441	\$39,690	2	\$300	\$39,990
					<u>\$68,625</u>

The total cost of engineering hours comes to \$68,625 for the complete project.

6 Future Work

Although much work has been completed for this project, we are not done. There are still some items that must be addressed to ensure that the product performs as expected. These items are as listed below:

1) Moment Arm Stress Fatigue Analysis

Although forces in this system are quite low and stress was never a concern during the design process, it is important to understand how they would be able to affect the system over its lifetime. A fatigue analysis will need to be conducted to understand the lifecycle of the product.

2) Thermal analysis of spring

The weather in Canada can vary as much as 80°C over a year. This can have large effects on metals such as the ones used in this product. A detailed analysis of the effect of temperature change will need to be conducted to ensure that the product behaves as expected.

3) Prototyping & Wind Tunnel Testing

A prototype of the model should be created and tested on the system in a wind tunnel to ensure that it behaves as expected. This will allow for any changes to be made before the system is fully deployed on campus.

4) Work with the client on guy wires and emergency brakes

The client has committed to implementing a guy wire system to stabilize the turbine and an emergency braking system to stop it in high wind speed conditions. It will be important to change and optimize the design for these new features.

7 Conclusion

The objective of this design was to provide braking for a microgeneration wind turbine. The way this was accomplished was by using a governor system that would increase the moment of inertia to store and release energy. When wind speeds were above 18 km/h the governor masses would act on an aluminum shield to provide braking to the turbine. There was a 29.67% increase in overall efficiency for wind turbine generating hours, this is from a corresponding increase in 1813 generating minutes. There is a maximum energy storage increase of 481%. The total cost of the project parts and manufacturing was \$4508.20 with a cost of \$68,625 for engineering work performed. This sums up a total project cost of \$73133.20 with a total of 762.5 hours of engineering design work.

There is additional work planned, such as an emergency brake and wind tunnel testing which will optimize the design in tandem with the clients' proposed changes to their wind turbine system.

References

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2. “Common Types of Sheet Metal”, *MetaFab*, Apr 23, 2020. Accessed: Dec 6, 2023. [Online]. Available: <https://www.metafab.com/common-types-of-sheet-metal/>
3. “Aluminum 6061-T6; 6061-T651”, *MatWeb*. Accessed: Dec 6, 2023. [Online]. Available: <https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6>
4. “Cartridge Brass, UNS C26000 (260 Brass), OS070 Temper flat product”, *MatWeb*. Accessed: Dec 6, 2023. [Online]. Available: <https://www.matweb.com/search/datasheet.aspx?matguid=83677ae92338456da4d4fe8fe4b815c5&ckck=1>
5. “AK Steel ZINCGRIP Hot Dip Galvanized Carbon Steel, Commercial Steel (CS Type B), Standard Grade”, *MatWeb*. Accessed: Dec 6, 2023. [Online]. Available: <https://www.matweb.com/search/datasheet.aspx?matguid=ce87ebe67e37455d983c48447d309360>

Appendices

7.1 Appendix A– Gantt Chart

GANTT CHART

PROJECT TITLE: Regenerative Breaking System for Wind Turbine
 COMPANY NAME: MACH Innovations
 PROJECT MANAGER: N/A
 DATE: 12/5/23

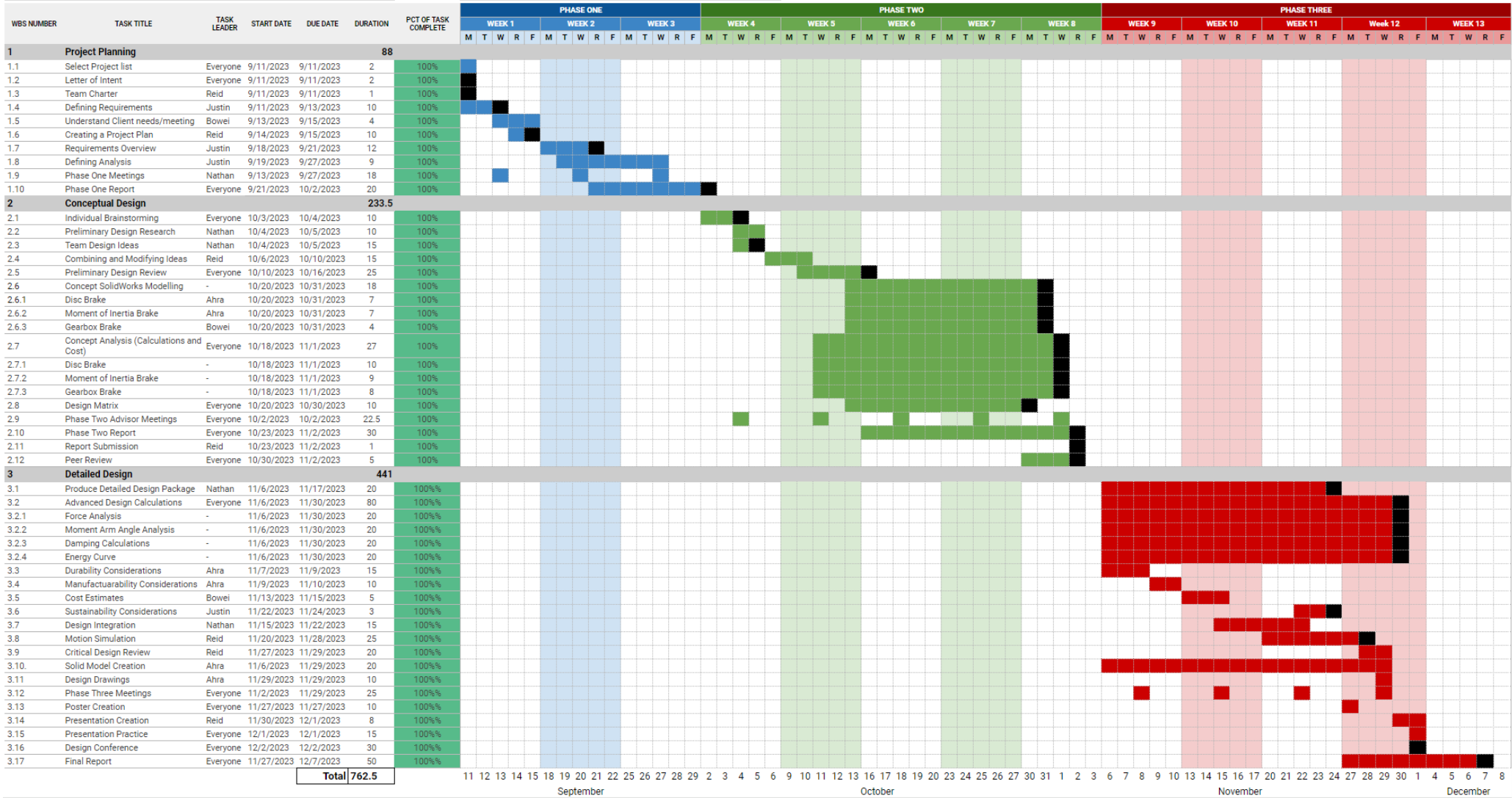


Figure 14 – Gantt Chart

7.2 Appendix B – Design Specification Matrix

Requirement Number	Requirement Version	Requirement Last Updated	Design Function Consideration	Design Specification/Requirement	Importance	Weighting	Source/Justification	Design Authority
Braking Specifications								
1.1	1	Sept-12-2023	Outdoor Durability	System must be suitable for continuous outdoor operation, duration of at 2 years.	Must	5	The braking system will be installed on an outdoor wind turbine system, so resistance to outdoor elements and temperature changes is a must for reliable system operation.	Team, Specific Standard
1.2	1	Sept-12-2023	Feedback System	System must measure turbine speed and respond with brake action with no user input within 100ms.	Must	5	The braking system is to protect the turbine from resonance and high wind speeds. To complete this, the system must be able to measure the turbine speed and respond with braking action.	Team
1.3	1	Oct-23-2023	Wind speed range	System should increase operational time during gusting conditions, at gusts up to 90 km/h	Should	4	The braking system will allow the turbine to operate in a larger variety of wind speeds without damage and will therefore increase the operational energy output of the turbine.	Team
1.4	1	Oct-23-2023	Braking Method	System should not “bleed off” braking energy as heat, energy is to be captured and stored	Should	3	Regenerative braking could allow for increased operating efficiency of the turbine braking system allowing for more generation at high wind speeds.	Team
1.5	1	Sept-13-2023	Non-Consumable Components	System should have few or no consumable components, consumable components should last 2 years.	Should	3	Consumable components require service which can be expensive to maintain and create waste.	Client
1.6	1	Sept-13-2023	Size Constraints	System may be compact, turbine blade is only ~300mm tall and ~100mm wide	May	2	System should not increase the footprint of the turbine but a small increase may be allowed if required for design or budgetary reasons.	Team
1.7	1	Sept-13-2023	System Integration	System may be retrofitted into the existing wind turbine system	May	2	The braking system must be able to be integrated into the	Team

							existing wind turbine system. Alterations to the existing system are allowed.	
1.8	1	Sept-13-2023	Back-up Braking	System may include a back-up braking system capable of withstanding gusts of 150kmh	May	1	The system may include a back-up braking system which will have the ability to prevent damage to the turbine at much higher speeds.	Team
Environmental Factors								
2.1	1	Sept-13-2023	Material	System should be environmentally friendly in its material and prototyping	Should	3	The Goal of the Renewable Energy club at the U of A is to create sustainable energy through projects such as this one, meaning environmental and sustainability considerations are important.	Client
2.2	1	Sept-13-2023	Efficiency	System should increase operating efficiency to greater than 30%	Should	3	Increased efficiency is the goal of a regenerative braking system, as such, maximizing the efficiency of the system is a priority.	Team
Regulations and Standards								
3.1	1	Sept-13-2023	Standards and Regulations	System shall follow legal standards and regulations in material selection and prototyping	Must	4	To ensure safe operation of the turbine, legal and safety standards such as the Canadian Electrical Code and the CSA Guide to Canadian Wind Turbine Codes and Standards will be followed.	Standards
3.2	1	Sept-13-2023	Human Safety	Operation of the system must not cause harm to humans operating on the system	Must	4	Negating possible risk factors is a big priority in order to increase the safety of the turbine. Maintenance must be done to the turbine at regular intervals and the safety of humans must be considered.	Team
Commercial Requirements								
4.1	1	Sept-13-2023	Cost	Cost of system may be between \$350-1000	May	2	Price ranges were given by client based on previous experiences designing and building the wind	Client

							turbines the system will be attached too.	
4.2	1	Sept-13-2023	Ease of Manufacturing	System may be producible in the Elko garage and MecE shop	May	1	Client currently has a system of 9 turbines installed, ease of prototyping replicas (manufacturing) should be considered.	Client

7.3 Appendix C – Detailed Cost Analysis

A detailed cost analysis can be found below. Parts were all sourced from reputable stores, so lead times are assumed to be negligible.

Table 8 - Detailed Part Cost Breakdown

Part Name	Cost per Part	# of Part	Total Cost	Manufacturer
Governor System				
Zinc Plated Steel Hex Nuts - Grade 5 [1/4"-20]	\$8.95 for 100	1	\$8.95	McMaster-Carr
Steel Lock Nut – Grade 8 [1/4"-20]	\$4.49 for 25	1	\$4.49	McMaster-Carr
18-8 Stainless Steel Washer [1/4"]	\$8.51 for 100	1	\$8.51	McMaster-Carr
Carbon Steel Clevis Rod End [1/4" -20]	\$6.79	18	\$122.22	McMaster-Carr
Zinc Yellow-Chromate Plated Steel 6" Threaded Rod [1/4"-20]	\$9.46	18	\$173.52	McMaster-Carr
Black-Oxide 1215 Carbon Steel Shaft Collar 1/2"	\$2.45	9	\$22.05	McMaster-Carr
Extension Spring 40.4mm	\$13.35 for 2	18	\$120.15	McMaster-Carr
Braking Shield				
Aluminum Sheet 18"x18"	\$118.44	9	\$1065.96	McMaster-Carr
Zinc Plated Steel Hex Nuts – Grade 5 [1/2"-20]	\$24.52 for 100	1	\$24.52	McMaster-Carr
Grade B7 - Steel 2" Threaded Rod [1/2"-20]	\$4.08	54	\$220.32	McMaster-Carr
Aluminum Flange	\$81	9	\$729	McMaster-Carr
18-8 Stainless Steel Washer [1/2"]	\$8.51 for 100	1	\$8.51	
Final Total Part Cost				\$2508.20

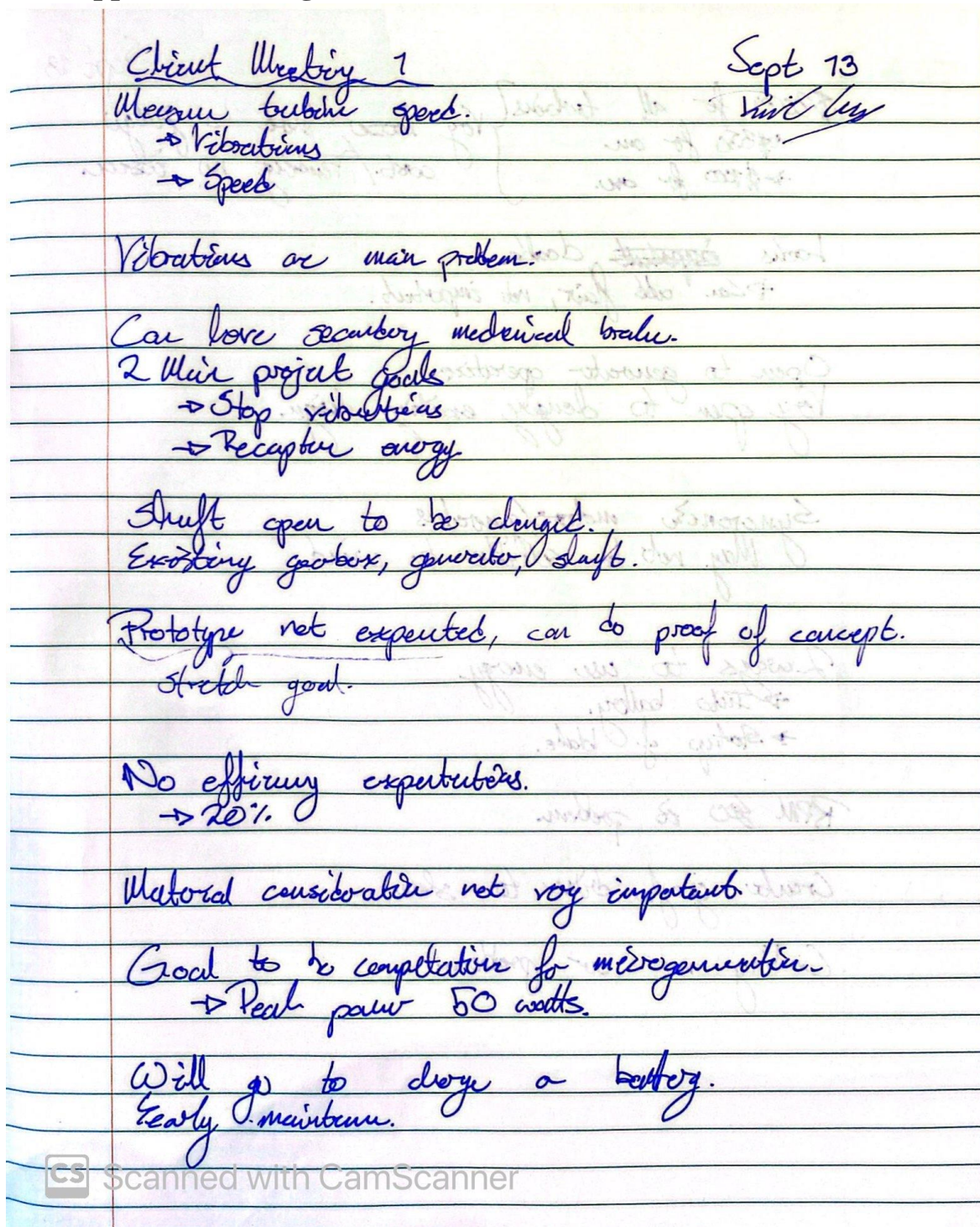
Shop hours are estimated using industry sources. These are rough estimates of how long and the typical cost that can be expected for a project of this complexity. They are subject to change when actual prototypes begin to be developed.

Table 9 - Shop Hour Cost Breakdown

Shop Type	Hours	Cost per Hour	Total Cost
Machining	10	\$100	\$1000
Welding	10	\$100	\$1000

This leads to a final total cost of \$4508.20.

7.4 Appendix D - Logbooks



Phase 1 Presentation to Prof Sept 27.

→ Regenerative braking is out of project scope.

→ Must find a way to mechanically brake the wind turbines

→ Energy generation moves to priority of 2 or 3.

Presentation went well, give less speaking time to Arha while still including her.

Advisor Meeting

→ Make sure to get Phase 1 Report handed in by Thursday afternoon for review.

→ Can go to him for clarification on scope of project.

→ Should set up meeting with Prof. about project scope



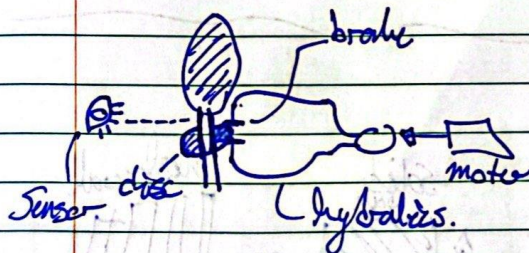
Scanned with CamScanner

New Ideas

Sept 27
Muller

① Brake system

- ↳ Disc brakes (Bike brakes)
- ↳ Hydraulic actuators
- ↳ Maybe can just attach bike brakes to turbine shaft and attach a motor to actuate the hydraulics.
- ↳ Hard to maintain & service
- ↳ Easy?
- ↳ Went last in best conditions (overheating, debris build up)



motor & sensor can communicate to turn on brake.


Low volume of "damaging" work speeds.
Can make systems that are only active for small periods of time.

Oct 15

Roller

Initial Calculations

Moment of inertia:



rod: $I = \frac{mr^2}{2}$

Turbine: $m = 355.05 \text{ g}$.



~~diameter = 5.11~~

$d = 74.35 \text{ cm}$

$l = 44.3 \text{ cm}$

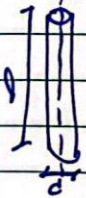
Assume turbine is solid shaft.

$I_1 = \frac{mr^2}{2} = 9.1391 \times 10^{-4}$

Drawing package may be wrong cause everything has no units and is scaled weird.

Every ~~calc~~ value is $\times 10^2$.

Shaft: $m = 371.95 \text{ g}$.



$d = 1.27 \text{ cm}$

$l = 24 \text{ cm}$

$I_2 = 7.499 \times 10^{-6}$

$\therefore I_T = 9.27409 \times 10^{-4}$

$\tau = I\omega$ where ω is shaft rotation.

$\omega = 194.78 \rightarrow 567.58 \text{ RPM}$

$= 20.366 \rightarrow 59.437 \text{ rad/s}$

$\therefore \tau = 0.0188 \rightarrow 0.05477$

Nov 22

Andy

Intro

- Thanks for coming
- MACH Innovations
- Introduce
- Renewable Energy Design Club
- Braking System for WGW

Outline

- Tell story of our design. & detailed calculations.
- Problem Definition & Scope Development
- Design Objectives & Key Requirements
- Concept development
- Concept selection
- Design Analysis
 - Technical
 - Economical

PD & SD

- Begin with PD & SD
- Develop understanding of client needs
- Our capabilities.

Problem Definition

- Created roticle axis wind turbine
- Team of 9
- Located between building, rotor offset
- Gusts, up to 90 km/h
- Overloading causes vibrations, causes damage
- Occurs @ 18 mph
- No braking system

Scanned with CamScanner

Proposal choosing

- satellite boom optimization
- regenerative turbine brake
- bike bell
- wave generator
- gear box
- waste recycle
- odorant
- coffee roaster

→ final proposal: Regenerative Braking System Design

Consider electrical car

- hydraulic and regenerative braking force

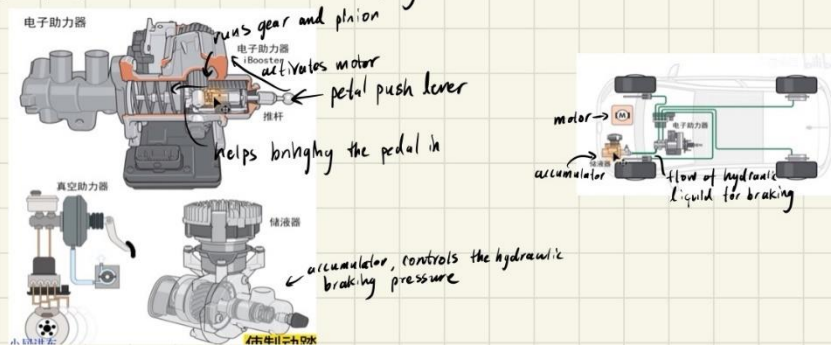
↓
hydraulic braking system

↓
electric motor

- when the car is braking, motor becomes generator
- wheel motion drives generator to generate power, which causes the wheels to break
- electrical car uses i-booster or e-booster - differs from traditional combustion engine cars that uses vacuum booster

iBooster: how it works

- pressing braking pedal will cause a lever to translate forward
- which activates a motor that aids moving the braking pedal with gears and pinion racks
- which interns serves as a boost to make braking easier



Meeting Note - Sept 13 1:15:00 | 6:00PM ~ 7:15PM

→ can have a few consumable component, but try to leave it little as possible

input suggestion ⇒ input by vibration
input by speed

- backup braking in case of critical failure
- doesn't necessary have to entirely be retrofitted into the existing system
 - can redesign gearbox
 - won't be expecting prototype → can increase shaft length, etc
- brake mount between blade and base
- list of standard and Regulation will provide
- no real expectation for efficiency, 20% would be nice
 - generator → 85-88% efficient
 - charge into a battery (DC voltage) → turbine has quite some resistance - cutting speed
 - approximately yearly maintenance
 - turbine make about 50W
 - \$350 ~ \$1000
 - venturi effect
 - aesthetic design if possible
 - fairly integrated if possible

designs

1st: time mechanically actuated system
→ magnet braking

- fly wheel

2nd: switch system with bank of coils ⇒ different inductor to resist against wind speed

→ energy from braking can go to battery or used as start up energy

→ the oscillation, which is the problem of the turbine, is exclusive to the blade shaft

• consider energy lost at start up

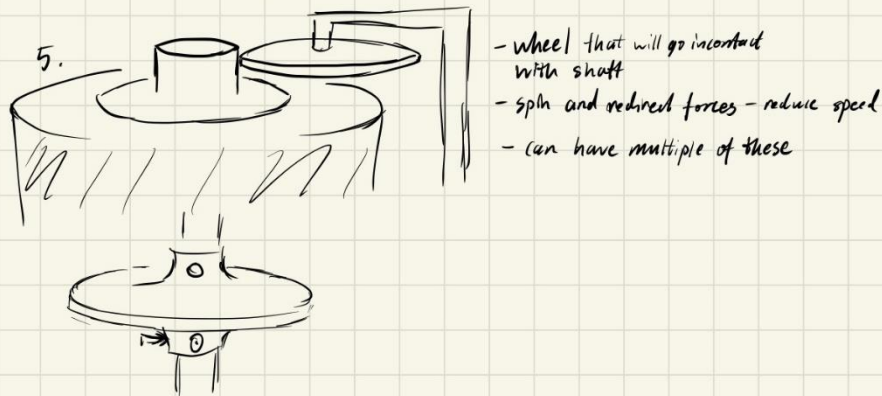
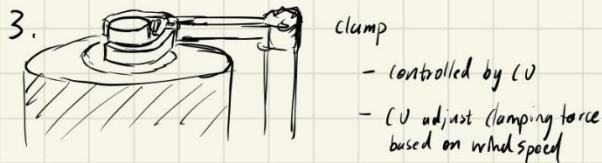
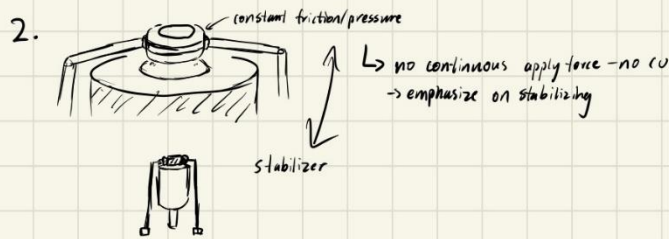
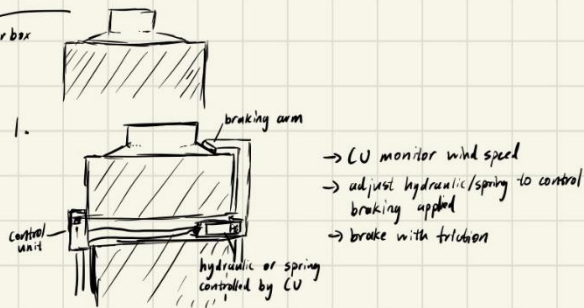
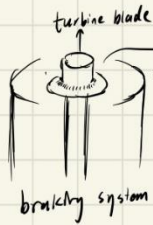
3rd: clutch engagement to a second generator

Activity 5 - Individual Ideation

Oct 4, 2023

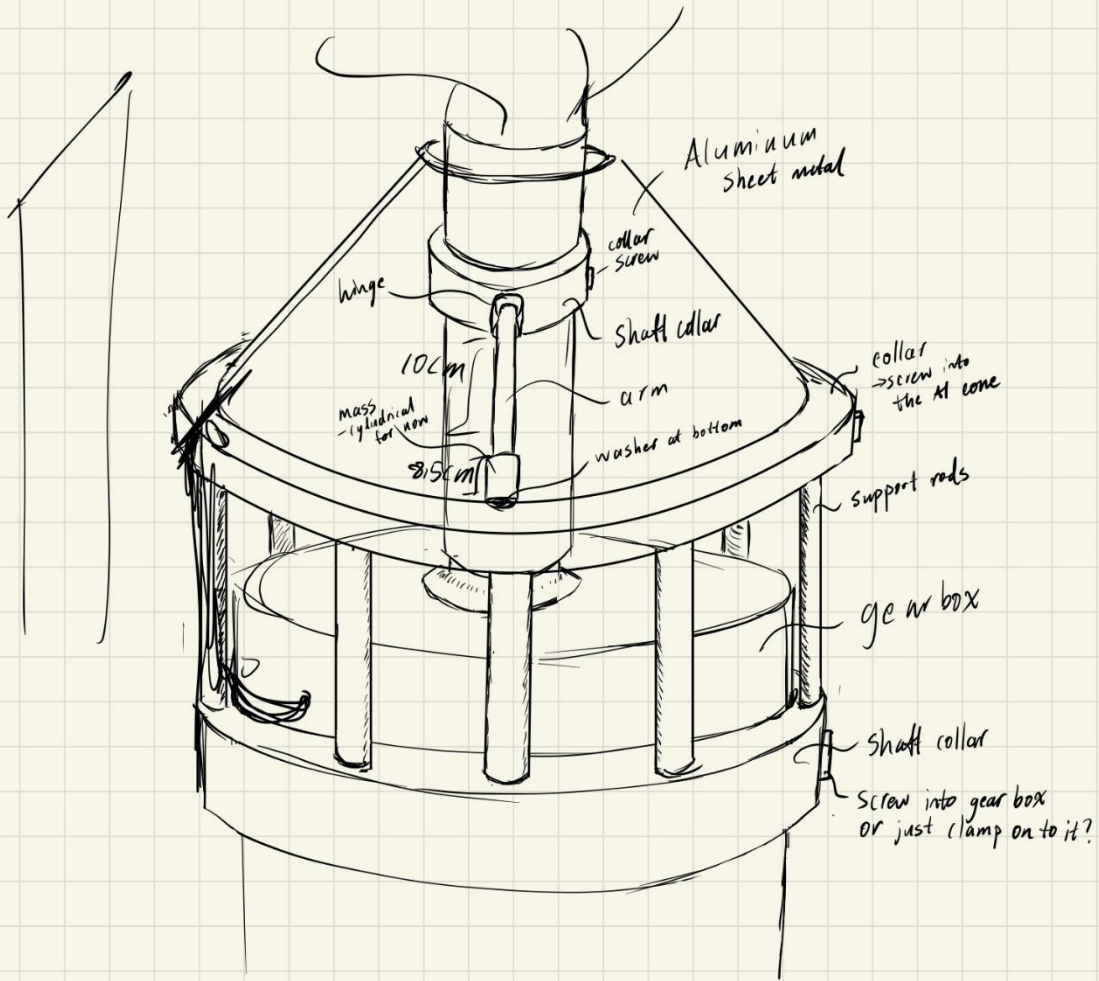
Bowei Huang

This document shows 5 ideations I came up with for the conceptual portion of this project. Took about an hour for these 5, the emphasis is more on how to apply the brake.

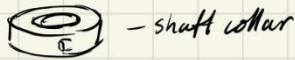


SW list

- | | | |
|----------------|----------------------|------------------------------|
| governor clamp | - shaft collar | cone - aluminium/sheet metal |
| governor hinge | | cone clamp |
| governor arm | - threaded rod | cone hinge |
| governor mass | - washer/nut/bushing | cone attachment - steel rod |



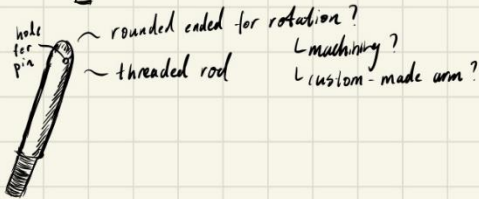
Assembly 1: governor



- shaft collar



- hinge, with central pin for the arm → 2 of these, 180° from each other
- on the shaft collar



hole for pin
- rounded ended for rotation?
- threaded rod
↳ machining?
↳ custom-made arm?



- mass
- specialized nut from what Justin said
↳ no need to screw it in with the thread
↳ rubber inside the nut that will act like socket?



- washer
→ at the bottom end of the nut

1 set of these on each of the two pins

Assembly 2: cone



- Aluminium sheet metal

hole for screw - screwed into the metal



← all the way through



- shaft collar to hold the Al cone

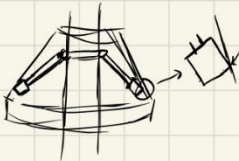


supporting rod - brass maybe?
- welded on to the shaft collar on both ends
- equally space on the collar
- 5? 6?

2 collar should be same diameter so rods don't tilt



← shaft collar on the gear box

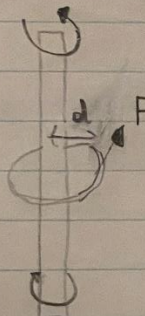


Phase 1 Example

$$\tau = I\alpha$$

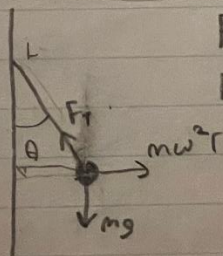
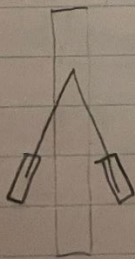
$$Fd = I\alpha$$

$$F_N \times d = I\alpha$$



$$F_N(0.4)(0.1) = (9.14 \times 10^{-4} + 9.24 \times 10^{-4})(6.28)$$

$$k_E = \frac{1}{2} I \omega^2 \rightarrow k_E = \frac{1}{2} (1.1 I) \left(\frac{1}{\sqrt{1.1}} \omega \right)^2$$



$$F_T \cos \theta - mg = 0 \rightarrow F_T = \frac{mg}{\cos \theta}$$

$$F_T \sin \theta - m\omega^2 r = 0$$

$$\frac{mg \sin \theta}{\cos \theta} - m\omega^2 r = 0$$

$$g \tan \theta - \omega^2 L \sin \theta = 0$$

$$\frac{g}{\cos \theta} = \omega^2 L$$

$$\theta = \cos^{-1} \left(\frac{g}{\omega^2 L} \right)$$

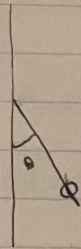
$$\cos \theta = \frac{g}{\omega^2 L}$$

$$\omega = \sqrt{\frac{g}{L \cos \theta}}$$

$$\frac{Mg \sin \theta}{\cos \theta} - M(4) \omega^2 r = 0$$

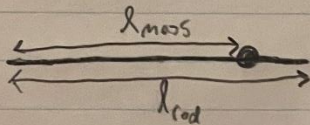
$$g \frac{\sin \theta}{\cos \theta} - 4L \omega^2 \sin \theta = 0$$

Phase 2 example



$$\theta = \arccos\left(\frac{g}{\omega^2 L}\right)$$

center of mass



uniform bar with 1 mass

L = length of bar

x = distance to mass

$$\frac{m_{\text{mass}}}{m_{\text{rod}} + m_{\text{mass}}} x + \frac{m_{\text{rod}}}{m_{\text{mass}} + m_{\text{rod}}} \frac{L}{2} = \frac{x_{\text{mass}} m_{\text{mass}} + \frac{L}{2} m_{\text{rod}}}{m_{\text{mass}} + m_{\text{rod}}} = L$$

additional moment of inertia

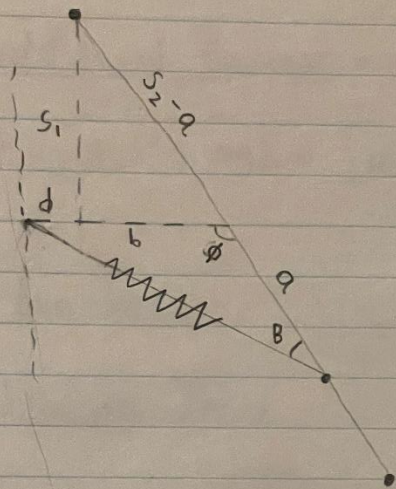
$$I = Mr^2 = M(L \sin \theta)^2 = ML^2 \sin^2\left(\cos^{-1}\left(\frac{g}{\omega^2 L}\right)\right)$$

$$\sin^2(\cos^{-1}(x)) = 1 - x^2$$

$$= ML^2 \left(1 - \left(\frac{g}{\omega^2 L}\right)^2\right) = ML^2 - \frac{g^2}{\omega^4 L^2} ML^2 = \sqrt{ML^2} - \frac{Mg^2}{\omega^4}$$

additional energy

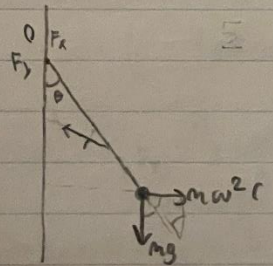
$$E = \frac{1}{2} I \omega^2 + Mgh = \frac{1}{2} \left(ML^2 - \frac{Mg^2}{\omega^4}\right) \omega^2 + MgL \cos \theta$$
$$= \frac{ML^2 \omega^2}{2} - \frac{Mg^2}{2\omega^2} + Mgk \frac{g}{\omega^2 k} = \frac{ML^2 \omega^2}{2} - \frac{Mg^2}{2\omega^2} + \frac{Mg^2}{\omega^2} = \frac{M}{2} \left(L^2 \omega^2 + \frac{g^2}{\omega^2}\right)$$



a, b, c

$$\frac{\sin C}{c} = \frac{\sin B}{b}$$

$$B = \sin^{-1}\left(b \frac{\sin C}{c}\right) = \sin^{-1}\left(b(\theta) \frac{\sin(\theta + 90)}{L_s(\theta)}\right)$$



$$\sum M_0 = mg \sin \theta - mw^2 r \cos \theta + \sin(B(\theta)) k L_{ds}(\theta) = 0$$

$$\sum F_y \rightarrow F_y - mg + \sin(p(\theta)) k L_{ds}(\theta) = 0$$

$$\sum F_x \rightarrow F_x + mw^2 L \sin \theta + \cos(p(\theta)) k L_{ds}(\theta) = 0$$

$$mg \sin \theta + \sin(B(\theta)) k L_{ds}(\theta) = mw^2 L \sin \theta \cos \theta$$

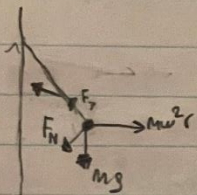
$$\omega(\theta) = \sqrt{\frac{mg \sin \theta + \sin(B(\theta)) k L_{ds}(\theta)}{m L \sin \theta \cos \theta}}$$

additional Energy

$$E = \frac{1}{2} I \omega^2 + mgh + \frac{1}{2} k L_{AS}^2 = \frac{1}{2} I(\omega) \omega^2 + mgL \cos(\theta(\omega)) + \frac{1}{2} k L_{AS}(\omega)^2$$

translence

braking force



$$F_T \cos \theta - mg - \sin \theta F_N = 0$$

$$-F_T \sin \theta + m\omega^2 L \sin \theta - \cos \theta F_N = 0$$

$$F_T \cos \theta \sin \theta - mg \sin \theta - \sin^2 \theta F_N = 0$$

$$-F_T \cos \theta \sin \theta + m\omega^2 L \sin \theta \cos \theta - F_N \cos^2 \theta = 0$$

$$m\omega^2 L \sin \theta \cos \theta - mg \sin \theta - F_N \sin^2 \theta - F_N \cos^2 \theta = 0$$

$$m\omega^2 L \sin \theta \cos \theta - mg \sin \theta = F_N (\sin^2 \theta + \cos^2 \theta)$$

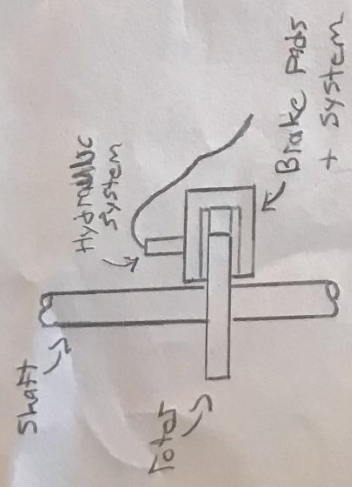
$$m \sin \theta (\omega^2 L \cos \theta - g) = F_N$$

$$F_f = \mu_k F_N = \mu_k m \sin \theta (\omega^2 L \cos \theta - g)$$

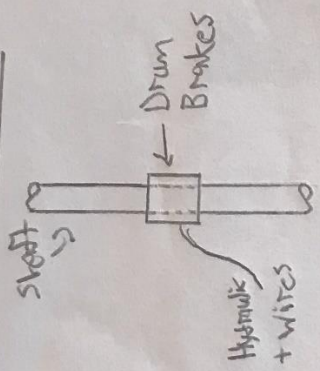
$$E_{lost} = \mu_k F_N d \rightarrow P_{lost} = \mu_k F_N v \rightarrow v = \omega r = \omega L \sin \theta$$

$$P_{lost} = F_f v = \mu_k m \sin \theta (\omega^2 L \cos \theta - g) \omega L \sin \theta$$

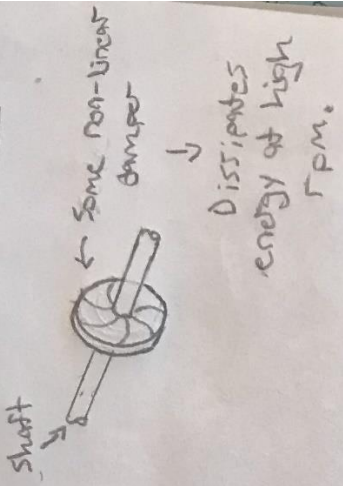
Rotor Brakes



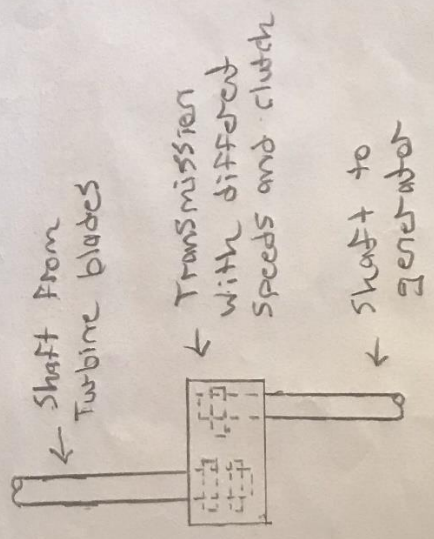
Drum Brakes



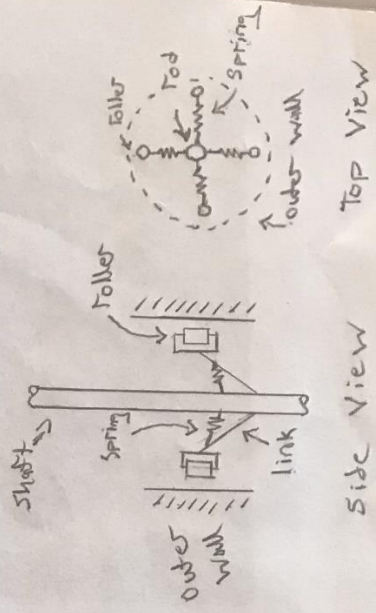
Non-linear Damper



3-Speed Transmission

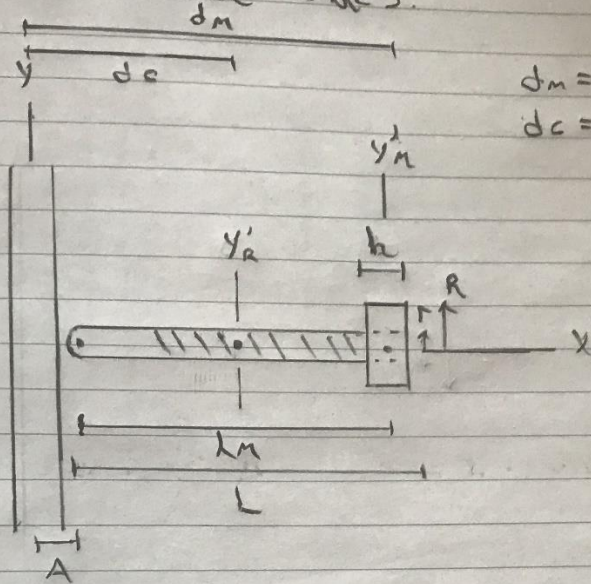


Self Retracting Rollers that are Activated by Rotation



Justin Van Engelen

Govet not Excel Calc5



$$d_m = A + Lm$$

$$d_c = A + L/2$$

$$I_{\text{cyl, center}} = \frac{1}{12} M_c (3r^2 + L^2)$$

$$I_{\text{mass, center}} = \frac{1}{12} M_m (3(R^2 + r^2) + h^2)$$

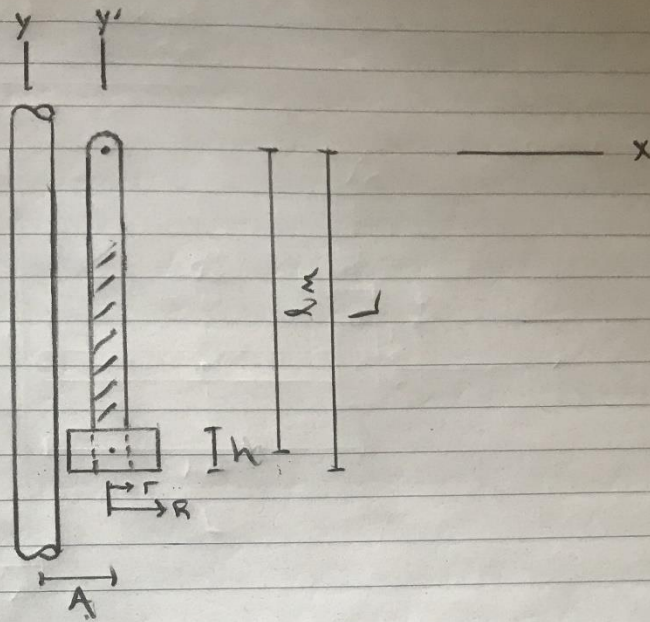
$$I_{\text{total}} = I_{\text{cm}} + M d^2$$

$$I_{T, 90^\circ} = I_c + M_c \cdot d_c^2 + I_m + M_m \cdot d_m^2$$

$$= \left[\frac{1}{12} M_c (3r^2 + L^2) \right] + M_c \cdot d_c^2$$

$$+ \left[\frac{1}{12} M_m (3(R^2 + r^2) + h^2) \right] + M_m \cdot d_m^2$$

A L h Lm R r 0.00158 0.0008462



$$I_{\text{cyl, center}} = \frac{1}{2} m r^2$$

$$I_{\text{mass, center}} = \frac{1}{2} M (R^2 + r^2)$$

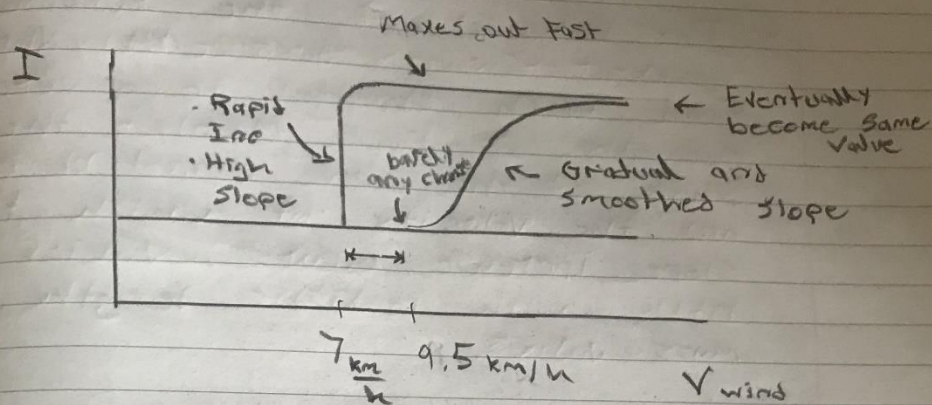
$$I_{\text{total}} = I_{\text{cen}} + M d^2$$

$$I_{T, 0^\circ} = I_c + M_c A^2 + I_m + M_m \cdot A^2$$

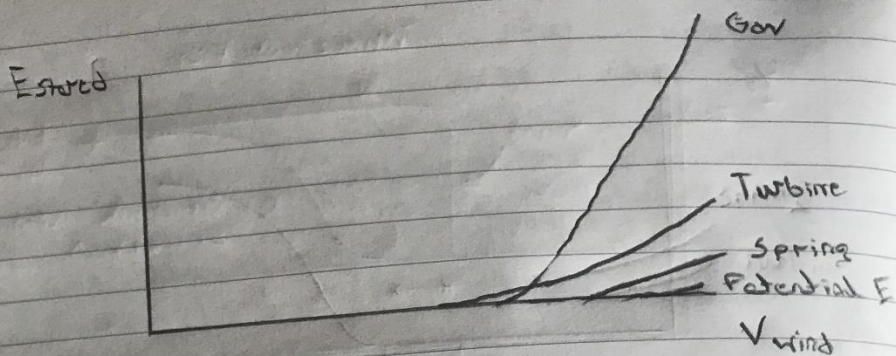
$$= \left[\frac{1}{2} m r^2 \right] + M_c \cdot A^2 + \left[\frac{1}{2} M (R^2 + r^2) \right] + M_m \cdot A^2$$

$$I_\theta = \sin(\theta) \cdot I_{T, 90^\circ} + \cos(\theta) \cdot I_{T, 0^\circ}$$

$$\left[\frac{A^2}{\theta} \right]$$



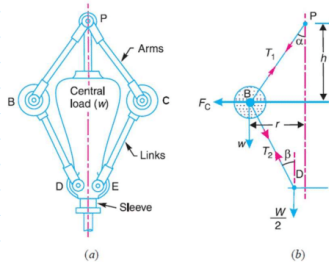
- To kick off the design portion:
- 3 - different $I - V$ curves
- I change is good because,
 - Reduces the response of the system to fluctuations.
 - While capturing gust and overspeed energy as angular momentum.
 - Allows for braking operation at damaging RPM
- Original turbine design has no change in inertia.
- Turbine with governor attachment:
 - Rapid slope increase and maxed out I values at 7 km/h .
 - When I maxes out the brakes activate.
 - Brakes need to activate at 18 km/h not 7 km/h .
 - This braking



- While the turbine is rotating, some of the energy applied to the system by the wind is stored as
 - Governor kinetic energy
 - Turbine kinetic energy
 - Spring Potential energy
 - Potential Energy of raised masses
- Note that the governor arms have the ability to store the most amount of energy out of any components, in the system.
- The most important take away from this, is that our system is able to perform its duty as a transient regulator and a brake, while storing the excess energy so that it can eventually be recovered.

Porter Governor

October 30, 2023 7:26 PM



$m =$ mass of the ball

$M =$ mass of the central load

$F_c =$ centrifugal force acting on the ball $= M\omega^2 r$

$T_1 =$ force in the arm

$T_2 =$ force in the link

Force Method :

Determine the relation b/w the height of the governor (h) and the angular speed of the ball (ω)

Forces at D :

$$\sum F_y = 0 ; T_2 \cos \beta = \frac{W}{2} = \frac{M \cdot g}{2}$$

$$T_2 = \frac{Mg}{2 \cos \beta}$$

Forces at B :

$$\sum F_y = 0 ; T_1 \cos \alpha - W - T_2 \cos \beta = 0$$

$$T_1 \cos \alpha = T_2 \cos \beta + mg$$

$$T_1 \cos \alpha = \frac{Mg}{2} + mg \quad - (1)$$

$$\sum F_x = 0 ; T_1 \sin \alpha - F_c + T_2 \sin \beta = 0$$

$$F_c = T_1 \sin \alpha + T_2 \sin \beta$$

$$F_c = T_1 \sin \alpha + \frac{Mg}{2 \cos \beta} \sin \beta$$

$$F_c = T_1 \sin \alpha + \frac{Mg}{2} \tan \beta$$

$$T_1 \sin \alpha = F_c - \frac{Mg}{2} \tan \beta$$

Dividing (2) by (1) ,

$$\frac{T_1 \sin \alpha}{T_1 \cos \alpha} = \frac{F_c - \frac{Mg}{2} \tan \beta}{\frac{Mg}{2} + mg}$$

$$\tan \alpha \left(\frac{Mg}{2} + mg \right) = F_c - \frac{Mg}{2} \tan \beta$$

Governor Page 1

$$F_c = mg \tan \alpha + \frac{Mg}{2} (\tan \alpha + \tan \beta)$$

Dividing throughout by $\tan \alpha$,

$$\frac{F_c}{\tan \alpha} = mg + \frac{Mg}{2} \left(1 + \frac{\tan \beta}{\tan \alpha} \right)$$

$$\frac{m\omega^2 h}{\tan \alpha} = mg + \frac{Mg}{2} (1 + q)$$

$$m\omega^2 h = mg + \frac{Mg}{2} (1 + q)$$

$$h = \frac{mg + \frac{Mg}{2} (1 + q)}{m\omega^2}$$

$$h = \frac{m + \frac{M}{2} (1 + q)}{m} \left(\frac{g}{\omega^2} \right)$$

$$\omega^2 = \frac{m + \frac{M}{2} (1 + q)}{m} \left(\frac{g}{h} \right)$$

$$\tan \beta = \frac{HD}{BD}$$

$$\times \tan \alpha = \frac{r}{h}$$

$$\times q = \frac{\tan \beta}{\tan \alpha}$$

$$\times F_c = m\omega^2 r$$

Example 1:

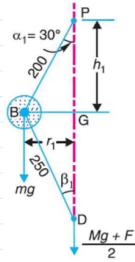
$$PB = 200 \text{ mm}$$

$$BD = 250 \text{ mm}$$

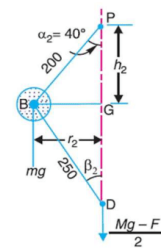
$$m = 2 \text{ kg}$$

$$M = 15 \text{ kg}$$

∴



(a) Minimum position.

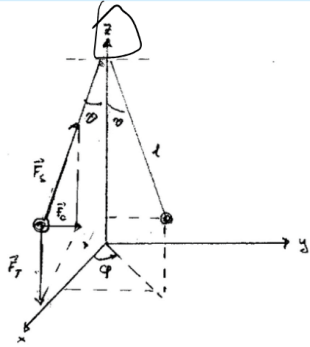


(b) Maximum position.

All dimensions in mm.

Conical pendulum

October 31, 2023 2:16 PM



$$x = l \sin \theta \cos \varphi$$

$$y = l \sin \theta \sin \varphi$$

$$z = l (1 - \cos \theta)$$

$$KE = \frac{1}{2} m v^2 = \frac{1}{2} m (\dot{x}^2 + \dot{y}^2 + \dot{z}^2) = T$$

$$PE = m g z = U$$

Velocities along two polar angles:

$$v_\theta = r \dot{\theta} \quad \& \quad v_\varphi = r \sin \theta \dot{\varphi}$$

$$v^2 = v_\theta^2 + v_\varphi^2 \quad (\text{since orthogonal})$$

Apply Lagrange:

$$L = T - U$$

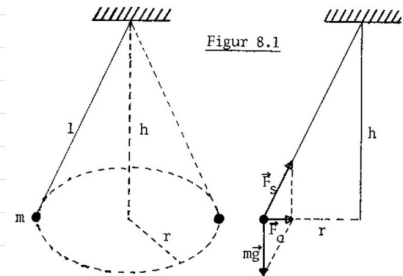
Using generalized coordinates (q_i):

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = 0$$

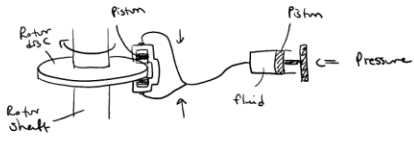
$$T = \frac{1}{2} m (l^2 \dot{\theta}^2 + l^2 \sin^2 \theta \dot{\varphi}^2) = \frac{1}{2} m l^2 (\dot{\theta}^2 + \sin^2 \theta \dot{\varphi}^2)$$

and

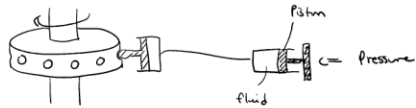
$$U = m g l (1 - \cos \theta)$$



Sample #1

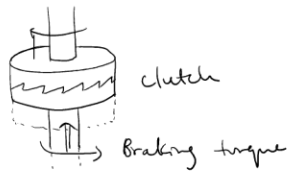


Sample #2

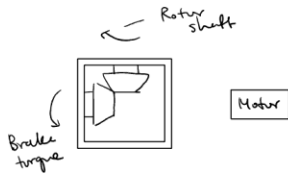


Sample #3

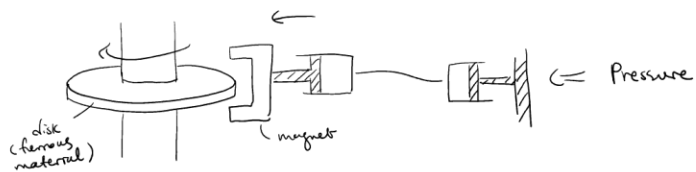
== == ==



Sample #4



Sample #5



7.5 Appendix E – Client Wind Data

Time	Load (ohm)	RPM	Wind (m/s)	Voltage (V)
1.34	450	153	2.49	0.5256936564
1.34	450	152	2.51	0.5256936564
1.34	450	148	2.49	0.5256936564
1.34	450	236	2.75	0.8130117324
1.34	450	235	2.72	0.8130117324
1.34	450	234	2.74	0.8130117324
1.34	450	300	2.99	1.047297755
1.34	450	303	3.01	1.047297755
1.34	450	302	3	1.047297755
1.34	450	355	3.21	1.233943989
1.34	450	357	3.24	1.233943989
1.34	450	359	3.27	1.233943989
1.34	450	414	3.55	1.432906963
1.34	450	415	3.52	1.432906963
1.34	450	416	3.5	1.432906963
1.34	450	465	3.75	1.60542055
1.34	450	465	3.75	1.60542055
1.34	450	462	3.74	1.60542055
1.34	450	510	4	1.767166083
1.34	450	509	4	1.767166083
1.34	450	512	4.02	1.767166083
1.34	450	561	4.23	1.934955776
1.34	450	559	4.24	1.934955776
1.34	450	560	4.31	1.934955776
1.34	450	602	4.52	2.082384271
1.34	450	600	4.49	2.082384271
1.34	450	601	4.52	2.082384271
missing	450	638	4.76	#N/A
missing	450	635	4.76	#N/A
missing	450	634	4.71	#N/A
missing	450	680	5.04	#N/A
missing	450	676	4.96	#N/A
missing	450	679	4.98	#N/A
missing	450	678	5	#N/A
missing	450	679	4.95	#N/A
2.02	450	645	4.75	2.209887289
2.02	450	647	4.75	2.209887289
2.02	450	642	4.74	2.209887289
2.02	450	641	4.7	2.209887289
2.02	450	687	5.04	2.357072682
2.02	450	686	5.02	2.357072682
2.02	450	688	5.04	2.357072682

1.46	900	676	4.96	2.338741373
1.46	900	677	4.96	2.338741373
1.46	900	677	4.96	2.338741373
1.46	900	638	4.7	2.209975369
1.46	900	639	4.71	2.209975369
1.46	900	641	4.75	2.209975369
1.46	900	598	4.46	2.069542291
1.46	900	598	4.5	2.069542291
1.46	900	599	4.45	2.069542291
1.46	900	564	4.33	1.936164104
1.46	900	559	4.23	1.936164104
1.46	900	560	4.23	1.936164104
1.46	900	519	4.02	1.784476088
1.46	900	516	4.01	1.784476088
1.46	900	515	4.03	1.784476088
1.46	900	475	3.78	1.62868136
1.46	900	470	3.74	1.62868136
1.46	900	469	3.75	1.62868136
1.46	900	417	3.49	1.442015377
1.46	900	418	3.5	1.442015377
1.46	900	418	3.49	1.442015377
1.52	900	370	3.25	1.268269512
1.52	900	368	3.23	1.268269512
1.52	900	367	3.22	1.268269512
1.52	900	323	3.03	1.108762815
1.52	900	323	2.99	1.108762815
1.52	900	322	3.01	1.108762815
1.52	900	268	2.78	0.9139765983
1.52	900	270	2.76	0.9139765983
1.52	900	268	2.78	0.9139765983
1.52	900	194	2.46	0.6605786482
1.52	900	194	2.46	0.6605786482
1.52	900	193	2.5	0.6605786482

Client wind data – wind tunnel test trials

	Cut in	Cut out
1	3.2	2.27
2	3.19	2.27
3	3.48	2.29
4	3.95	2.3
5	3.64	2.28
Average	3.49	2.28

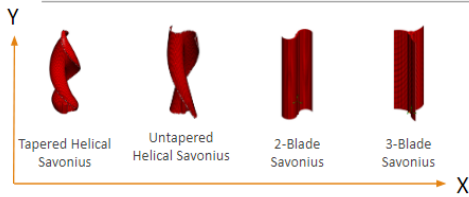
Client wind data – wind tunnel cut in/cut out observed values

Time	Wind(km/h)	Wind Direction(Å°)	average wind speed over 60 min (km/h)	wind direction as cos(rad)	Wind direction place holder (°)	average direction over 60 min (°)	corrected average direction over 60 minutes (°)
Sep/30 11:13 AM	2.9	158	3.6	-0.9	158.0	173.9	173.9
Sep/30 11:14 AM	0	184	3.6	-1.0	184.0	173.8	173.8
Sep/30 11:15 AM	0	184	3.7	-1.0	184.0	174.1	174.1
Sep/30 11:16 AM	0	184	3.8	-1.0	184.0	174.3	174.3
Sep/30 11:17 AM	0	184	3.9	-1.0	184.0	174.6	174.6
Sep/30 11:18 AM	0	184	3.9	-1.0	184.0	175.1	175.1
Sep/30 11:19 AM	0.7	184	4.0	-1.0	184.0	174.8	174.8
Sep/30 11:20 AM	3.6	163	4.0	-1.0	163.0	174.9	174.9
Sep/30 11:21 AM	7.9	179	4.0	-1.0	179.0	175.0	175.0
Sep/30 11:22 AM	1.1	159	3.9	-0.9	159.0	174.9	174.9
Sep/30 11:23 AM	2.5	159	4.0	-0.9	159.0	175.4	175.4
Sep/30 11:24 AM	3.2	181	4.1	-1.0	181.0	175.1	175.1
Sep/30 11:25 AM	2.9	187	4.0	-1.0	187.0	175.0	175.0
Sep/30 11:26 AM	1.8	164	4.0	-1.0	164.0	174.7	174.7
Sep/30 11:27 AM	2.2	196	4.1	-1.0	196.0	175.0	175.0
Sep/30 11:28 AM	0.4	194	4.1	-1.0	194.0	174.7	174.7
Sep/30 11:29 AM	1.1	194	4.1	-1.0	194.0	174.8	174.8
Sep/30 11:30 AM	4.7	158	4.2	-0.9	158.0	175.4	175.4
Sep/30 11:31 AM	2.9	158	4.1	-0.9	158.0	176.3	176.3
Sep/30 11:32 AM	0	155	4.1	-0.9	155.0	176.9	176.9
Sep/30 11:33 AM	1.1	154	4.1	-0.9	154.0	176.9	176.9
Sep/30 11:34 AM	3.2	165	4.1	-1.0	165.0	177.4	177.4
Sep/30 11:35 AM	1.4	167	4.1	-1.0	167.0	178.8	178.8
Sep/30 11:36 AM	1.1	167	4.2	-1.0	167.0	178.9	178.9
Sep/30 11:37 AM	5.8	215	4.3	-0.8	215.0	179.7	179.7
Sep/30 11:38 AM	5	184	4.3	-1.0	184.0	179.7	179.7
Sep/30 11:39 AM	3.6	193	4.2	-1.0	193.0	179.6	179.6
Sep/30 11:40 AM	5.4	182	4.2	-1.0	182.0	180.0	180.0
Sep/30 11:41 AM	4.7	193	4.2	-1.0	193.0	179.9	179.9
Sep/30 11:42 AM	3.2	146	4.2	-0.8	146.0	179.8	179.8
Sep/30 11:43 AM	3.6	172	4.2	-1.0	172.0	180.4	180.4
Sep/30 11:44 AM	5	169	4.2	-1.0	169.0	180.6	180.6
Sep/30 11:45 AM	3.6	151	4.1	-0.9	151.0	180.7	180.7
Sep/30 11:46 AM	6.1	168	4.1	-1.0	168.0	181.3	181.3
Sep/30 11:47 AM	4	160	4.1	-0.9	160.0	182.0	182.0
Sep/30 11:48 AM	2.9	171	4.0	-1.0	171.0	182.2	182.2

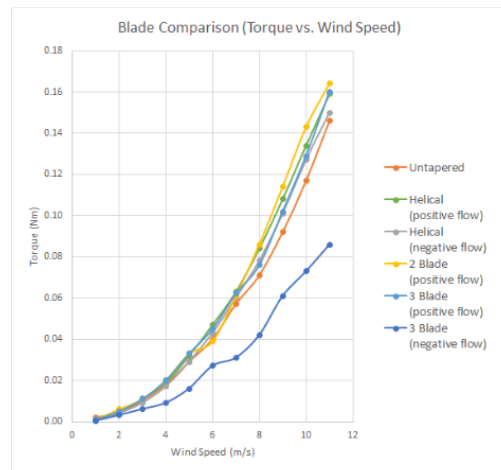
Client wind data – minute data points sample

The full dataset is approximately 28000 data points

Blade Design



- Finals results of the simulations shown on the table.
 - You will notice positive and negative flow in the legends, this only means the wind flow is varied either in the direction of the x-axis or opposite.
 - The blade with the highest torque values came out to be the 2-Blade, however, since we focused more on creativity and aesthetics, the Helical was chosen.



Client wind data – CFD tests

7.6 Appendix F – Advisor Meeting Minutes

Title: Team 15 Weekly Advisor Meeting

Date: September 13, 2023 **Time:** 1:00 pm **Location:** Dr. Brian Fleck's Office (DICE Floor 10)

Chairing Meeting: Dr Brian Fleck

Attendees: Reid Mix, Ahra Ko, Nathan Correia, Bowei Huang, Justin Van Engelen

Those Absent: N/A

General Meeting Outline

- Team Introductions
- Understand advisor and roles that he can play in helping us
- Plan next steps

Item Description	Date Initiated	Person Responsible	Status/Date
Contact Client	Sept 13	Reid Mix	

Figure 15 - Advisor Meeting Minutes (1)

Title: Team 15 Weekly Advisor Meeting

Date: September 20, 2023 **Time:** 1:00 pm **Location:** Dr. Brian Fleck's Office (DICE Floor 10)

Chairing Meeting: Dr Brian Fleck

Attendees: Reid Mix, Ahra Ko, Nathan Correia, Bowei Huang, Justin Van Engelen

Those Absent: N/A

General Meeting Outline

- Discuss possible project ideas
- Understand what the client wants from the scope of the project
- Understand how we can use renewable energy to brake a turbine
- Learn more about turbine design

Item Description	Date Initiated	Person Responsible	Status/Date
Set up another client meeting	September 20	Reid Mix	

Figure 16 - Advisor Meeting Minutes (2)

Title: Team 15 Weekly Advisor Meeting

Date: September 27, 2023 **Time:** 1:00 pm **Location:** Dr. Brian Fleck's Office (DICE Floor 10)

Chairing Meeting: Dr Brian Fleck

Attendees: Reid Mix, Ahra Ko, Nathan Correia, Bowei Huang, Justin Van Engelen

Those Absent: N/A

General Meeting Outline

- Discuss strategies for professor meeting about phase 1 report
- Discuss advisor's role in helping refine phase 1 report
-

Item Description	Date Initiated	Person Responsible	Status/Date
Completion of phase 1 report	September 27	Everyone	

Figure 17 - Advisor Meeting Minutes (3)

Title: Team 15 Weekly Advisor Meeting

Date: October 4, 2023 **Time:** 1:00 pm **Location:** Dr. Brian Fleck's Office (DICE Floor 10)

Chairing Meeting: Dr Brian Fleck

Attendees: Reid Mix, Ahra Ko, Nathan Correia, Bowei Huang, Justin Van Engelen

Those Absent: N/A

General Meeting Outline

- Discuss possible design ideas
- Talk about refined scope now that electrical solutions are deemphized.
-

Item Description	Date Initiated	Person Responsible	Status/Date

Figure 18 - Advisor Meeting Minutes (4)

Title: Team 15 Weekly Advisor Meeting

Date: October 11, 2023 **Time:** 1:00 pm **Location:** Dr. Brian Fleck's Office (DICE Floor 10)

Chairing Meeting: Dr Brian Fleck

Attendees: Reid Mix, Ahra Ko, Nathan Correia, Bowei Huang, Justin Van Engelen

Those Absent: N/A

General Meeting Outline

- Discuss the three main concepts that we want to use
- Discuss viability and buildability of our concepts
- Discuss presentation to be created for professor on concepts

Item Description	Date Initiated	Person Responsible	Status/Date
Slide deck creations	October 11	everyone	
Begin building solid models	October 11	Ahra	

Figure 19 - Advisor Meeting Minutes (5)

Title: Team 15 Weekly Advisor Meeting

Date: October 25, 2023 **Time:** 1:00 pm **Location:** Dr. Brian Fleck's Office (DICE Floor 10)

Chairing Meeting: Dr Brian Fleck

Attendees: Reid Mix, Ahra Ko, Nathan Correia, Bowei Huang, Justin Van Engelen

Those Absent: N/A

General Meeting Outline

- Discuss strategies for second professor meeting
- Discuss project so far and final 3 concepts

Item Description	Date Initiated	Person Responsible	Status/Date
Finalize Concept Choice	October 24	Everyone	
Create List of arguments on concept choice			

Figure 20 - Advisor Meeting Minutes (6)

Title: Team 15 Weekly Advisor Meeting

Date: November 1, 2023 **Time:** 1:00 pm **Location:** Dr. Brian Fleck's Office (DICE Floor 10)

Chairing Meeting: Dr Brian Fleck

Attendees: Reid Mix, Ahra Ko, Nathan Correia, Bowei Huang, Justin Van Engelen

Those Absent: N/A

General Meeting Outline

- Finalize Phase 2 report structure
- Talk about completing peer review
- Address any teamwork issues or concerns
- Pick final concept that will be used

Item Description	Date Initiated	Person Responsible	Status/Date
Finish phase 2 report	October 28	Everyone	

Figure 21 - Advisor Meeting Minutes (7)

Title: Team 15 Weekly Advisor Meeting

Date: November 22, 2023 **Time:** 1:00 pm **Location:** Dr. Brian Fleck's Office (DICE Floor 10)

Chairing Meeting: Dr Brian Fleck

Attendees: Reid Mix, Ahra Ko, Nathan Correia, Bowei Huang, Justin Van Engelen

Those Absent: N/A

General Meeting Outline

- Meeting was changed to online
- Discuss project progress
- Discuss ancillary projects that need to be completed
- Discus strategies for presentation and poster

Item Description	Date Initiated	Person Responsible	Status/Date
Ancillary Projects	November 22	Reid, Bowei, Ahra	
Finish Calculations	November 15	Justin, Nathan	

Figure 22 - Advisor Meeting Minutes (8)

Title: Team 15 Weekly Advisor Meeting

Date: November 29, 2023 **Time:** 1:00 pm **Location:** Dr. Brian Fleck's Office (DICE Floor 10)

Chairing Meeting: Dr Brian Fleck

Attendees: Reid Mix, Ahra Ko, Nathan Correia, Bowei Huang, Justin Van Engelen

Those Absent: N/A

General Meeting Outline

- Final Meeting with advisor
- Go over presentation preparedness and poster
- Discuss how project has gone so far

Item Description	Date Initiated	Person Responsible	Status/Date
Finish presentation		Everyone	
Finish poster1		Bowei, Reid	
Practice presentation		Everyone	

Figure 23 - Advisor Meeting Minutes (9)

7.7 Appendix G – Material Sheets for Cone

7.7.1 6061-T6 Aluminum Properties.



Subcategory: 6000 Series Aluminum Alloy; Aluminum Alloy; Metal; Nonferrous Metal

Close Analogs:

Composition Notes:

Aluminum content reported is calculated as remainder.
Composition information provided by the Aluminum Association and is not for design.

Key Words: al6061, UNS A96061; ISO AlMg1SiCu; Aluminium 6061-T6, AD-33 (Russia); AA6061-T6; 6061T6, UNS A96061; ISO AlMg1SiCu; Aluminium 6061-T651, AD-33 (Russia); AA6061-T651

Component	Wt. %	Component	Wt. %	Component	Wt. %
Al	95.8 - 98.6	Mg	0.8 - 1.2	Si	0.4 - 0.8
Cr	0.04 - 0.35	Mn	Max 0.15	Ti	Max 0.15
Cu	0.15 - 0.4	Other, each	Max 0.05	Zn	Max 0.25
Fe	Max 0.7	Other, total	Max 0.15		

Material Notes:

Information provided by Alcoa, Starmet and the references. General 6061 characteristics and uses: Excellent joining characteristics, good acceptance of applied coatings. Combines relatively high strength, good workability, and high resistance to corrosion; widely available. The T8 and T9 tempers offer better chipping characteristics over the T6 temper.

Applications: Aircraft fittings, camera lens mounts, couplings, marine fittings and hardware, electrical fittings and connectors, decorative or misc. hardware, hinge pins, magneto parts, brake pistons, hydraulic pistons, appliance fittings, valves and valve parts; bike frames.

Data points with the AA note have been provided by the Aluminum Association, Inc. and are NOT FOR DESIGN.

Physical Properties	Metric	English	Comments
Density	2.7 g/cc	0.0975 lb/in ³	AA; Typical
Mechanical Properties			
Hardness, Brinell	95	95	AA; Typical; 500 g load; 10 mm ball
Hardness, Knoop	120	120	Converted from Brinell Hardness Value
Hardness, Rockwell A	40	40	Converted from Brinell Hardness Value
Hardness, Rockwell B	60	60	Converted from Brinell Hardness Value
Hardness, Vickers	107	107	Converted from Brinell Hardness Value
Ultimate Tensile Strength	310 MPa	45000 psi	AA; Typical

Tensile Yield Strength	276 MPa	40000 psi	AA; Typical
Elongation at Break	12 %	12 %	AA; Typical; 1/16 in. (1.6 mm) Thickness
Elongation at Break	17 %	17 %	AA; Typical; 1/2 in. (12.7 mm) Diameter
Modulus of Elasticity	68.9 GPa	10000 ksi	AA; Typical; Average of tension and compression. Compression modulus is about 2% greater than tensile modulus.
Notched Tensile Strength	324 MPa	47000 psi	2.5 cm width x 0.16 cm thick side-notched specimen, $K_t = 17$.
Ultimate Bearing Strength	607 MPa	88000 psi	Edge distance/pin diameter = 2.0
Bearing Yield Strength	386 MPa	56000 psi	Edge distance/pin diameter = 2.0
Poisson's Ratio	0.33	0.33	Estimated from trends in similar Al alloys.
Fatigue Strength	96.5 MPa	14000 psi	AA; 500,000,000 cycles completely reversed stress; RR Moore machine/specimen
Fracture Toughness	29 MPa-m ^{1/2}	26.4 ksi-in ^{1/2}	K_{Ic} ; TL orientation.
Machinability	50 %	50 %	0-100 Scale of Aluminum Alloys
Shear Modulus	26 GPa	3770 ksi	Estimated from similar Al alloys.
Shear Strength	207 MPa	30000 psi	AA; Typical

Electrical Properties

Electrical Resistivity	3.99e-006 ohm-cm	3.99e-006 ohm-cm	AA; Typical at 68°F
------------------------	------------------	------------------	---------------------

Thermal Properties

CTE, linear 68°F	23.6 $\mu\text{m}/\text{m}\cdot^\circ\text{C}$	13.1 $\mu\text{in}/\text{in}\cdot^\circ\text{F}$	AA; Typical; Average over 68-212°F range.
CTE, linear 250°C	25.2 $\mu\text{m}/\text{m}\cdot^\circ\text{C}$	14 $\mu\text{in}/\text{in}\cdot^\circ\text{F}$	Estimated from trends in similar Al alloys. 20-300°C.
Specific Heat Capacity	0.896 J/g·°C	0.214 BTU/lb·°F	
Thermal Conductivity	167 W/m·K	1160 BTU-in/hr-ft ² ·°F	AA; Typical at 77°F
Melting Point	582 - 652 °C	1080 - 1205 °F	AA; Typical range based on typical composition for wrought products 1/4 inch thickness or greater; Eutectic melting can be completely eliminated by homogenization.
Solidus	582 °C	1080 °F	AA; Typical
Liquidus	652 °C	1205 °F	AA; Typical


Processing Properties

Solution Temperature	529 °C	985 °F	
Aging Temperature	160 °C	320 °F	Rolled or drawn products; hold at temperature for 18 hr
Aging Temperature	177 °C	350 °F	Extrusions or forgings; hold at temperature for 8 hr

References for this datasheet.

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7.7.2 260 Brass OS070 Temper Properties



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Cartridge Brass, UNS C26000 (260 Brass), OS070 Temper flat products

Categories: [Metal](#); [Nonferrous Metal](#); [Copper Alloy](#); [Brass](#)

Material Notes: Fair to excellent corrosion resistance. Excellent cold workability; good hot formability.

Applications: radiator cores and tanks, flashlight shells, lamp fixtures, fasteners, locks, hinges, ammunition components, plumbing accessories, pins, rivets.

Test specimen: flat products - 1mm thickness.

Key Words: 70/30 brass, CDA 260, CZ106, ISO CuZn30, CEN CW505L

Vendors: Visit [Metalmen Sales](#) for your metals needs. Products include special chemistry, tight tolerances, custom tempers, odd dimensions/forms, and small quantities. Phone 1-800-767-9494.

[Click here to view all available suppliers for this material.](#)

Please [click here](#) if you are a supplier and would like information on how to add your listing to this material.

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Physical Properties	Metric	English	Comments
Density	8.53 g/cc	0.308 lb/in ³	
Mechanical Properties			
	Metric	English	Comments
Hardness, Rockwell F	58	58	
Hardness, Rockwell 30T	15	15	
Tensile Strength, Ultimate	315 MPa	45700 psi	
Tensile Strength, Yield	95.0 MPa	13800 psi	
Elongation at Break	65 %	65 %	In 50 mm
Modulus of Elasticity	110 GPa	16000 ksi	
Poissons Ratio	0.375	0.375	
Fatigue Strength	90.0 MPa @# of Cycles 1.00e+8	13100 psi @# of Cycles 1.00e+8	Reverse Bending
Machinability	30 %	30 %	UNS C36000 (free-cutting brass) = 100%
Shear Modulus	40.0 GPa	5800 ksi	
Shear Strength	220 MPa	31900 psi	
Thermal Properties			
	Metric	English	Comments
CTE, linear	19.9 μm/m-°C @Temperature 20.0 - 300 °C	11.1 μin/in-°F @Temperature 68.0 - 572 °F	
Specific Heat Capacity	0.375 J/g-°C	0.0896 BTU/lb-°F	

Thermal Conductivity	120 W/m-K @Temperature 20.0 °C	833 BTU-in/hr-ft ² -°F @Temperature 68.0 °F	
Melting Point	915 - 955 °C	1680 - 1750 °F	
Solidus	915 °C	1680 °F	
Liquidus	955 °C	1750 °F	
Processing Properties	Metric	English	Comments
Annealing Temperature	425 - 750 °C	797 - 1380 °F	
Hot-Working Temperature	725 - 850 °C	1340 - 1560 °F	
Component Elements Properties	Metric	English	Comments
Copper, Cu	68.5 - 71.5 %	68.5 - 71.5 %	
Iron, Fe	<= 0.050 %	<= 0.050 %	
Lead, Pb	<= 0.070 %	<= 0.070 %	
Other, total	<= 0.15 %	<= 0.15 %	
Zinc, Zn	28.5 - 31.5 %	28.5 - 31.5 %	

Descriptive Properties

Hall Coefficient	26 pV · m/A · T	
Velocity of Sound	3660 m/s	at 20°C

[References](#) for this datasheet.

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[Cartridge Brass, UNS C26000 \(260 Brass\), H01 Temper flat products](#)
[Cartridge Brass, UNS C26000 \(260 Brass\), OS015 Temper flat products](#)
[Cartridge Brass, UNS C26000 \(260 Brass\), OS035 Temper flat products](#)

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7.7.3 ASTM A653 Galvanized Steel Properties



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AK Steel ZINCGRIP® Hot Dip Galvanized Carbon Steel, Commercial Steel (CS Type B), Standard Grade

Categories: [Metal](#); [Ferrous Metal](#); [Carbon Steel](#); [Low Carbon Steel](#)

Material Notes: May be moderately formed. A specimen cut in any direction can be bent flat on itself without cracking.
Information provided by AK Steel

Vendors: No vendors are listed for this material. Please [click here](#) if you are a supplier and would like information on how to add your listing to this material.

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Physical Properties	Metric	English	Comments
Density	7.87 g/cc	0.284 lb/in ³	
Mechanical Properties	Metric	English	Comments
Tensile Strength, Ultimate	345 MPa	50000 psi	.0275 - .035 inches sheet thickness; ASTM A 370
Tensile Strength, Yield	303 MPa	43900 psi	.0275 - .035 inches sheet thickness; ASTM A 370
Elongation at Break	38 %	38 %	.0275 - .035 inches sheet thickness; ASTM A 370
Modulus of Elasticity	200 GPa	29000 ksi	
Electrical Properties	Metric	English	Comments
Electrical Resistivity	0.0000142 ohm-cm	0.0000142 ohm-cm	
Thermal Properties	Metric	English	Comments
Specific Heat Capacity	0.481 J/g-°C	0.115 BTU/lb-°F	@Temperature 50.0 - 100 °C @Temperature 122 - 212 °F

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[AK Steel Cold Rolled Carbon Steel, Commercial Steel \(CS Type B\), Standard Grade](#)
[AK Steel Hot Rolled Carbon Steel, Commercial Steel \(CS Type B\), Standard Grade](#)

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7.8 Appendix H – CSA Guidelines

Standard and Code	Short Description	Source
CSA C22.1 Canadian Electrical Code	CSA Guide to Canadian Wind Turbine Codes and Standards	https://www.csagroup.org/documents/codes-and-standards/standards/energy/ CSAGuidetoCanadianWindTurbineCodes.pdf
CAN/CSA IEC 61400-12-1:2022	Wind energy generation systems – part 12-1: Power performance measurement of electricity producing turbines	https://store-csagroup- org.login.ezproxy.library.ualberta.ca/ ondemand/s/mylibrary?searchString=electricity% 20wind%20turbine&entitlementMethod =User&userIdentifier= 0051I0000057i6wQAA#collapse-2702734
CSA C22.2 NO. 272:20	Wind turbine electrical systems	https://store-csagroup- org.login.ezproxy.library.ualberta.ca/ ondemand/s/mylibrary?searchString= wind%20turbine%20control&entitlementMethod= User&userIdentifier=0051I0000057i6wQAA

7.9 Appendix I – Client Confirmation Email



Darren Paetz
to me, Erin ▾

Dec 6, 2023, 5:48 PM (17 hours ago) ☆ ↶ ⋮

Hi Reid,

Apologies for the delay - I have reviewed the specifications document you provided and can confirm via this email that they are approved.

Please let Erin and myself know if there is anything further you require from us.

Warmly,
Darren Paetz

⋮

7.10 Appendix J – Detailed Design Calculations

Appendix J: Detailed Design Calculations

Center of Mass Calculations

For all FBD and any following analysis to be done, the center of the mass/rod system must first be determined as this is where most of the forces including gravity and centripetal force will act.

We can see the mass/rod system pictured here with all the variable lengths listed. The calculations will be conducted analytically so that these parameters can be adjusted once the final calculations are finished.

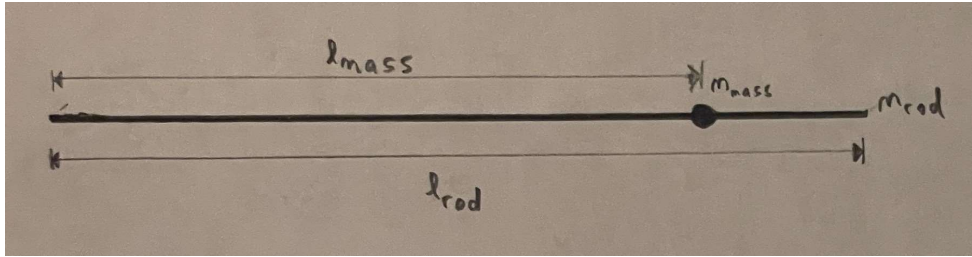


Figure C1: parameters of variable rod

$$\sum_{i=1}^n \frac{m_{center.i}}{m_{center.tot}} \cdot l_i = L_{center}$$

$$\sum_{i=1}^n m_{center.i} = m_{center}$$

Center of mass position calculation

$$L_{center} = \frac{m_{mass}}{m_{mass} + m_{rod}} \cdot l_{mass} + \frac{m_{rod}}{m_{mass} + m_{rod}} \cdot \frac{l_{rod}}{2}$$

$$L_{center} = \frac{m_{mass} \cdot l_{mass}}{m_{mass} + m_{rod}} + \frac{\frac{1}{2} \cdot m_{rod} \cdot l_{rod}}{m_{mass} + m_{rod}}$$

$$L_{center} = \frac{m_{mass} \cdot l_{mass} + \frac{1}{2} \cdot m_{rod} \cdot l_{rod}}{m_{mass} + m_{rod}}$$

Center of mass total mass calculation

$$m_{center} = m_{mass} + m_{rod}$$

For the remainder of the calculations and for simplicity,

$$L_{center} = L \quad \text{and} \quad m_{center} = m$$

□

Wind speed relation

One of the first required calculations is the relation between wind speed and rotational speed of the turbine.

This relation is crucial as it describes the behaviour of the turbine.

The client has provided Mach innovations with wind tunnel data which can be used to calculate the relation between wind speed and angular speed.

The turbine takes time to spin up, however for now we will only consider the steady state rotational speed of the turbine at a specific wind speed.

The data is shown in Appendix G

We can create a plot and trendline for the data, and can see that the data matches a the linear trendline very closely.

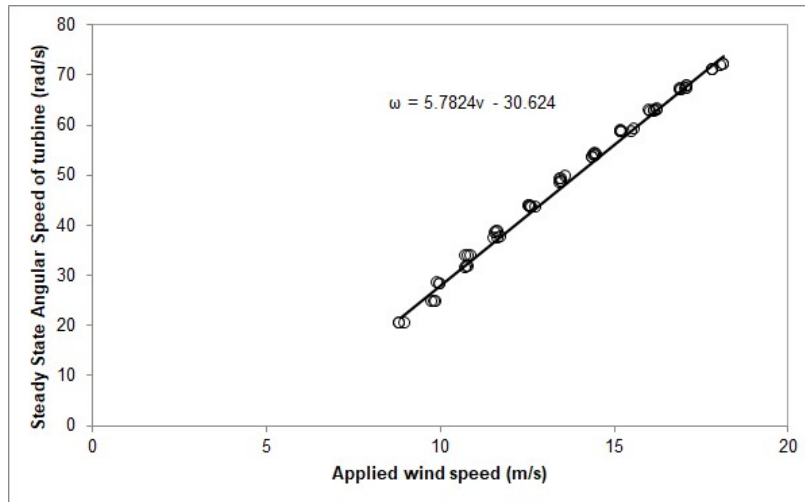


Figure C2: Wind speed to rotational speed relation

The relation between wind speed and angular speed was therefore taken as

$$\omega = 5.7824 \cdot v - 30.624$$

No Spring Calculations

Free Body Diagram

First a free body diagram of the setup was created, so that the various forces on the system could be calculated

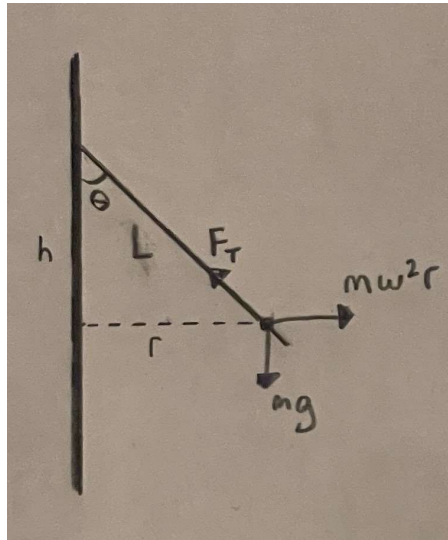


Figure C3: FBD of moment arm

$$\sum_{i=1}^n F_y = 0 \quad F_T \cdot \cos(\theta) - mg = 0 \quad (1)$$

$$\sum_{i=1}^n F_x = 0 \quad F_T \cdot \sin(\theta) - m\omega^2 \cdot r = 0 \quad (2)$$

$$r = L \sin(\theta) \quad (3)$$

solving (1) for F_T

$$F_T = \frac{mg}{\cos(\theta)} \quad (4)$$

substituting (3) and (4) into (2)

$$\frac{mg}{\cos(\theta)} \cdot \sin(\theta) - m\omega^2 \cdot L \sin(\theta) = 0$$

cancelling $\sin(\theta)$ and m

$$\frac{g}{\cos(\theta)} - \omega^2 \cdot L = 0$$

final relation

$$\frac{g}{\cos(\theta)} = \omega^2 \cdot L$$

Rotational speed and angle

first ω is isolated as a function of θ

$$\frac{g}{\cos(\theta)} = \omega^2 \cdot L$$

multiply both sides by 1/L

$$\frac{g}{L \cos(\theta)} = \omega^2$$

square root of both sides

$$\sqrt{\frac{g}{L \cos(\theta)}} = \omega$$

final relation

$$\omega(\theta) = \sqrt{\frac{g}{L \cos(\theta)}}$$

next θ is isolated as a function of ω

multiply both sides by $\cos(\theta)$

$$g = \omega^2 \cdot L \cdot \cos(\theta)$$

divide by $L\omega^2$

$$\frac{g}{\omega^2 \cdot L} = \cos(\theta)$$

inverse cosine of both sides

$$\arccos\left(\frac{g}{\omega^2 \cdot L}\right) = \theta$$

final relation

$$\theta(\omega) = \arccos\left(\frac{g}{\omega^2 \cdot L}\right)$$

This relation is very useful as many components of energy and moment of inertia require the angle of the moment bars to be known.

we can plot this relation using some sample values to see how the angle varies with rotational velocity.

$$L := 0.075$$

$$g := 9.81$$

$$\omega := x$$

$$\theta(\omega) := \arccos\left(\frac{g}{\omega^2 \cdot L}\right)$$

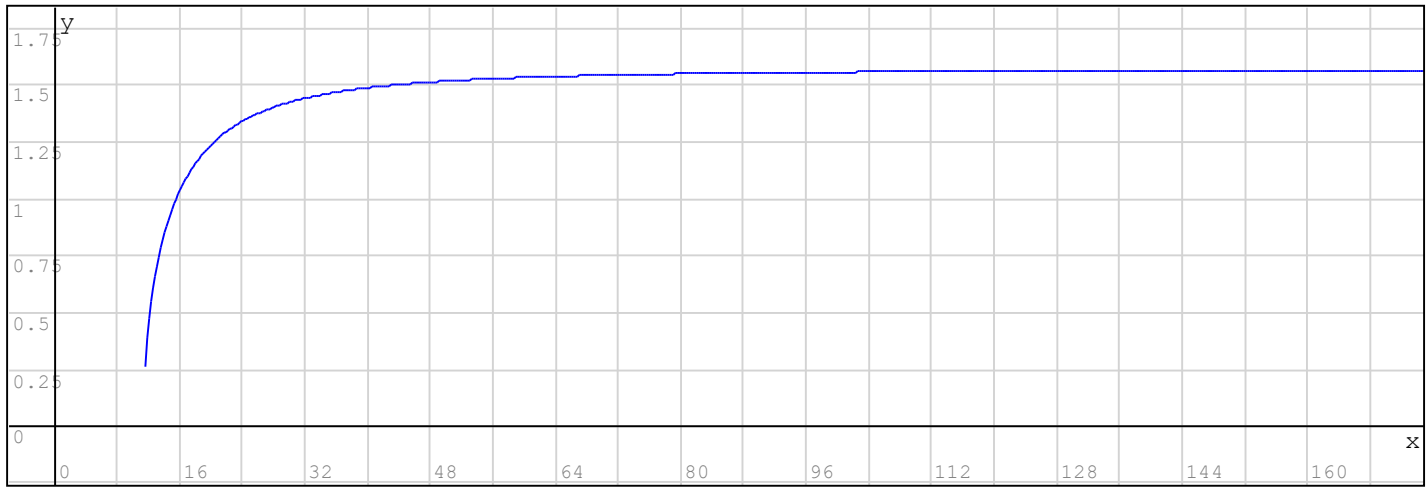

 $\theta(\omega)$

Figure C4: moment arm angle to rotational speed relation

$$\theta(71) = 1.5448$$

$$\frac{\pi}{2} = 1.5708$$

as we can see the angle increases very quickly to its maximum of $\pi/2$ rad, near the damaging wind speed of ~ 70 rad/s the arms have already travelled 98.3% of their maximum angle.

$$\frac{\theta(71)}{\frac{\pi}{2}} \cdot 100 = 98.348$$

□

Moment of Inertia

Now that the angle of the moment bars is known, we can find the increase to the moment of inertia of the system caused by the governor.

To do this we will utilise the following property of moment of inertia states and rotation, if we know the moment of inertia at the base state as well as the moment of inertia at the final state of 90 degrees, we can calculate the moment of inertia for all θ , using the following relation.

$$I = I_{90} \cdot \sin(\theta) + I_0 \cdot \cos(\theta)$$

This will calculate the extra moment of inertia added by one arm as a function of the angle the arm makes relative to the shaft.

However we must now calculate I_{90} and I_0 .

First I_0 , the figure below shows the governor at its base state

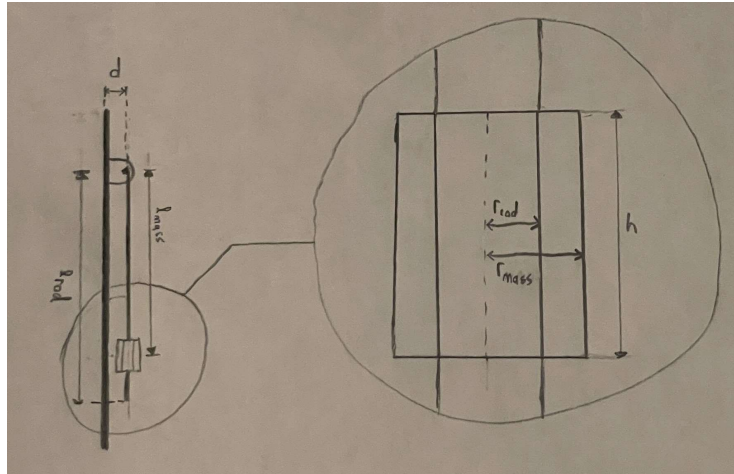


Figure C5: Parameters of rod and mass for moment of inertia calcs at base state

We can use the parallel axis theorem,

$$I = I_x + m \cdot d^2$$

to calculate the moment of inertia of the system

$$I_0 = I_{rod} + m_{rod} \cdot d_{rod}^2 + I_{mass} + m_{mass} \cdot d_{mass}^2$$

I_{rod} and I_{mass} can be found using the tabulated formulas for moment of inertia of various shapes from reference [1]

the rod is modelled as a uniform cylinder and the mass is modelled as a cylinder with a cylindrical hole in the center

$$I_{rod} = \frac{1}{2} \cdot m_{rod} \cdot r_{rod}^2$$

$$I_{mass} = \frac{1}{2} \cdot m_{mass} \cdot \left(r_{rod}^2 + r_{mass}^2 \right)$$

We also know from the figure that

$$d = d_{mass} \quad d = d_{rod}$$

Thus the final equation for I_0 is

$$I_0 = \frac{1}{2} \cdot m_{rod} \cdot r_{rod}^2 + m_{rod} \cdot d^2 + \frac{1}{2} \cdot m_{mass} \cdot \left(r_{rod}^2 + r_{mass}^2 \right) + m_{mass} \cdot d^2$$

The same process can be used for the moment of inertia at 90 degrees

The figure below shows the governor at 90 degree

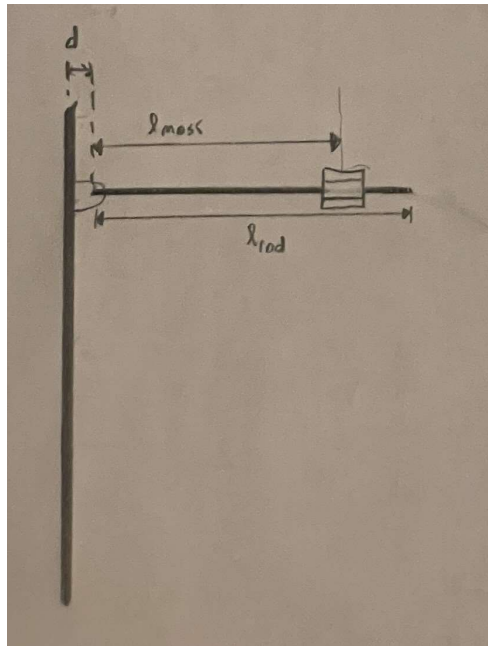


Figure C6: Parameters of rod and mass for moment of inertia calcs at full extension

We can again use the parallel axis theorem to show that the moment of inertia at an angle of 90 degrees is

$$I_{90} = I_{rod} + m_{rod} \cdot d_{rod}^2 + I_{mass} + m_{mass} \cdot d_{mass}^2$$

Using the same shape assumptions, but different axis of rotation from the textbook we get the following,

$$I_{rod} = \frac{1}{12} \cdot m_{rod} \left(3 \cdot r_{rod}^2 + l_{rod}^2 \right)$$

and

$$I_{mass} = \frac{1}{12} \cdot m_{mass} \cdot \left((3 \cdot r_{rod})^2 + (3 \cdot r_{mass})^2 + h_{mass}^2 \right)$$

This time, d_{mass} and d_{rod} are different

$$d_{mass} = d + l_{mass}$$

$$d_{rod} = d + \frac{l_{rod}}{2}$$

We can now find the equation for I_{90}

$$I_{90} = \frac{1}{12} \cdot m_{rod} \left(3 \cdot r_{rod}^2 + l_{rod}^2 \right) + m_{rod} \cdot \left(d + \frac{l_{rod}}{2} \right)^2 + \frac{1}{12} \cdot m_{mass} \cdot \left((3 \cdot r_{rod})^2 + (3 \cdot r_{mass})^2 + h_{mass}^2 \right) + m_{mass} \cdot (d + l_{mass})^2$$

We can now show the final equation for the moment of inertia of the arm as a function of the moment arm angle

$$\begin{aligned} I(\theta) &= \frac{1}{12} \cdot m_{rod} \left(3 \cdot r_{rod}^2 + l_{rod}^2 \right) \cdot \sin^2(\theta) + m_{rod} \cdot \left(d + \frac{l_{rod}}{2} \right)^2 \cdot \sin^2(\theta) \\ &+ \frac{1}{12} \cdot m_{mass} \cdot \left((3 \cdot r_{rod})^2 + (3 \cdot r_{mass})^2 + h_{mass}^2 \right) \cdot \sin^2(\theta) \\ &+ m_{mass} \cdot (d + l_{mass})^2 \cdot \sin^2(\theta) + \frac{1}{2} \cdot m_{rod} \cdot r_{rod}^2 \cdot \cos^2(\theta) \\ &+ m_{rod} \cdot d^2 \cdot \cos^2(\theta) + \frac{1}{2} \cdot m_{mass} \cdot (r_{rod}^2 + r_{mass}^2) \cdot \cos^2(\theta) \\ &+ m_{mass} \cdot d^2 \cdot \cos^2(\theta) \end{aligned}$$

since there are two arms and their moment of inertia adds to the original turbine inertia we can write

$$I_{total} = I_{turbine} + 2 \cdot I$$

we can then substitute the relation between θ and ω in order to find the moment of inertia each arm adds as a function of only the rotational speed of the turbine

$$I(\omega) = \frac{1}{6} \cdot m_{rod} \left(3 \cdot r_{rod}^2 + l_{rod}^2 \right) \cdot \sin^2 \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + 2 \cdot m_{rod} \cdot \left(d + \frac{l_{rod}}{2} \right)^2 \cdot \sin^2 \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + m_{mass} \cdot (d + l_{mass})^2 \cdot \sin^2 \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + \frac{1}{2} \cdot m_{rod} \cdot r_{rod}^2 \cdot \cos^2 \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + m_{rod} \cdot d^2 \cdot \cos^2 \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + \frac{1}{2} \cdot m_{mass} \cdot (r_{rod}^2 + r_{mass}^2) \cdot \cos^2 \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + m_{mass} \cdot d^2 \cdot \cos^2 \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right)$$

$$\begin{aligned}
& + \frac{1}{6} \cdot m_{mass} \cdot \left[(3 \cdot r_{rod})^2 + (3 \cdot r_{mass})^2 + h_{mass}^2 \right] \cdot \sin \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) \\
& + 2 \cdot m_{mass} \cdot (d + l_{mass})^2 \cdot \sin \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + m_{rod} \cdot r_{rod}^2 \cdot \cos \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) \\
& + 2 \cdot m_{rod} \cdot d^2 \cdot \cos \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + m_{mass} \cdot (r_{rod}^2 + r_{mass}^2) \cdot \cos \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) \\
& + 2 \cdot m_{mass} \cdot d^2 \cdot \cos \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + I_{turbine}
\end{aligned}$$

We can then plot this relation to show the moment of inertia as a function of angular velocity, $I(\omega)$. Due to the limitations of SMath, the plot was made using desmos software instead and shows the moment of inertia as a function of the angle of the bar, $I(\theta)$.

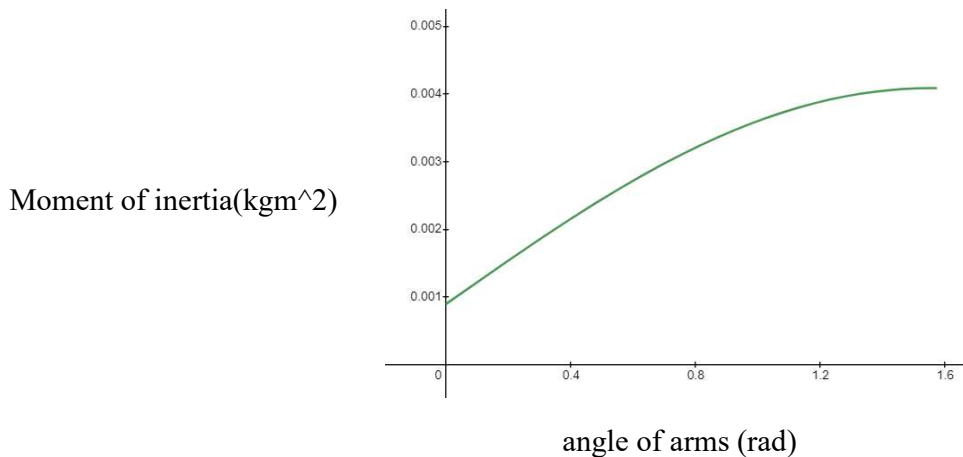


Figure C7: moment of inertia to moment arm angle relation

□

Energy Calculations

Now that the moment of inertia has been determined, the stored energy of the turbine can be calculated

We must consider the kinetic energy of the original turbine, the rotational kinetic energy of the moment arms, and the potential energy of the masses lifting

we know that

$$KE = \frac{1}{2} \cdot I \cdot \omega^2$$

and

$$PE = m \cdot g \cdot h$$

but h and I are functions of ω

we can see geometrically from the FBD figure that

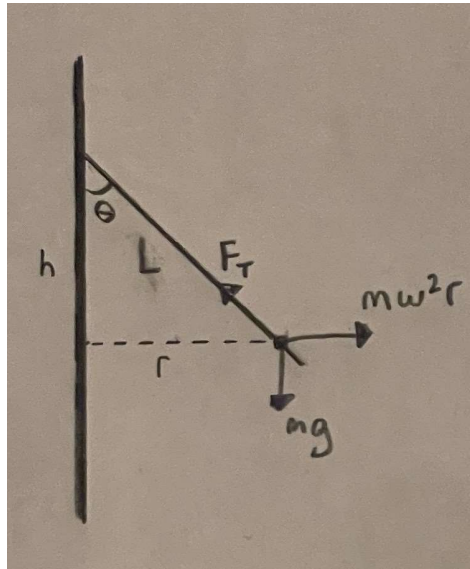


Figure C8: FBD to calculate $h(\omega)$

$$h = L \cdot \cos(\theta)$$

using the $\theta(\omega)$ relation,

$$h = L \cdot \cos\left(\arccos\left(\frac{g}{\omega^2 \cdot L}\right)\right)$$

cancelling the cosines,

$$h = L \cdot \frac{g}{\omega^2 \cdot L}$$

cancelling L ,

$$h = \frac{g}{\omega^2}$$

We can now sum the Energies to obtain the following

$$E_{tot} = \frac{1}{2} \cdot I_{turbine} \cdot \omega^2 + \frac{1}{2} \cdot I(\omega) \cdot \omega^2 + m \cdot \frac{g}{\omega^2}$$

We can then plot the total energy

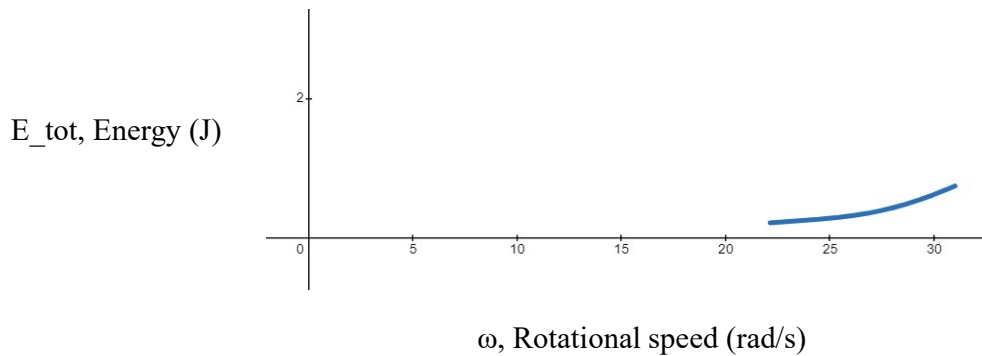


Figure C9: Total energy as a function of rotational speed

We can see that the energy increase is very limited due to the moment arms beginning their braking function earlier than anticipated. This is a problem as it means the stored energy in the system does not vary greatly meaning little

□

Mass acceleration diagram

We can also calculate the acceleration that the moment arms will experience by using the same methods as the FBD, but without assuming steady state conditions.

if we do this, we can see the following on the two figures below

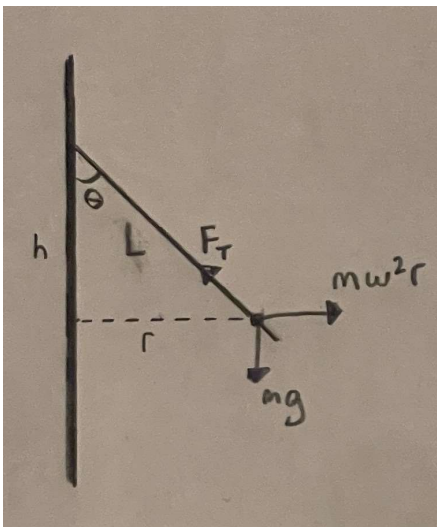


Figure C9: FBD of forces

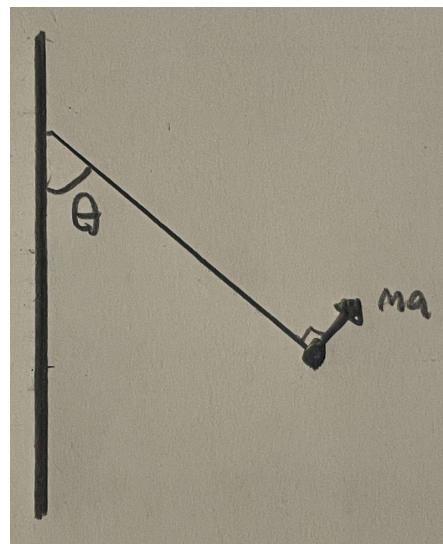


Figure C10: MAD of resultant motion

and we can use our force balance equations to show

$$\sum_{\square = \square}^{\square} F_y = 0 \quad F_T \cdot \cos(\theta) - mg = \sin(\theta) \cdot m \cdot a \quad (1)$$

$$\sum_{\square = \square}^{\square} F_x = 0 \quad -(F_T \cdot \sin(\theta)) + m\omega^2 \cdot r = \cos(\theta) \cdot m \cdot a \quad (2)$$

multiplying (1) by $\sin(\theta)$ $F_T \cdot \cos(\theta) \cdot \sin(\theta) - mg \cdot \sin(\theta) = \sin(\theta)^2 \cdot m \cdot a \quad (3)$

multiplying (2) by $-\cos(\theta)$ $F_T \cdot \sin(\theta) \cdot \cos(\theta) - m\omega^2 \cdot L \cdot \sin(\theta) \cdot \cos(\theta) = -(\cos(\theta)^2 \cdot m \cdot a) \quad (4)$

subtracting (3)-(4) $-mg \cdot \sin(\theta) + m\omega^2 \cdot L \cdot \sin(\theta) \cdot \cos(\theta) = (\sin(\theta)^2 + \cos(\theta)^2) \cdot m \cdot a$

cancelling m and $\sin^2 + \cos^2$ $-g \cdot \sin(\theta) + \omega^2 \cdot L \cdot \sin(\theta) \cdot \cos(\theta) = a$

final relation $a = \omega^2 \cdot L \cdot \sin(\theta) \cdot \cos(\theta) - g \cdot \sin(\theta)$

Using a sample value for L of 7.5cm we can plot the relation

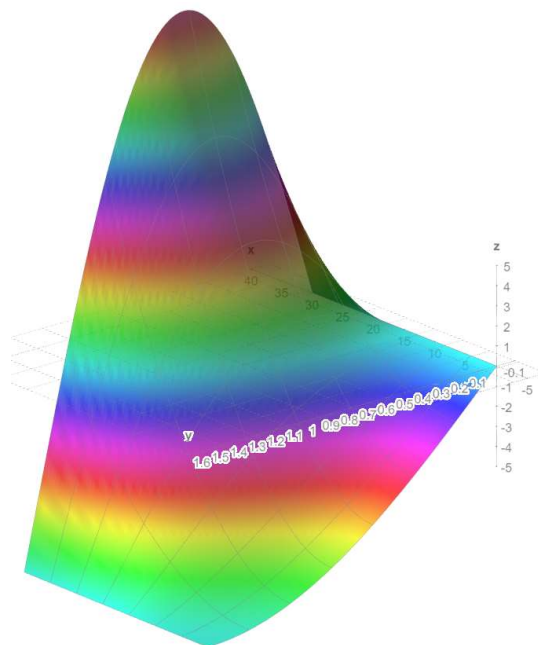


Figure C11: 3d acceleration plot as a function of moment arm angle (y) and roatation speed (x)

We can see in the figure above the acceleration behaviour of the mass as the rotation speed and angle vary. The light blue strip is approximately where $a = 0$. we can see that for certain values of ω , there is only a negative acceleration. This shows that below a threshold ω , the arms will not raise and if they do, they will fall back down to the base state. It also shows that there is high acceleration very close to the equilibrium curve of $a = 0$. This is a problem as it means that the raising speed of the moment arms may be very sensitive to small changes in the wind speed which could cause unwanted stresses on the system.

□

Performance discussion (no spring)

The original concept of the design did not include a spring as Mach innovations was unaware of the faults of the system without a mechanism to slow the extension of the arms.

We can see from the figures in the energy calculations, the moment of inertia calculations and the angle calculations that the arms raise very quickly to their maximum angle. We can also see that the arm raising speed is very sensitive to changes in the wind conditions.

This is a problem as it means that angle of the moment arms is very close to 90 degrees at the damaging wind speed and, specifically, a change in wind speed near the damaging wind speed has a very small impact on the angle of the moment arms.

This would mean that the friction cone would need to be placed at an extremely specific angle, and the arms would need to behave extremely close to the calculated behaviour for the system to work as intended.

It also implies that there is very little change in the moment of Inertia near the damaging wind speed which would defeat the purpose of a variable moment of inertia system such as the governor.

To remedy this problem, a spring was added to the system. It was mounted between the rotating shaft of the turbine and the rod of the moment arm, and as is shown in the following section, the spring had a great effect on the shape of the curve and allowed for much greater tuning of the system.

With Spring Calculations

Free Body Diagram

The free body diagram of the setup is no longer as simple. The force of the spring does not act at the center of mass of the moment arm and therefore the FBD must now extend to an analysis of the forces along the entire moment arm including the reaction forces at the hinge. We can take a sum of moments at point O on the diagram to solve

$$\sum M_O = 0 \quad m \cdot \omega^2 \cdot r \cdot \cos(\theta) \cdot L - mg \cdot \sin(\theta) \cdot L + \sin(B) \cdot k \cdot \Delta l = 0 \quad (1)$$

The problem here is that B and Δl are not immediately obvious and depend on θ . We can solve for them geometrically starting with some labels for the relevant lengths

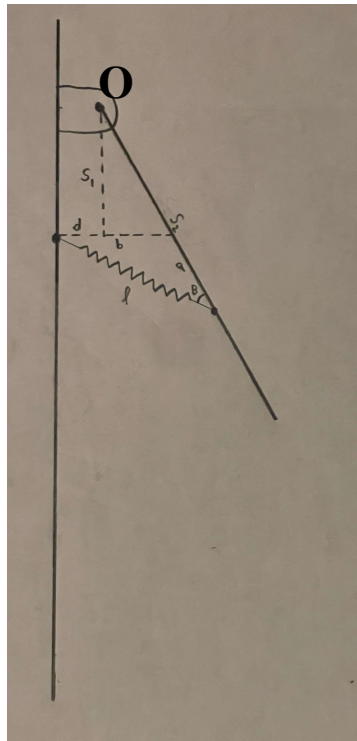


Figure C12: geometry of the system with attached spring

First we can determine the length of the spring, l , as a function of the angle θ .

To do this we must solve the triangle abl

first we can solve for a by subtracting the opposite portion of S_2 from itself

$$a = S_2 - \frac{S_1}{\cos(\theta)} \quad S_2 - \frac{S_1}{\cos(\theta)}$$

next we can find b using the tangent of the S_1, θ triangle and adding d

$$b = \tan(\theta) \cdot S_1 + d \quad \tan(\theta) \cdot S_1 + d$$

which means we can use the cosine law to solve for the length l

$$l = \sqrt{a^2 + b^2 - 2 \cdot a \cdot b \cdot \cos(\theta + 90)}$$

$$l(\theta) = \sqrt{\left(S_2 - \frac{S_1}{\cos(\theta)}\right)^2 + (\tan(\theta) \cdot S_1 + d)^2 - 2 \cdot \left(S_2 - \frac{S_1}{\cos(\theta)}\right) \cdot (\tan(\theta) \cdot S_1 + d) \cdot \cos(\theta + 90)}$$

this means that the extension of the spring can be solved for as

$$l_{\Delta}(\theta) = l(\theta) - l(0)$$

we can also now solve for the angle B using sine law

$$\frac{\sin(\theta + 90)}{l(\theta)} = \frac{\sin(B)}{b(\theta)}$$

$$B = \text{asin}\left(\frac{\sin(\theta + 90)}{l(\theta)} \cdot b(\theta)\right)$$

$$B(\theta) = \text{asin}\left(\frac{\sin(\theta + 90)}{\sqrt{(a(\theta))^2 + (b(\theta))^2 - 2 \cdot (a(\theta)) \cdot (b(\theta)) \cdot \cos(\theta + 90)}} \cdot b(\theta)\right)$$

we can now finally go back to the FBD equation, eq. 1, which we can now write as

$$m \cdot \omega^2 \cdot r \cdot \cos(\theta) \cdot L - mg \cdot \sin(\theta) \cdot L + \sin(B(\theta)) \cdot k \cdot l_{\Delta}(\theta) = 0$$

we can rearrange to get

$$mg \cdot \sin(\theta) + \sin(B(\theta)) \cdot k \cdot l_{\Delta}(\theta) = m \cdot \omega^2 \cdot L \cdot \sin(\theta) \cdot \cos(\theta)$$

w can then isolate ω as a function of solely θ

$$\omega = \sqrt{\frac{mg \cdot \sin(\theta) + \sin(B(\theta)) \cdot k \cdot l_{\Delta}(\theta)}{m \cdot L \cdot \sin(\theta) \cdot \cos(\theta)}}$$

we can plot this function and show that it has a much smoother curve than that of the original springless design

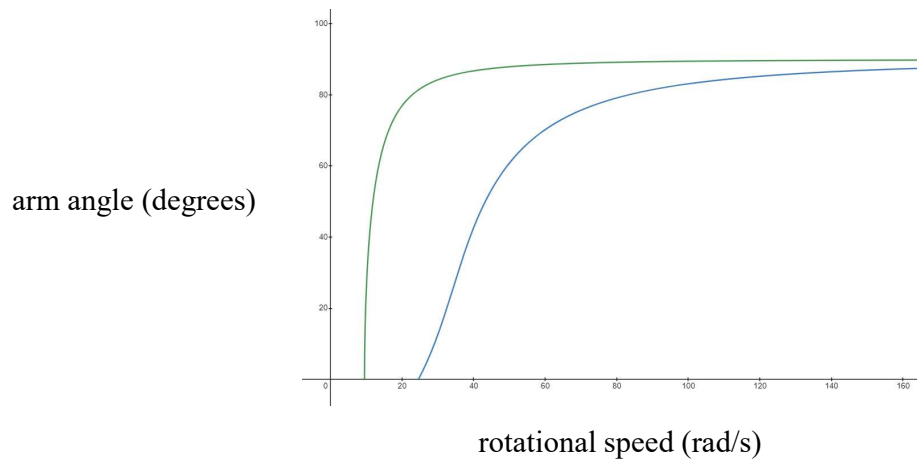


Figure C13: arm angle / rotational speed relation comparison

Pictured in blue is the new curve, while the green curve is without the spring. we can see that the moment arms now increase in angle much slower than before, meaning the friction cone can be placed at a specific angle and the arms will reliably hit the cone at the damaging speed.

□

Moment of Inertia with spring

Now that the angle of the moment bars is known, we can find the increase to the moment of inertia of the system caused by the governor.

To do this we will utilise the following property of moment of inertia states and rotation, if we know the moment of inertia at the base state as well as the moment of inertia at the final state of 90 degrees, we can calculate the moment of inertia for all θ , using the following relation.

$$I = I_{90} \cdot \sin(\theta) + I_0 \cdot \cos(\theta)$$

This will calculate the extra moment of inertia added by one arm as a function of the angle the arm makes relative to the shaft.

However we must now calculate I_{90} and I_0 .

First I_0 , the figure below shows the governor at its base state

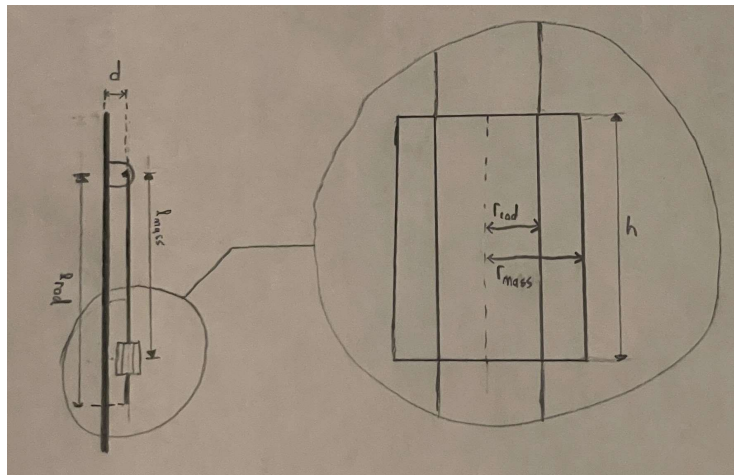


Figure C14: Parameters of rod and mass for moment of inertia calcs at base state

We can use the parallel axis theorem,

$$I = I_x + m \cdot d^2$$

to calculate the moment of inertia of the system

$$I_0 = I_{rod} + m_{rod} \cdot d_{rod}^2 + I_{mass} + m_{mass} \cdot d_{mass}^2$$

I_{rod} and I_{mass} can be found using the tabulated formulas for moment of inertia of various shapes from reference [1]

the rod is modelled as a uniform cylinder and the mass is modelled as a cylinder with a cylindrical hole in the center

$$I_{rod} = \frac{1}{2} \cdot m_{rod} \cdot r_{rod}^2$$

$$I_{mass} = \frac{1}{2} \cdot m_{mass} \cdot (r_{rod}^2 + r_{mass}^2)$$

We also know from the figure that

$$d = d_{mass} \quad d = d_{rod}$$

Thus the final equation for I_0 is

$$I_0 = \frac{1}{2} \cdot m_{rod} \cdot r_{rod}^2 + m_{rod} \cdot d^2 + \frac{1}{2} \cdot m_{mass} \cdot (r_{rod}^2 + r_{mass}^2) + m_{mass} \cdot d^2$$

The same process can be used for the moment of inertia at 90 degrees

The figure below shows the governor at 90 degree

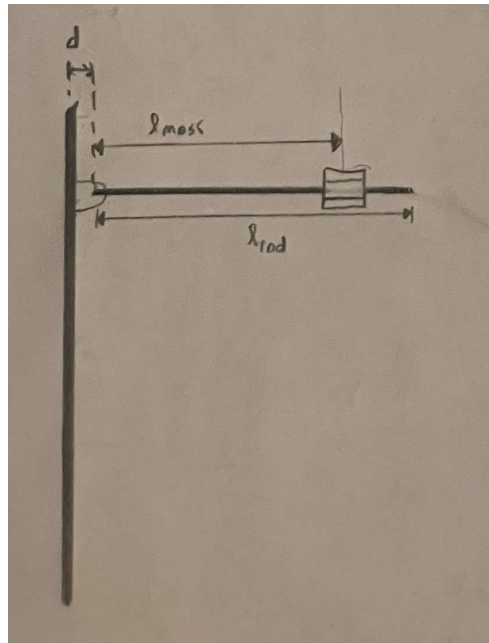


Figure C15: Parameters of rod and mass for moment of inertia calcs at full extension

We can again use the parallel axis theorem to show that the moment of inertia at an angle of 90 degrees is

$$I_{90} = I_{rod} + m_{rod} \cdot d_{rod}^2 + I_{mass} + m_{mass} \cdot d_{mass}^2$$

Using the same shape assumptions, but different axis of rotation from the textbook we get the following,

$$I_{rod} = \frac{1}{12} \cdot m_{rod} \left(3 \cdot r_{rod}^2 + l_{rod}^2 \right)$$

and

$$I_{mass} = \frac{1}{12} \cdot m_{mass} \cdot \left(\left(3 \cdot r_{rod} \right)^2 + \left(3 \cdot r_{mass} \right)^2 + h_{mass}^2 \right)$$

This time, d_{mass} and d_{rod} are different

$$d_{mass} = d + l_{mass}$$

$$d_{rod} = d + \frac{l_{rod}}{2}$$

We can now find the equation for I_{90}

$$I_{90} = \frac{1}{12} \cdot m_{rod} \left(3 \cdot r_{rod}^2 + l_{rod}^2 \right) + m_{rod} \cdot \left(d + \frac{l_{rod}}{2} \right)^2 + \frac{1}{12} \cdot m_{mass} \cdot \left(\left(3 \cdot r_{rod} \right)^2 + \left(3 \cdot r_{mass} \right)^2 + h_{mass}^2 \right) + m_{mass} \cdot \left(d + l_{mass} \right)^2$$

We can now show the final equation for the moment of inertia of the arm as a function of the moment arm angle

$$\begin{aligned} I(\theta) &= \frac{1}{12} \cdot m_{rod} \left(3 \cdot r_{rod}^2 + l_{rod}^2 \right) \cdot \sin(\theta) + m_{rod} \cdot \left(d + \frac{l_{rod}}{2} \right)^2 \cdot \sin(\theta) \\ &+ \frac{1}{12} \cdot m_{mass} \cdot \left(\left(3 \cdot r_{rod} \right)^2 + \left(3 \cdot r_{mass} \right)^2 + h_{mass}^2 \right) \cdot \sin(\theta) \\ &+ m_{mass} \cdot \left(d + l_{mass} \right)^2 \cdot \sin(\theta) + \frac{1}{2} \cdot m_{rod} \cdot r_{rod}^2 \cdot \cos(\theta) \\ &+ m_{rod} \cdot d^2 \cdot \cos(\theta) + \frac{1}{2} \cdot m_{mass} \cdot \left(r_{rod}^2 + r_{mass}^2 \right) \cdot \cos(\theta) \\ &+ m_{mass} \cdot d^2 \cdot \cos(\theta) \end{aligned}$$

since there are two arms and their moment of inertia adds to the original turbine inertia we can write

$$I_{total} = I_{turbine} + 2 \cdot I$$

we can then substitute the relation between θ and ω in order to find the moment of inertia each arm adds as a function of only the rotational speed of the turbine

$$\begin{aligned}
 I(\omega) = & \frac{1}{6} \cdot m_{rod} \left(3 \cdot r_{rod}^2 + l_{rod}^2 \right) \cdot \sin \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + 2 \cdot m_{rod} \cdot \left(d + \frac{l_{rod}}{2} \right)^2 \cdot \sin \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) \\
 & + \frac{1}{6} \cdot m_{mass} \cdot \left((3 \cdot r_{rod})^2 + (3 \cdot r_{mass})^2 + h_{mass}^2 \right) \cdot \sin \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) \\
 & + 2 \cdot m_{mass} \cdot (d + l_{mass})^2 \cdot \sin \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + m_{rod} \cdot r_{rod}^2 \cdot \cos \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) \\
 & + 2 \cdot m_{rod} \cdot d^2 \cdot \cos \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + m_{mass} \cdot (r_{rod}^2 + r_{mass}^2) \cdot \cos \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) \\
 & + 2 \cdot m_{mass} \cdot d^2 \cdot \cos \left(\arccos \left(\frac{g}{\omega^2 \cdot L} \right) \right) + I_{turbine}
 \end{aligned}$$

We can then plot this relation to show the moment of inertia as a function of angular velocity, $I(\omega)$. Due to the limitations of SMath, the plot was made using desmos software instead and shows the moment of inertia as a function of the angle of the bar, $I(\theta)$.

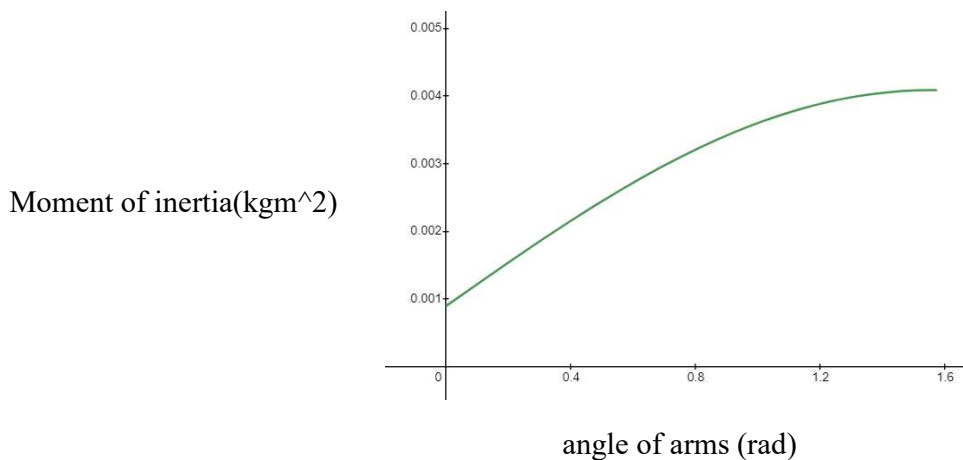


Figure C16: moment of inertia to moment arm angle relation

Energy Calculations

Now that the moment of inertia has been determined, the stored energy of the turbine can be calculated

We must consider the kinetic energy of the original turbine, the rotational kinetic energy of the moment arms, the potential energy of the masses lifting and now that there is a spring we must consider the potential energy of the extension of the spring

we know that

$$KE = \frac{1}{2} \cdot I \cdot \omega^2$$

and

$$PE = m \cdot g \cdot h$$

$$PE = \frac{1}{2} \cdot k \cdot \Delta l^2$$

but h , I and Δl are functions of ω

we have already derived the solutions for these functions, and so

We can now sum the energies to obtain the following

$$E_{tot} = \frac{1}{2} \cdot I_{turbine} \cdot \omega^2 + \frac{1}{2} \cdot I(\omega) \cdot \omega^2 + m \cdot g \cdot h(\omega) + \frac{1}{2} \cdot k \cdot l_{\Delta}(\omega)^2$$

We can then plot the total energy in the system using some sample values for physical parameters

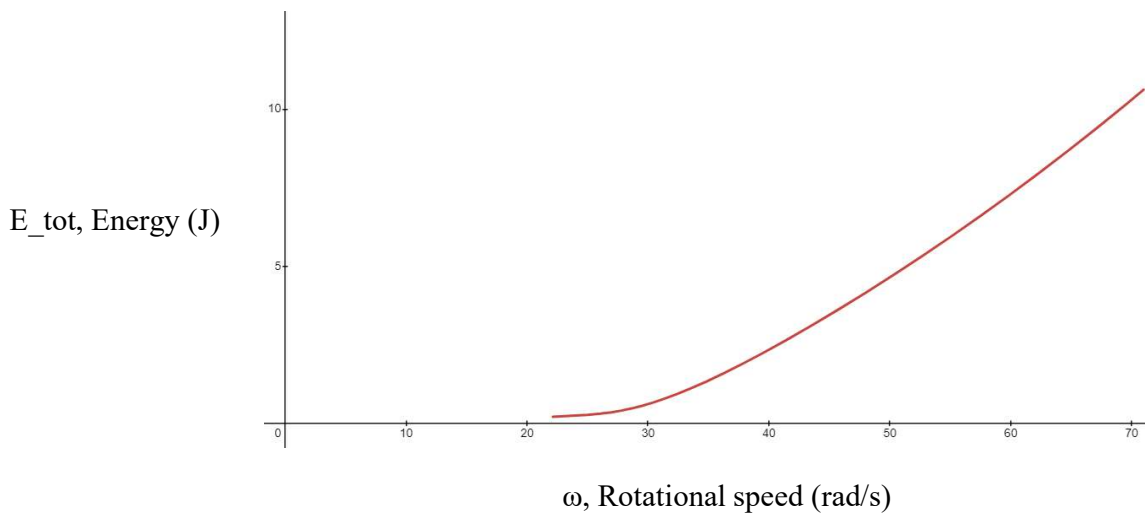


Figure C17: Total energy as a function of rotational speed

We can see that the energy increase is now much larger than before due to the increased rotational speed that the moment arms will contact the friction cone. The stored energy also does not increase heavily before 20 rad/s which is in line with the cut out speed of the turbine allowing

□

Braking force calculations

The braking force of the friction cone was also calculated to ensure that the moment arms will not overspeed

we can start with the visual of the system with the spring

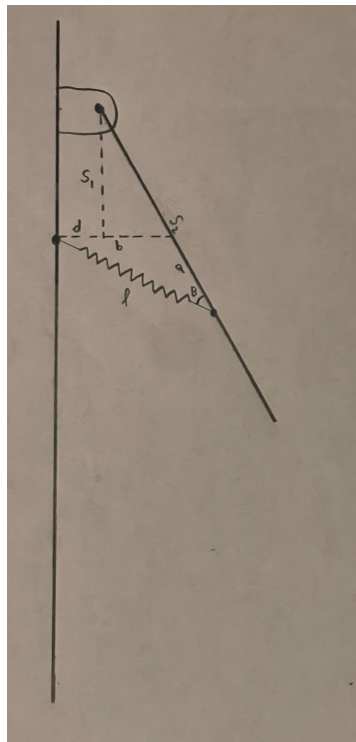


Figure C18: Geometry of system used for braking force

We know that the cone will stop the moment arm from raising and will therefore place a force on the mass-rod system tangent, but opposite, to its movement.

We can then calculate the force applied by the cone using the sum of forces in both directions

$$\sum_{\square} F_y = 0$$

$$F_T \cdot \cos(\theta) - mg - \sin(\theta) \cdot F_N = 0$$

$$\sum_{\square} F_x = 0$$

$$F_T \cdot \sin(\theta) - m\omega^2 \cdot r - \cos(\theta) \cdot F_N = 0$$

We can then isolate F_N as a function of ω

$$F_N = m \cdot \sin(\theta) \cdot \left(\omega^2 \cdot L \cdot \cos(\theta) - g \right)$$

since we know the friction force is proportiona to the normal force we can write

$$F_f = m \cdot \sin(\theta) \cdot \left(\omega^2 \cdot L \cdot \cos(\theta) - g \right) \cdot \mu_k$$

We can also show that the energy lost due to friction over time is proportional to the speed

$$P_f = m \cdot \sin(\theta) \cdot \left(\omega^2 \cdot L \cdot \cos(\theta) - g \right) \cdot \mu_k \cdot v$$

but v is a function of ω

$$v = \omega r$$

$$v = \omega \cdot L \cdot \sin(\theta)$$

$$P_f = m \cdot \sin(\theta) \cdot \left(\omega^2 \cdot L \cdot \cos(\theta) - g \right) \cdot \mu_k \cdot \omega \cdot L \cdot \sin(\theta)$$

final relation

$$P_f = m \cdot \mu_k \cdot L \cdot \omega \cdot \sin(\theta)^2 \cdot \left(\omega^2 \cdot L \cdot \cos(\theta) - g \right)$$

This relation was compared to the energy total energy stored in the turbine and due to the magnitude of the energy lost, we can show that the governor will always be able to maintain the turbine at a safe speed

□

Efficiency calculations

Due to the extra energy in the system, we can estimate the extra time taken for the turbine to speed up and for the turbine to slow down. From the client data, we know the original time taken for the wind turbine to accelerate. From this we can imply, using the extra energy stored, how long it will take the turbine to spin up to speed with the governor installed by taking the ratio of the old energy curve to the new one.

The data is shown for a few sample points in the tables below

Initial Speed (km/h)	Time To Cutout Without Governor System (s)	Time To Cutout With Governor System (s)	Difference (s)
9	1.6	1.6	0.0
10	2.1	2.6	0.5
12	4.3	16.3	12.1
15	9.3	45.7	36.4
18	15.2	75.9	60.7

Figure C19: Extra time taken to cutout

Gust Speed (km/h)	Time Until Braking Without Governor System (s)	Time Until Braking With Governor System (s)	Difference (s)
20	14.6	73.2	58.5
30	7.7	38.5	30.8
50	4.0	19.8	15.8
75	2.5	12.3	9.8
90	2.0	10.1	8.1

Figure C20: Extra time taken to brake

We can see that in both cases, a maximum time increase of approximately 1 min is observed

Mach innovations then analysed the wind speed data given by the client and calculated the extra amount of data points that the turbine would be spinning for. This was done by counting all points in the safe range of wind speeds and then adding a point each time the wind dropped off past the cutout speed or went above the damaging speed

This resulted in the following data

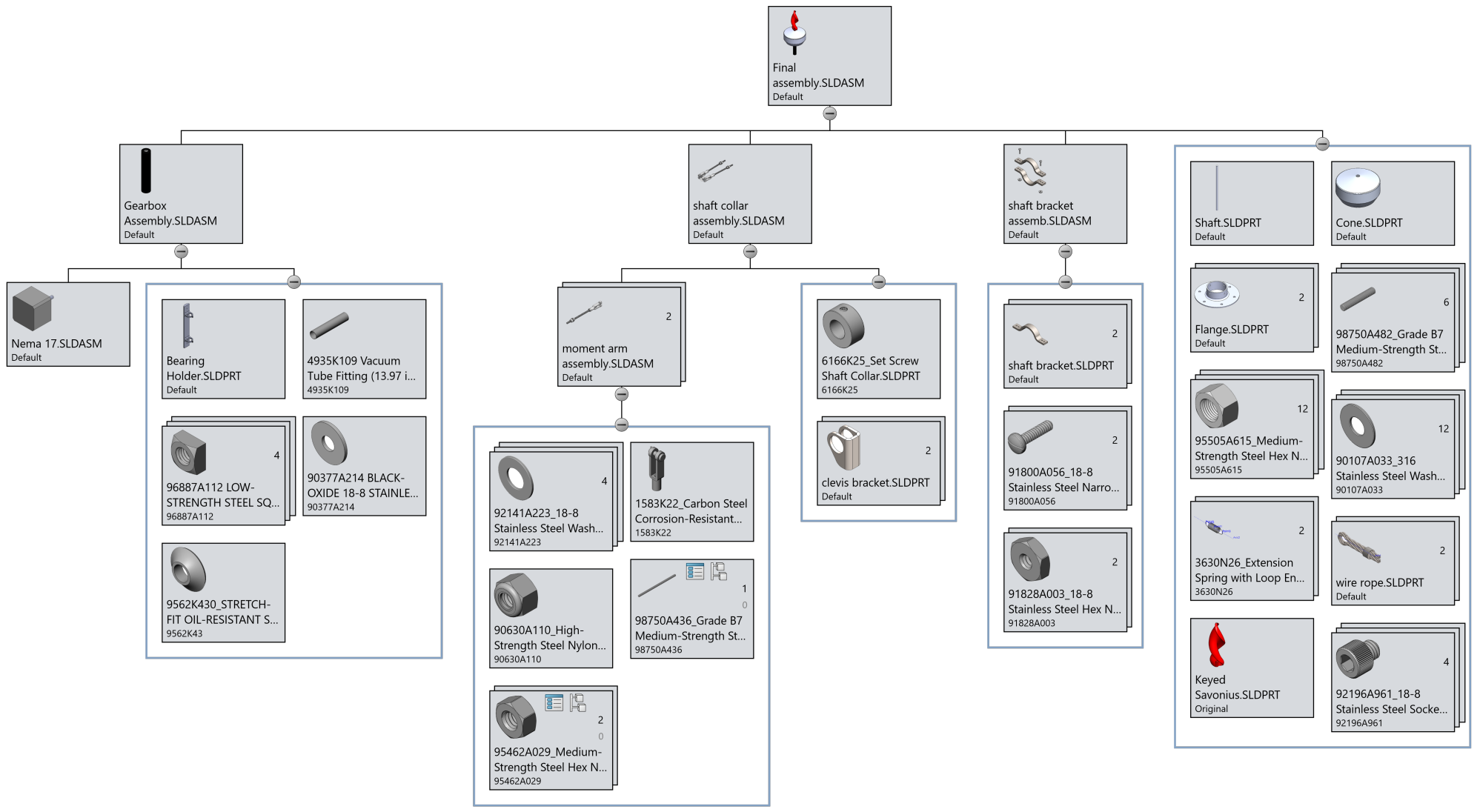
System Data	Minutes
Total Wind Data Time	28806
Time Spent Below 9km/h	22438
Time Spent Above 18km/h	195
Time Spent In Safe Range (No Governor System)	6174
Time Spent In Safe Range (With Governor System)	7987
Governor Efficiency Increase	29.67%

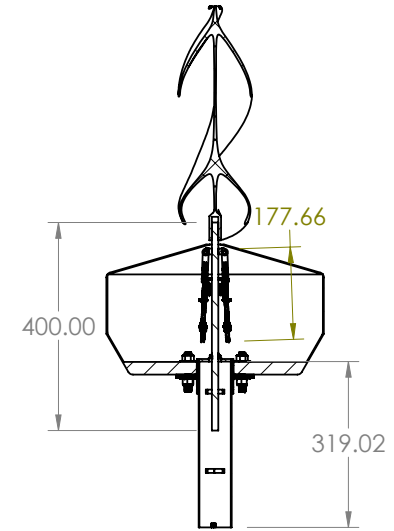
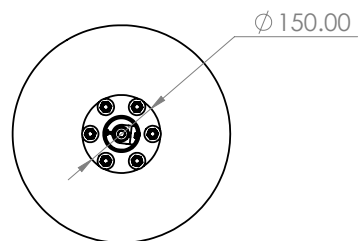
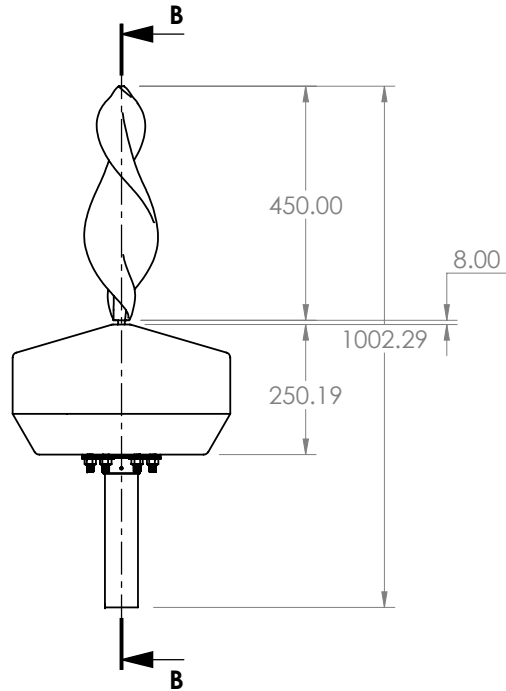
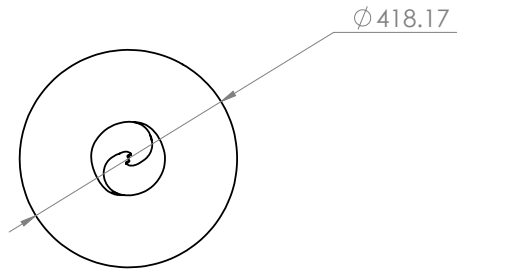
Figure C21: Efficiency increase

Mach innovations believes this is a reasonable estimate of the efficiency as each time the turbine speeds up or slows down, the extra energy that the system holds allows it to generate for longer

This does not include the times when the governor would have stopped the turbine from cutting altogether by allowing it to survive one data point of low wind, meaning this estimate is a minimum.

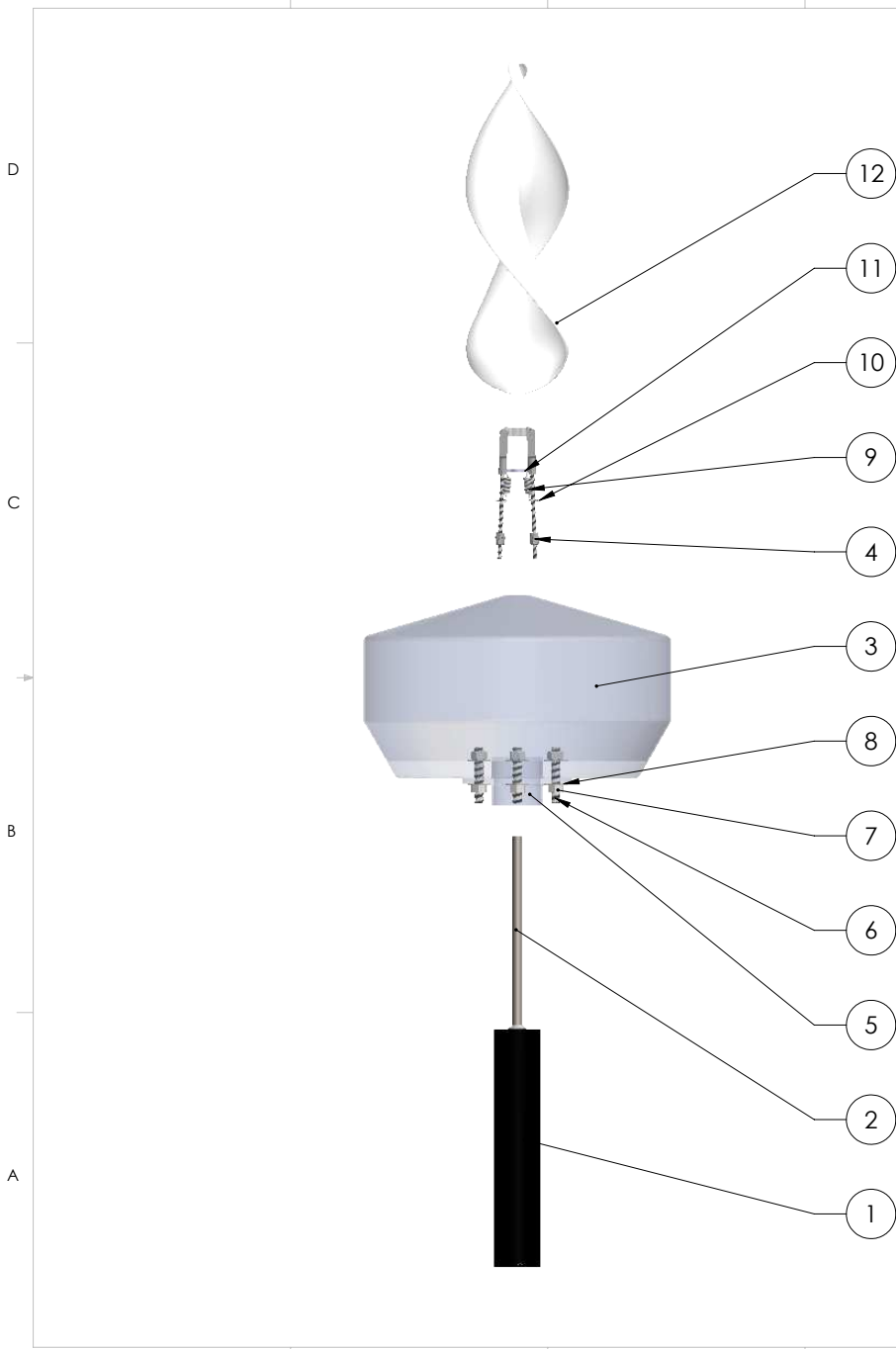
7.11 Appendix K – Drawing Package





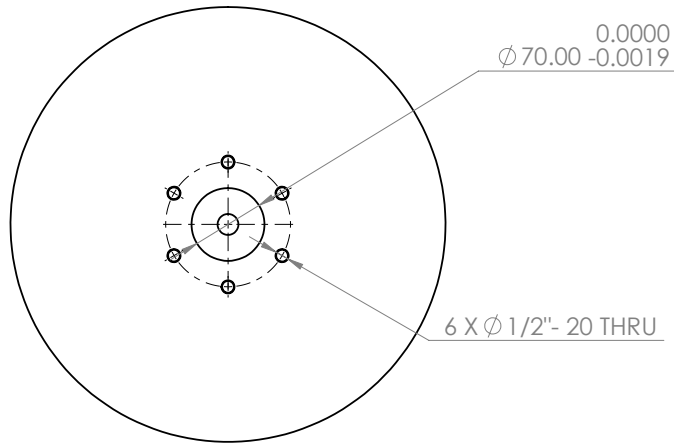
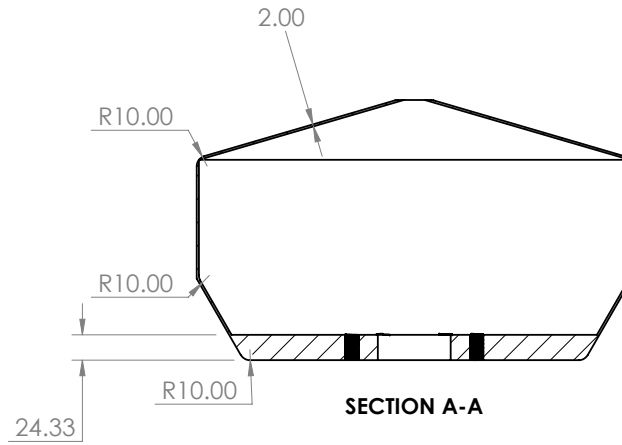
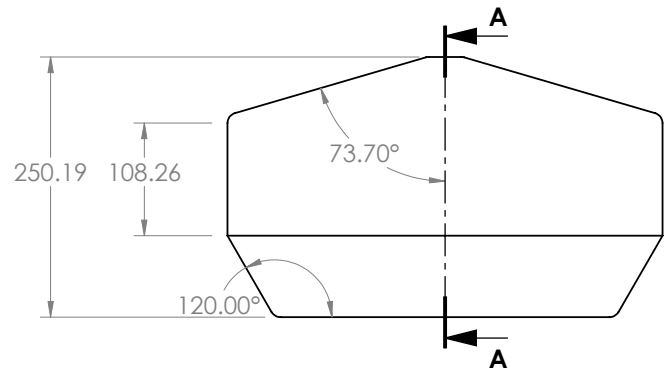
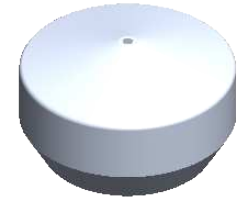
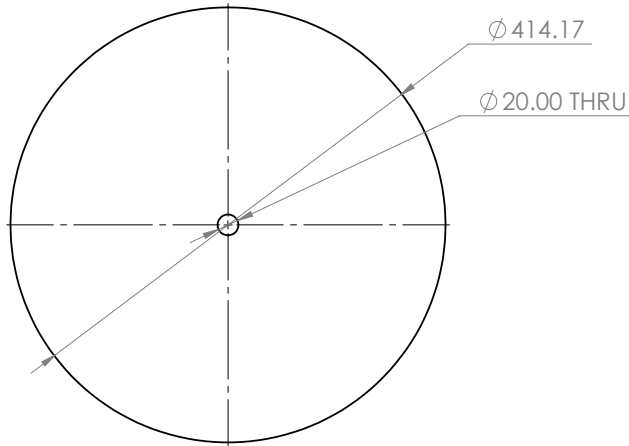
**SECTION B-B
SCALE 1 : 10**

MECE 460 Instructor: Dr. Michael Lipsett Comments: Comment: Edit in Assembly	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH μm 0.6 ✓ DO NOT SCALE DRAWING	DRAWN BY:		The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: VAWT WITH BRAKING SYSTEM		
		TEAM 15			Lab Day Edit in Assembly SM By WHO?: Edit in Assembly TA Initials Edit in Assembly	
MATERIAL: Material <not specified> FILE NAME: Final assembly		ahrr December 7, 2023 3:40:43 PM December 6, 2023 7:12:19 PM		SIZE B	Assignment Number Edit in Assembly	REV 1
SCALE: 1:20 Mass: 4963.86				SHEET 1 OF 1		

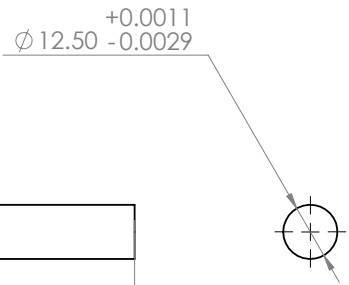
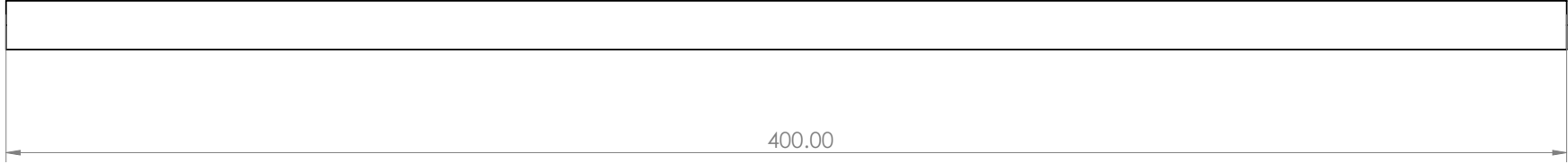
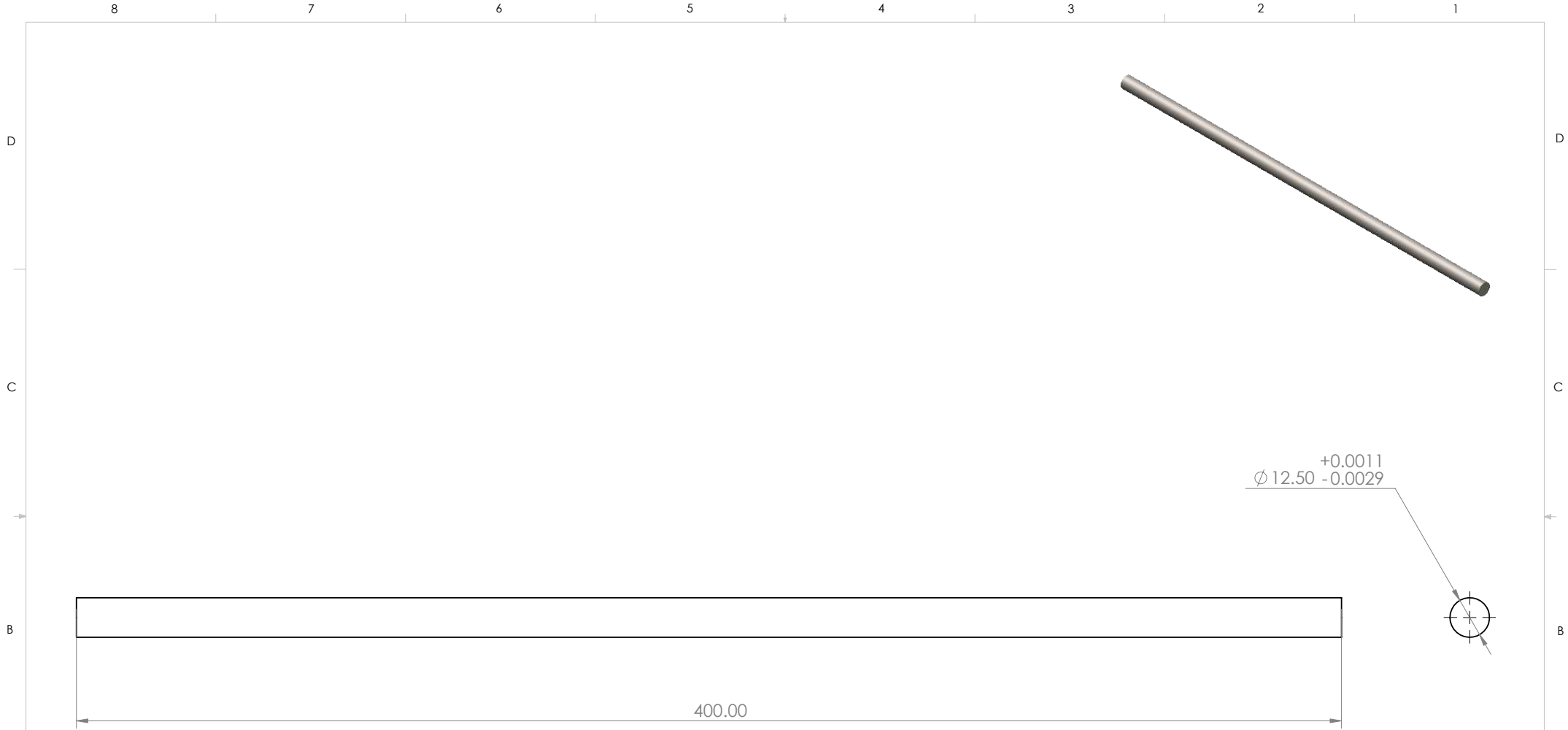


ITEM NO.	ITEM	VENDOR	QTY.
1	WIND TURBINE GEARBOX ASSEMBLY	RENEWABLE ENERGY CLUB	1
2	WIND TURBINE SHAFT	MACHINE SHOP	1
3	BRAKING SYSTEM CASING ASSEMBLY	MACHINE SHOP	1
4	MASS AND ROD ASSEMBLY	MACHINE SHOP	1
5	CUSTOM MADE FLANGE	MACHINE SHOP	2
6	98750A482 STEEL THREADED ROD	MCMMASTER-CARR	6
7	95505A615 STEEL HEX NUT	MCMMASTER-CARR	12
8	90107A033 STAINLESS STEEL WASHER	MCMMASTER-CARR	12
9	3630N26 EXTENSION SPRING	MCMMASTER-CARR	1
10	8908T27 STAINLESS STEEL WIRE ROPE	MCMMASTER-CARR	2
11	SHAFT CLAMP ASSEMBLY	MACHINE SHOP	1
12	KEYED SAVONIUS WIND TURBINE BLADE	RENEWABLE ENERGY CLUB	1

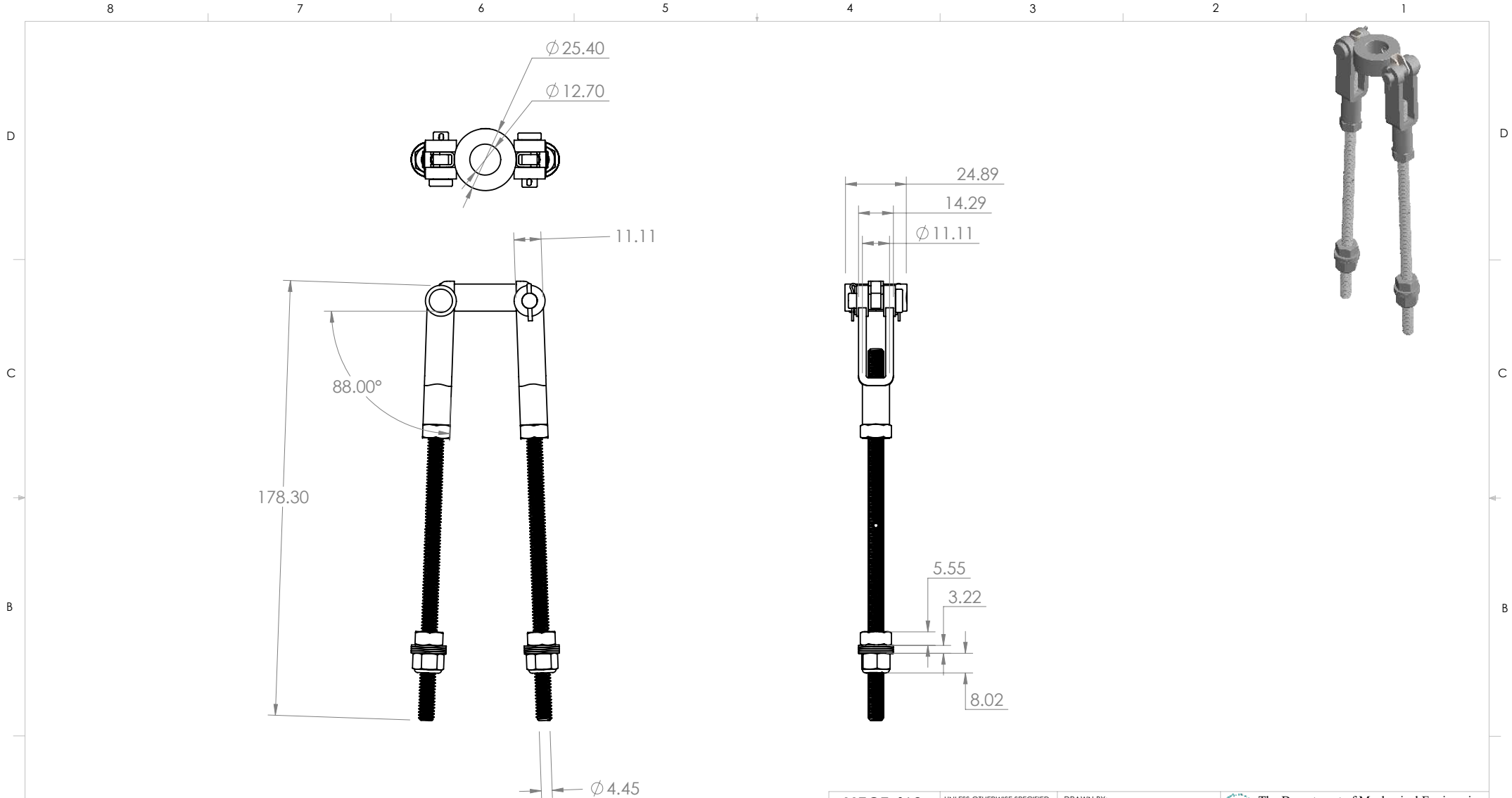
MECE 460 Instructor: DR. MICHAEL LIPSETT Comments: Comment: Edit in Assembly	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: $\pm 0.5^\circ$ LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH μm 0.6 ✓ DO NOT SCALE DRAWING	DRAWN BY:		The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: FULL ASSEMBLY EXPLODED VIEW	
		TEAM 15			Lab Day: Edit in Assembly
		SM By:	WHO?: Edit in Assembly		
		TA Initials:	Edit in Assembly		
MATERIAL: Material <not specified>		ahrar December 7, 2023 3:29:56 PM December 6, 2023 7:12:19 PM	SIZE B	Assignment Number Edit in Assembly	REV 1
FILE NAME: Final assembly			SCALE: 1:20 Mass: 4963.86		SHEET 1 OF 1



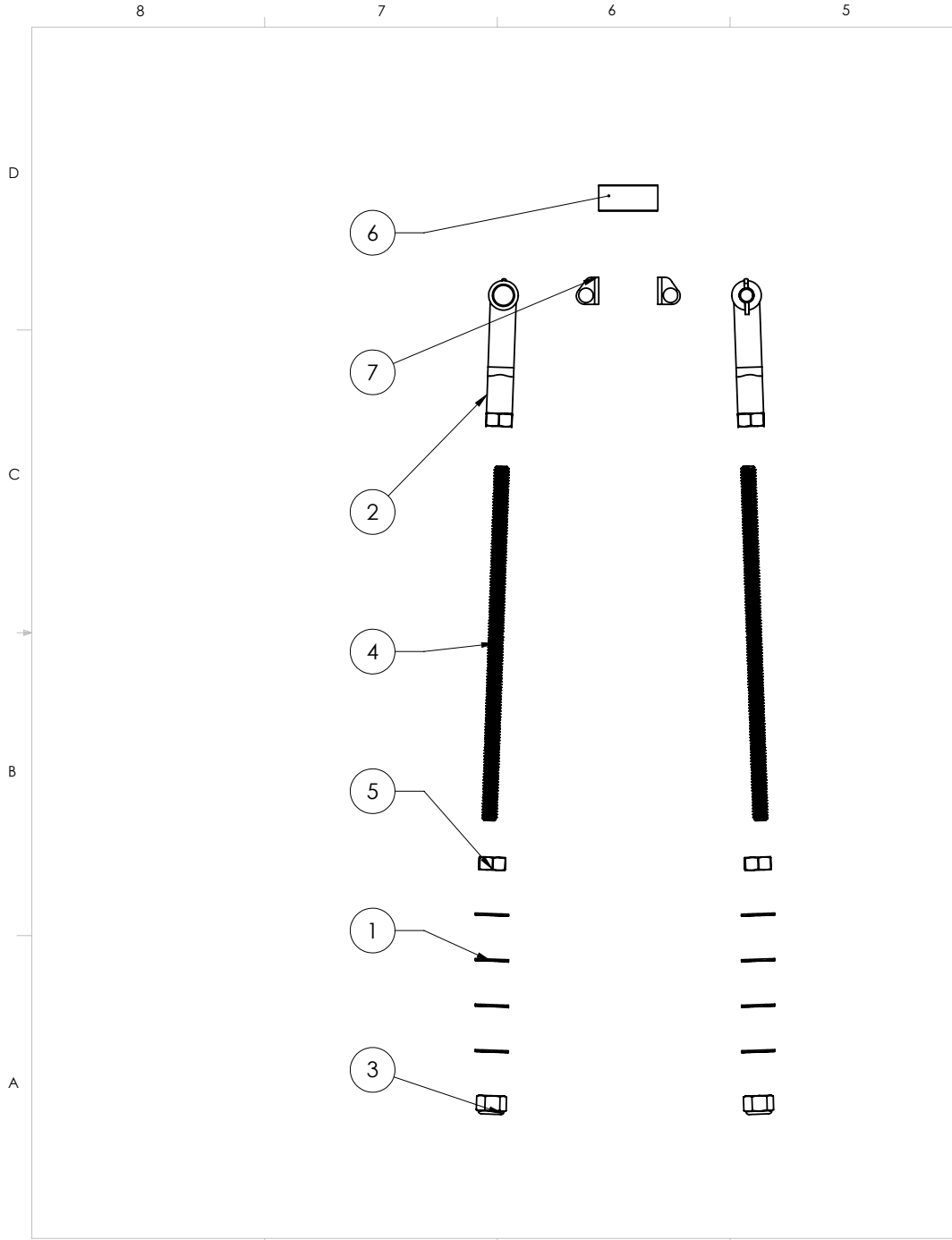
MECE 460 Instructor: DR. MICHAEL LIPSETT Comments: Comment: Edit in SM	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: $\pm 0.5^\circ$ LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH μm 0.6 ✓ DO NOT SCALE DRAWING	DRAWN BY:		The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: <h1>SHIELD</h1>
		TEAM 15		
 MATERIAL: Material <not specified> FILE NAME: Cone	SM By WHO?: Edit in SM TA Initials DSN ahrr December 7, 2023 4:27:47 AM November 27, 2023 8:10:51 PM	SIZE B	Assignment Number ALL	REV 1
		SCALE: 1:5	Mass: 2839.20	SHEET 1 OF 1



MECE 460		UNLESS OTHERWISE SPECIFIED:		DRAWN BY:		The Department of Mechanical Engineering UNIVERSITY OF ALBERTA	
Instructor: Dr. MICHAEL LIPSETT		DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5°		TEAM 15		TITLE: WIND TURBINE SHAFT	
Comments: Comment: Edit in SM		LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025		Lab Day	ALL	SIZE B	
		SURFACE FINISH µm		SM By	WHO?: Edit in SM	Assignment Number ALL	
		0.6 µm		TA Initials	DSN	REV 1	
MATERIAL: AISI 1045 Steel, cold drawn		DO NOT SCALE DRAWING		ahrar December 7, 2023 1:33:49 AM October 31, 2023 7:33:05 PM		SCALE: 1:5	
FILE NAME: Shaft						Mass: 385.34	SHEET 1 OF 1

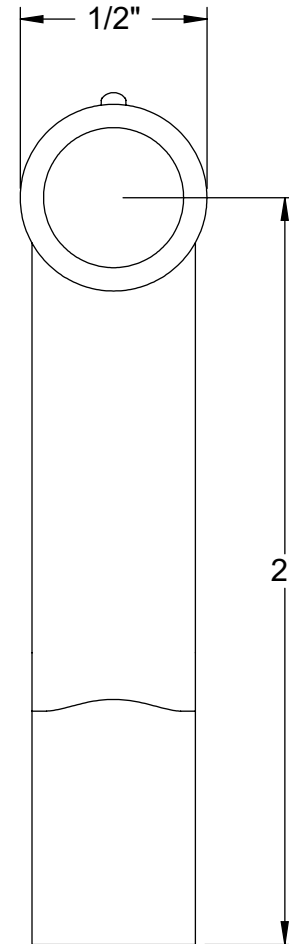
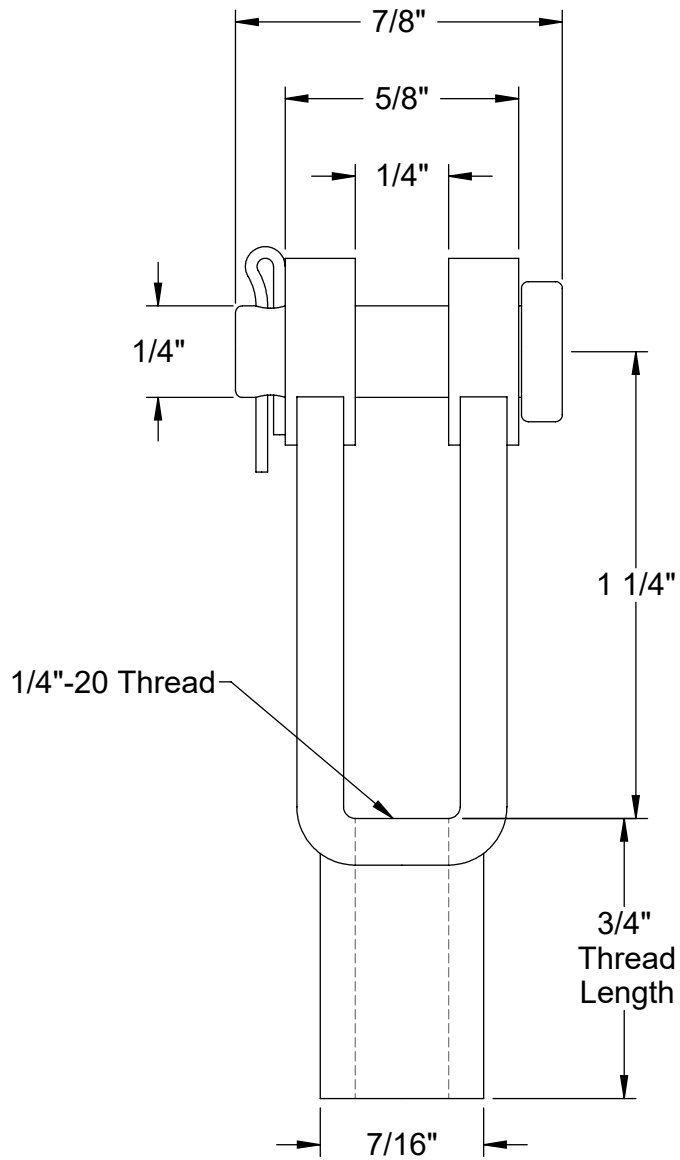


MECE 460 Instructor: DR. MICHAEL LIPSETT Comments: Comment: Edit in Assembly	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: $\pm 0.5^\circ$ LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH μm 0.6 ✓ DO NOT SCALE DRAWING	DRAWN BY:		The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: <h1>MOMENT ARM ASSEMBLY</h1>	
		TEAM 15			Lab Day
		SM By	WHO?: Edit in Assembly		
		TA Initials	Edit in Assembly		
MATERIAL: Material <not specified> FILE NAME: shaft collar assembly		ahrr December 7, 2023 3:13:07 PM November 29, 2023 7:54:14 PM	SIZE B	Assignment Number Edit in Assembly	REV 1
SCALE: 2:1			Mass: 28.03	SHEET 1 OF 1	



ITEM NO.	ITEM	PART NUMBER	DESCRIPTION	VENDOR	QTY.
1	General Purpose Washer	92141A223	18-8 Stainless Steel Washer for Number 1/4 Screw Size, 0.281" ID, 0.563" OD	MCMMASTER-CARR	8
2	Corrosion-Resistant Clevis Rod Ends	1583K22	Carbon Steel Corrosion-Resistant Clevis Rod End, 1/4"-20 Shank Thread, 2" Shank Center Length	MCMMASTER-CARR	2
3	High-Strength Steel Nylon-Insert Locknuts—Grade 8	90630A110	High-Strength Steel Nylon-Insert Locknut, Grade 8, 1/4"-20 Thread Size	MCMMASTER-CARR	2
4	Medium-Strength Steel Threaded Rods—Grade B7	98750A436	Grade B7 Medium-Strength Steel Threaded Rod, 1/4"-20 Thread Size, 6" Long	MCMMASTER-CARR	2
5	Medium-Strength Steel Hex Nuts—Grade 5	95462A029	Medium-Strength Steel Hex Nut, Grade 5, Zinc-Plated, 1/4"-20 Thread Size	MCMMASTER-CARR	4
6	Set Screw Shaft Collars	6166K25	Set Screw Shaft Collar for 1/2" Diameter, Sintered Steel	MCMMASTER-CARR	1
7	Clevis rod ends bracket	N/A	Custom made AISI 316 Stainless Steel Sheet (SS) bracket	MACHINE SHOP	2

MECE 460		UNLESS OTHERWISE SPECIFIED:		DRAWN BY:	
Instructor: DR. MICHAEL LIPSETT		DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025		TEAM 15	
Comments: Comment: Edit in Assembly		SURFACE FINISH µm 0.6 ✓		Lab Day Edit in Assembly	
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MATERIAL: Material <not specified>				TA Initials Edit in Assembly	
FILE NAME: shaft collar assembly				ahrar December 7, 2023 4:12:06 AM November 29, 2023 7:54:14 PM	
				TITLE: MOMENT ARM ASSEMBLY EXPLODED VIEW	
		SIZE B		Assignment Number Edit in Assembly	
				REV 1	
		SCALE: 1:2		Mass: 28.03	
				SHEET 1 OF 1	



McMASTER-CARR 

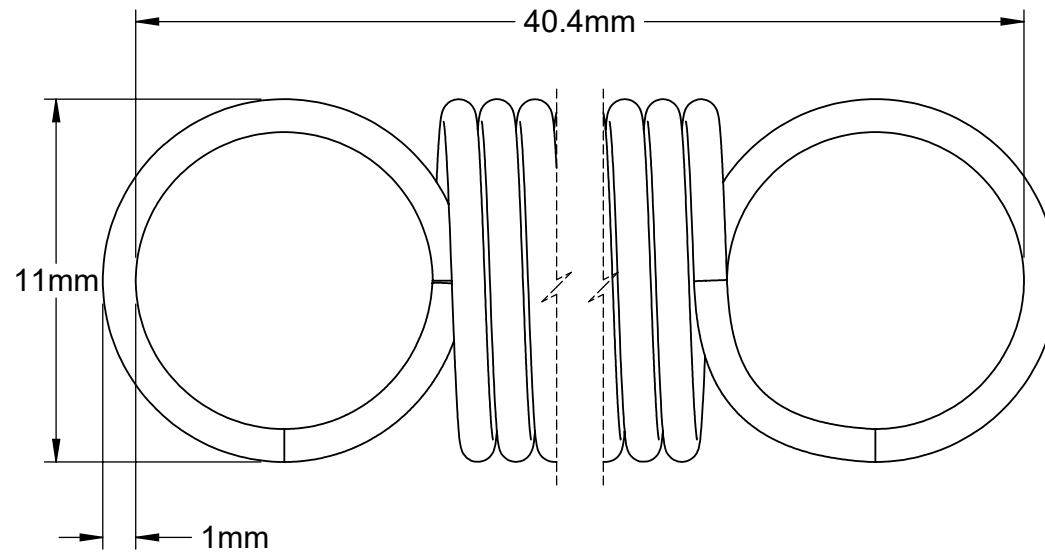
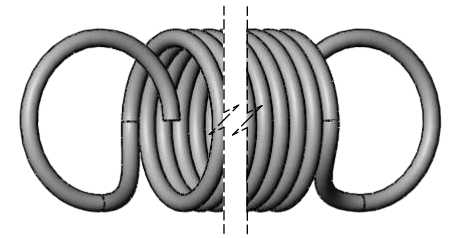
<http://www.mcmaster.com>
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Information in this drawing is provided for reference only.

PART
NUMBER

1583K22

Carbon Steel Corrosion-
Resistant Clevis Rod End



Extended Length: 102.3mm

McMASTER-CARR 

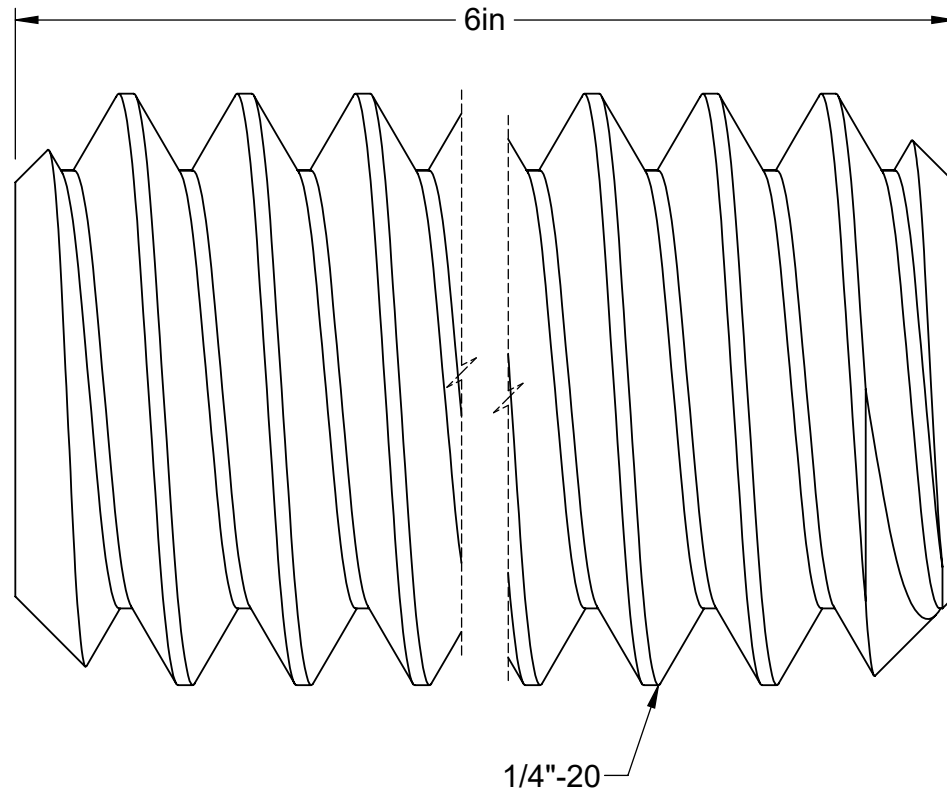
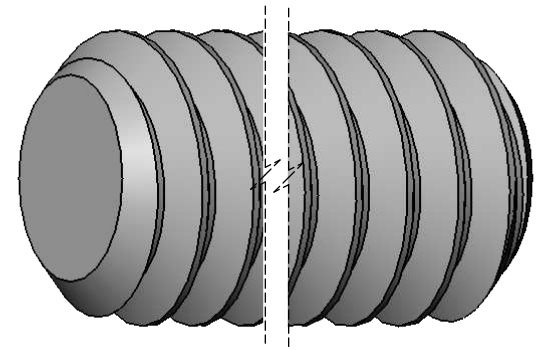
<http://www.mcmaster.com>
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Information in this drawing is provided for reference only.

PART
NUMBER

3630N26

Extension Spring
with Loop Ends



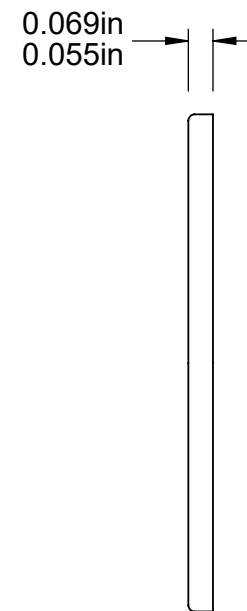
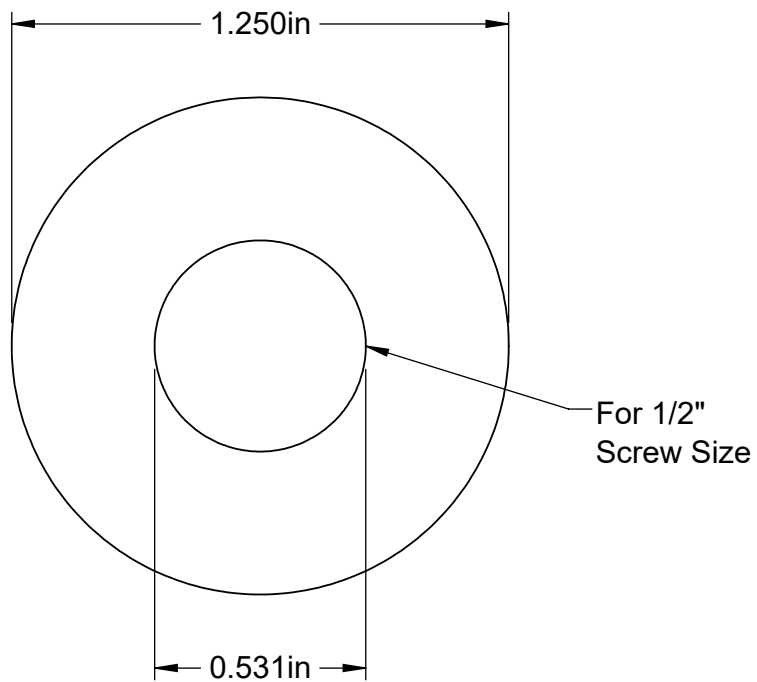
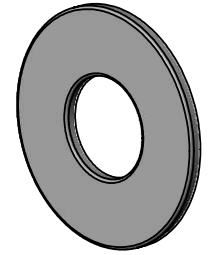
McMASTER-CARR 


<http://www.mcmaster.com>
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Information in this drawing is provided for reference only.

PART NUMBER **98750A436**

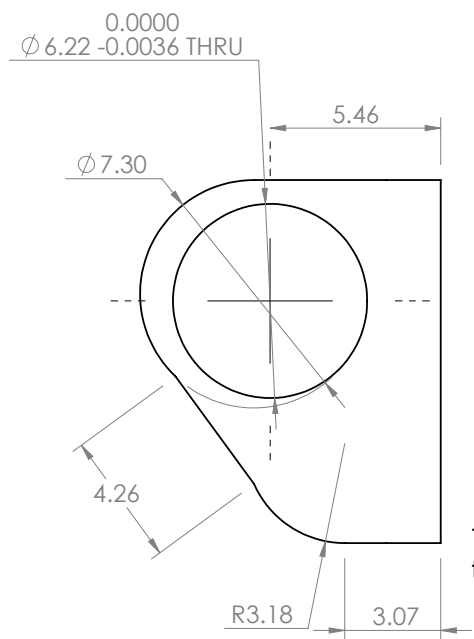
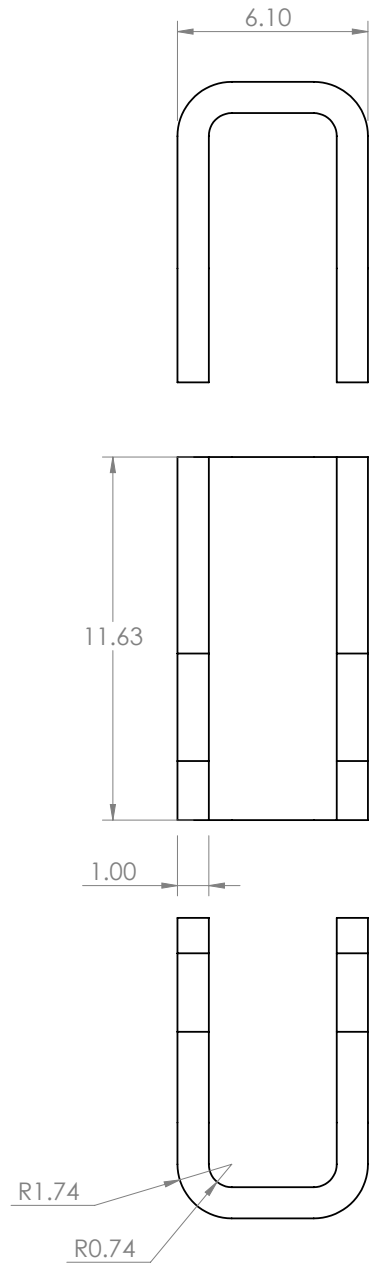
Grade B7 Medium-Strength
Steel Threaded Rod



McMASTER-CARR  http://www.mcmaster.com © 2023 McMaster-Carr Supply Company	PART NUMBER	90107A033
	316 Stainless Steel Washer	

Information in this drawing is provided for reference only.

D
C
B
A



This bracket will be welded on the shaft surface



MECE 460 Instructor: DR. MICHAEL LIPSETT Comments: Comment: Edit in SM	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH μm 0.6 ✓ DO NOT SCALE DRAWING	DRAWN BY:		The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: CLEVIS ROD BRACKET
		TEAM 15		
		Lab Day	ALL	
		SM By	WHO?: Edit in SM	
		TA Initials	DSN	
MATERIAL: AISI 316 Stainless Steel Sheet (SS) FILE NAME: clevis bracket		ahrrar December 7, 2023 3:06:50 AM November 29, 2023 10:15:40 PM		SIZE B
		Assignment Number ALL		REV 1
SCALE: 2:1		Mass: 1.26	SHEET 1 OF 1	

8 7 6 5 4 3 2 1

D

D

C

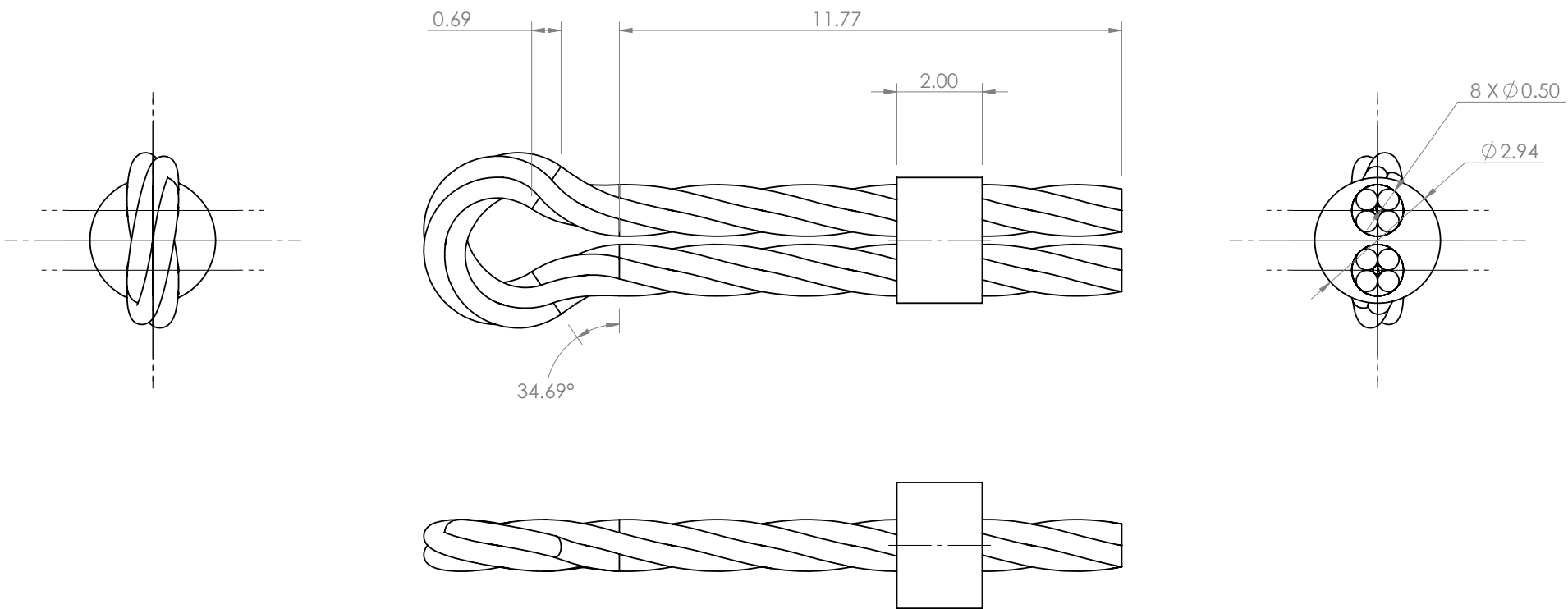
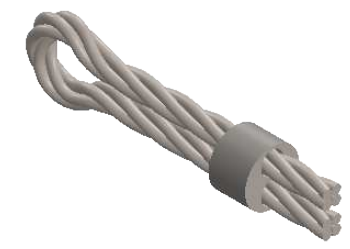
C

B

B

A

A



This wire rope will be fit into the hole of the threaded rod to connect with one end of the spring

MECE 460		UNLESS OTHERWISE SPECIFIED:		DRAWN BY:	
Instructor: Dr. Michael Lipsett		DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5°		Team 15	
Comments:		LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025		Lab Day	
		SURFACE FINISH μm 0.6 ✓		SM By	
		DO NOT SCALE DRAWING		TA Initials	
MATERIAL:				ahrar December 7, 2023 12:17:50 AM December 6, 2023 3:25:11 PM	
FILE NAME: wire rope		SCALE: 2:1		Mass:	
		SHEET 1 OF 1			

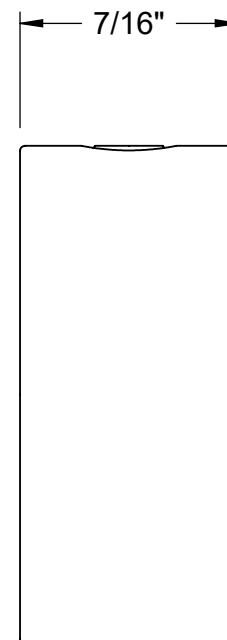
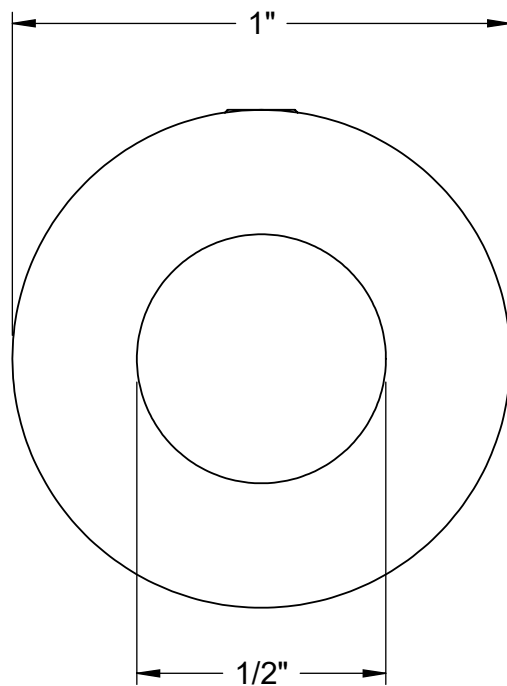
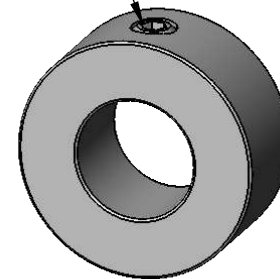
The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

TITLE:
WIRE ROPE

SIZE **B** Assignment Number REV

8 7 6 5 4 3 2 1

#10-32 x 1/4" Set Screw



McMASTER-CARR 

<http://www.mcmaster.com>

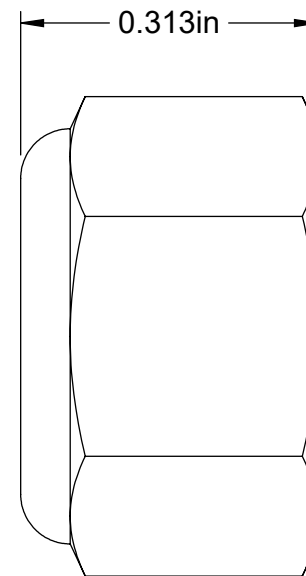
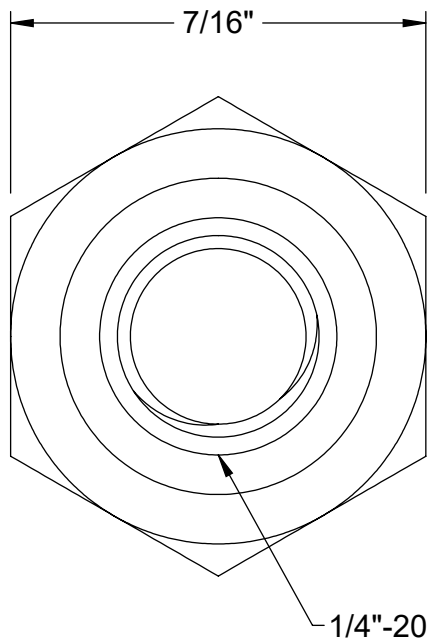
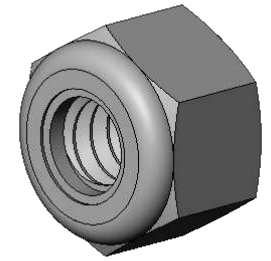
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Information in this drawing is provided for reference only.

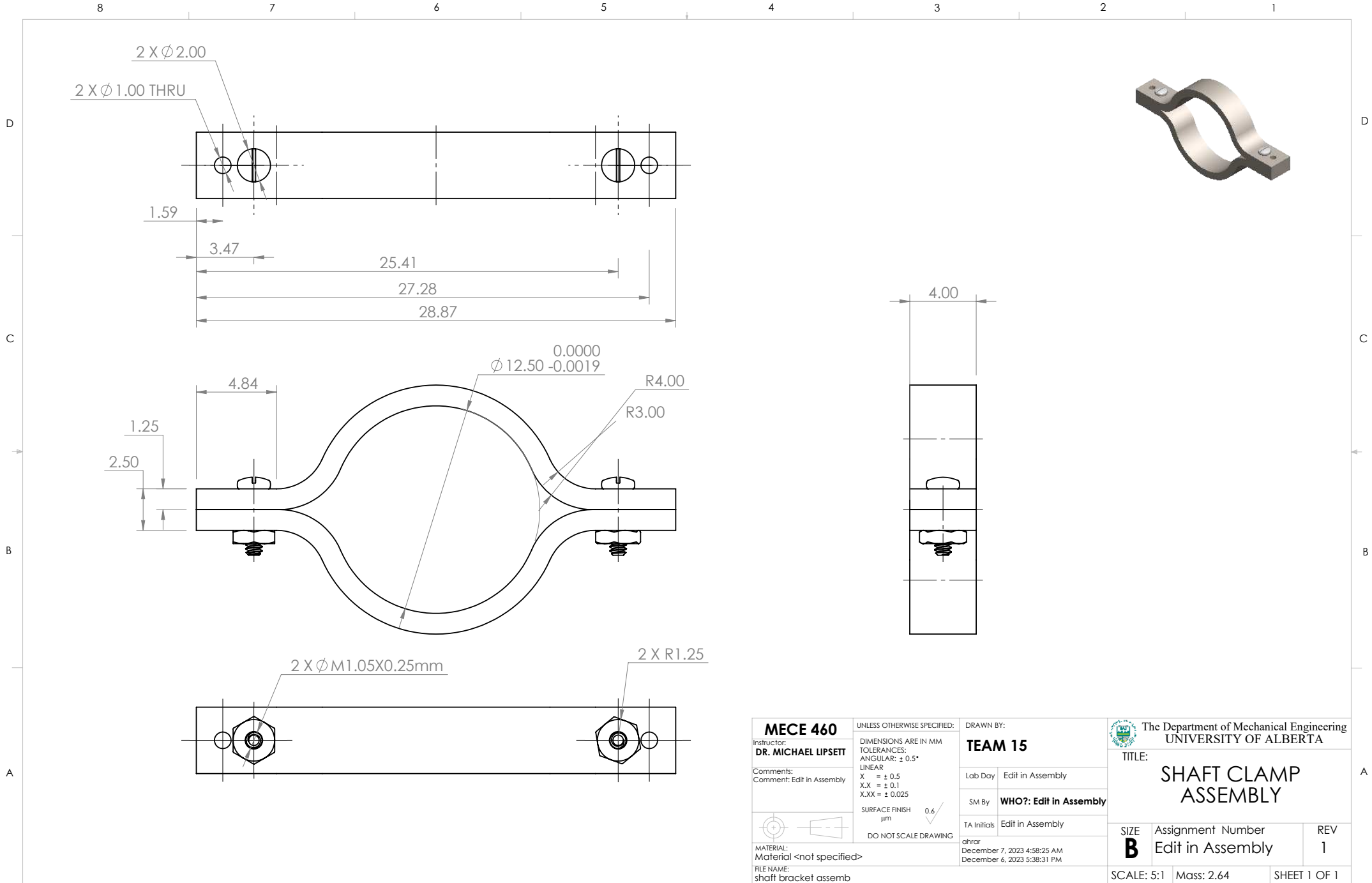
PART
NUMBER

6166K25

Set Screw
Shaft Collar

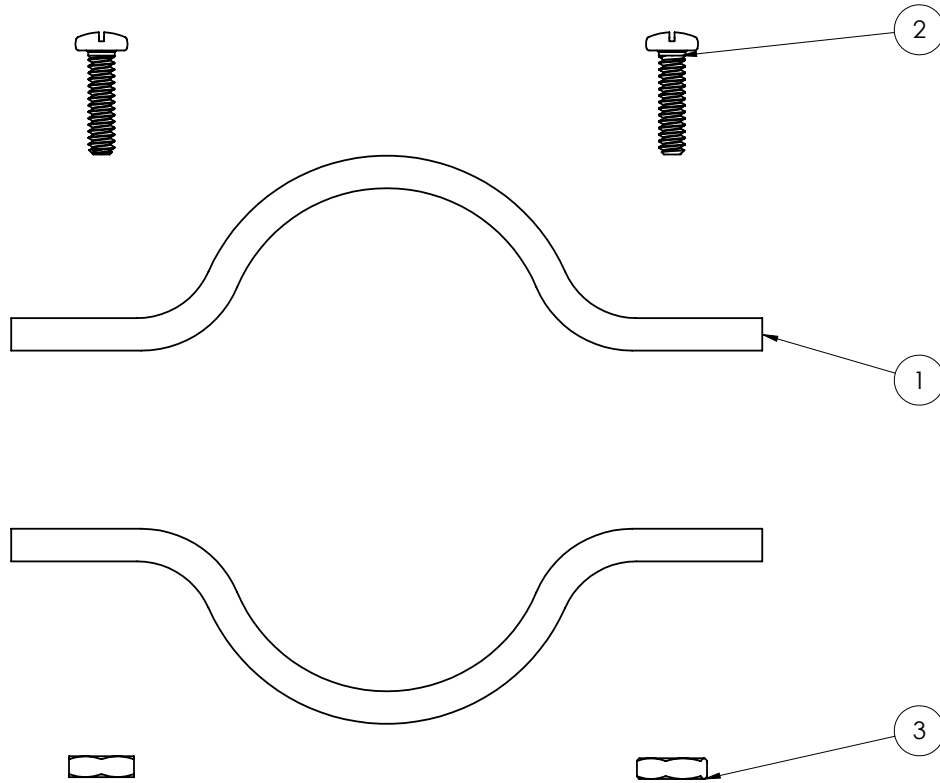


McMASTER-CARR 	PART NUMBER 90630A110
http://www.mcmaster.com	High-Strength Steel
© 2023 McMaster-Carr Supply Company	Nylon-Insert Locknut
Information in this drawing is provided for reference only.	

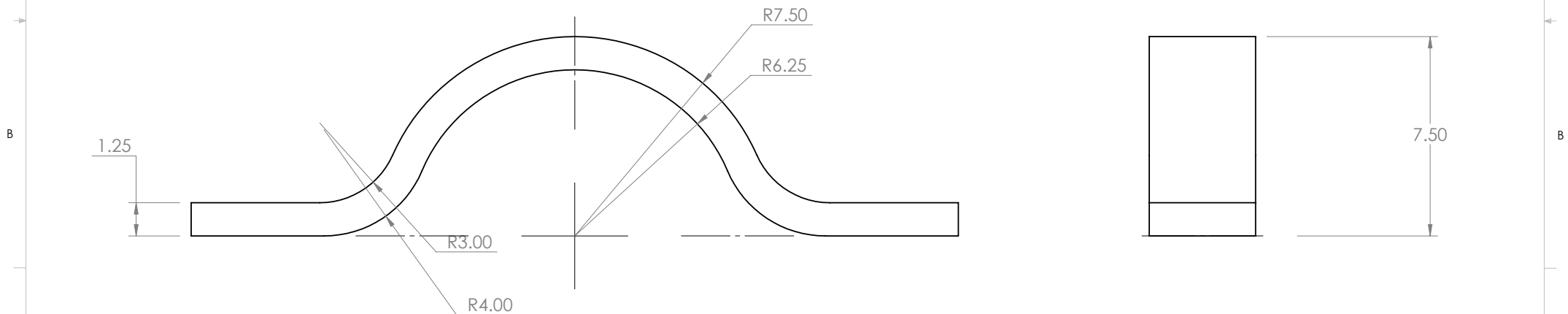
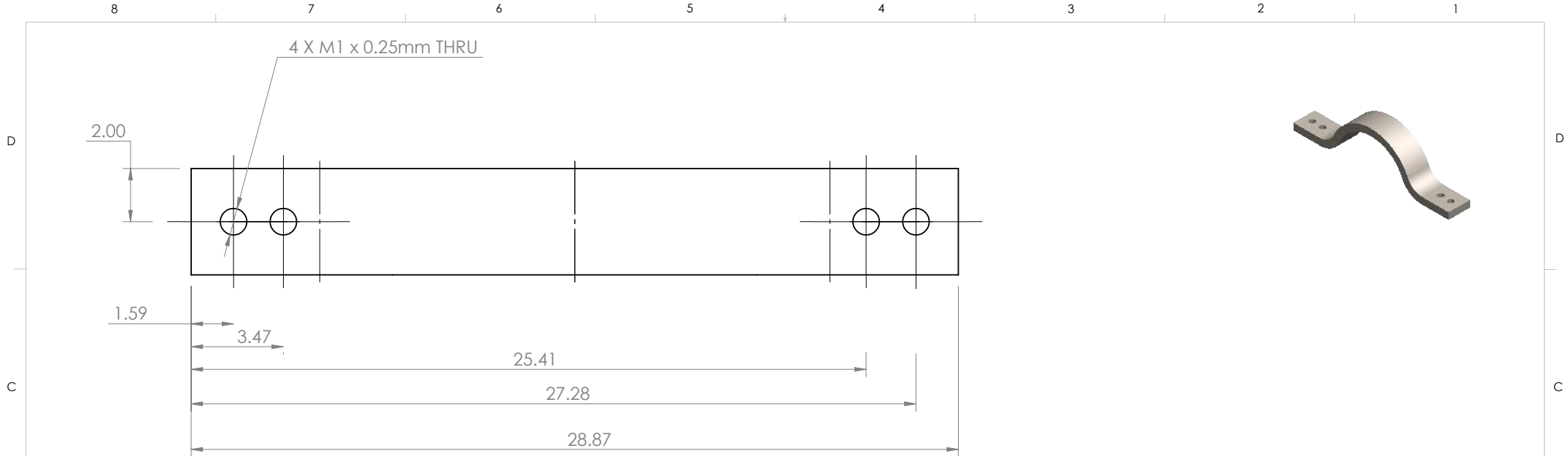


MECE 460 Instructor: DR. MICHAEL LIPSETT Comments: Comment: Edit in Assembly	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH μm 0.6 ✓ DO NOT SCALE DRAWING	DRAWN BY:		The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: <h2>SHAFT CLAMP ASSEMBLY</h2>	
		TEAM 15			Lab Day
		SM By	WHO?: Edit in Assembly		
		TA Initials	Edit in Assembly		
MATERIAL: Material <not specified> FILE NAME: shaft bracket assemb		alhrr December 7, 2023 4:58:25 AM December 6, 2023 5:38:31 PM	SIZE B	Assignment Number Edit in Assembly	REV 1
SCALE: 5:1			Mass: 2.64	SHEET 1 OF 1	

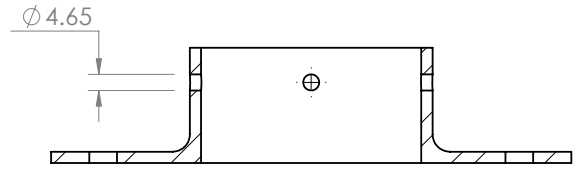
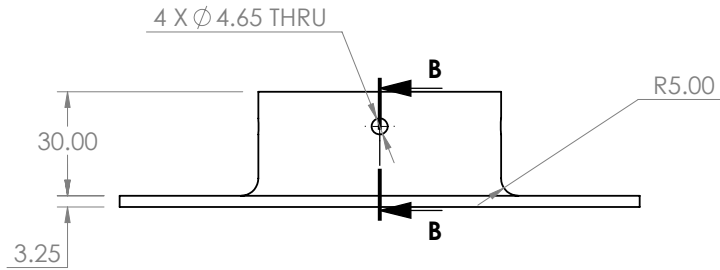
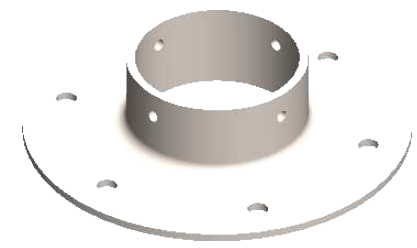
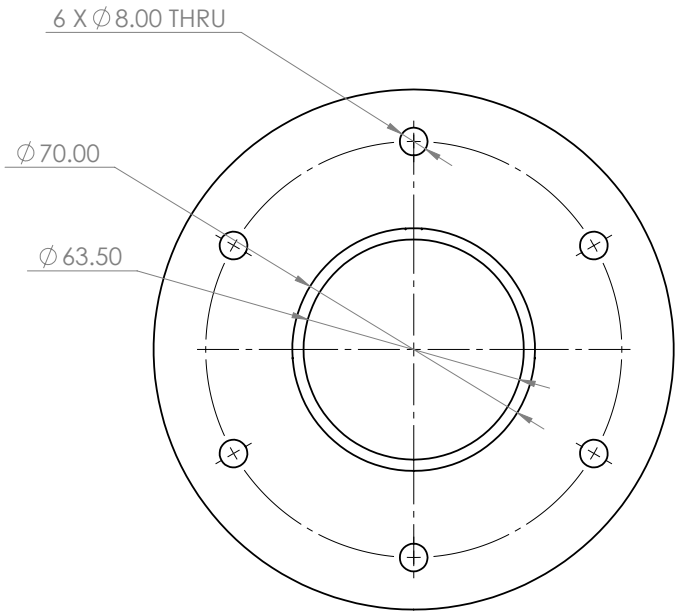
ITEM NO.	ITEM	PART NUMBER	DESCRIPTION	VENDOR	QTY.
1	Shaft Clamp	N/A	Custom made shaft clamp, AISI 1045 Steel, cold drawn	MACHINE SHOP	2
2	18-8 Stainless Steel Narrow Cheese Head Slotted Screws	91800A056	18-8 Stainless Steel Narrow Cheese Head Slotted Screws, M1 x 0.25mm Thread, 4mm Long	MCMaster-CARR	2
3	Metric 18-8 Stainless Steel Hex Nuts	91828A003	18-8 Stainless Steel Hex Nut, M1 x 0.25 mm Thread	MCMaster-CARR	2



MECE 460 Instructor: DR. MICHAEL LIPSETT Comments: Comment: Edit in Assembly	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: $\pm 0.5^\circ$ LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH μm 0.6 ✓ DO NOT SCALE DRAWING	DRAWN BY:		The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: SHAFT CLAMP ASSEMBLY EXPLODED VIEW	
		TEAM 15			Lab Day
		SM By	WHO?: Edit in Assembly		
		TA Initials	Edit in Assembly		
MATERIAL: Material <not specified> FILE NAME: shaft bracket assemb		ahrrar December 7, 2023 4:58:25 AM December 6, 2023 5:38:31 PM	SIZE B	Assignment Number Edit in Assembly	REV 1
SCALE: 2:1			Mass: 2.64	SHEET 1 OF 1	

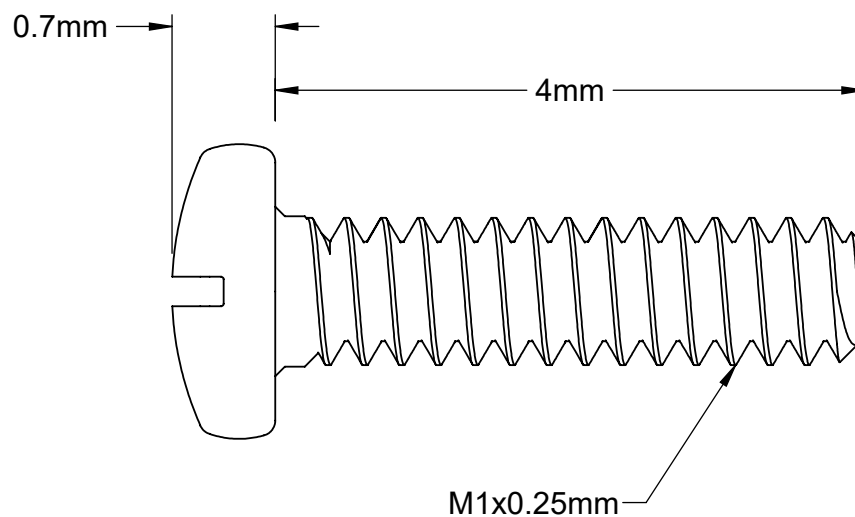
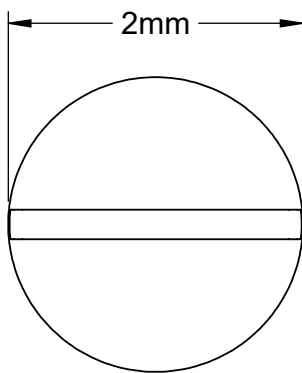
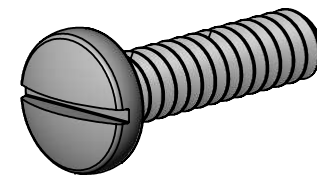


MECE 460 Instructor: Dr. Michael Lipsett Comments: Comment: Edit in SM	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: $\pm 0.5^\circ$ LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH μm 0.6 ✓ DO NOT SCALE DRAWING	DRAWN BY:		The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: SHAFT CLAMP	
		TEAM 15			Lab Day
		SM By	WHO?: Edit in SM		
		TA Initials	DSN		
MATERIAL: AISI 1045 Steel, cold drawn FILE NAME: shaft bracket		ahrrar December 7, 2023 4:57:48 AM December 6, 2023 5:30:18 PM	SIZE B	Assignment Number ALL	REV 1
SCALE: 2:1			Mass: 1.31	SHEET 1 OF 1	



SECTION B-B
SCALE 1 : 1.5

MECE 460 Instructor: DR. MICHAEL LIPSETT Comments: Comment: Edit in SM	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: $\pm 0.5^\circ$ LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH μm 0.6 <input checked="" type="checkbox"/> DO NOT SCALE DRAWING	DRAWN BY:		The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: <h1 style="text-align: center;">FLANGE</h1>
		TEAM 15		
	MATERIAL: AISI Type 316L stainless steel FILE NAME: Flange	SM By WHO?: Edit in SM	TA Initials DSN	SIZE B
		December 7, 2023 12:44:07 AM November 27, 2023 9:10:47 PM	Assignment Number ALL	REV 1



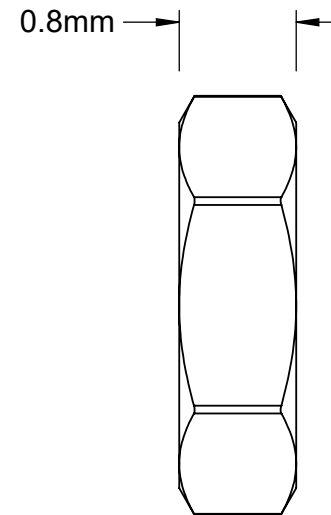
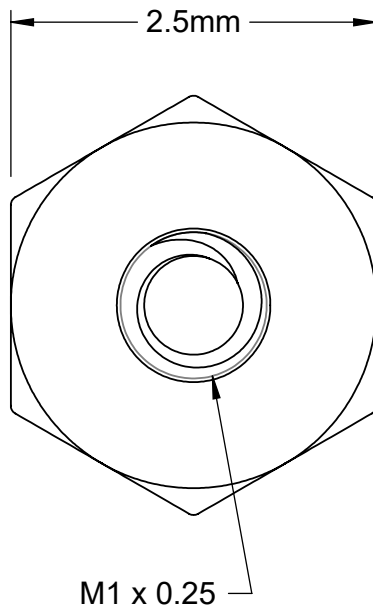
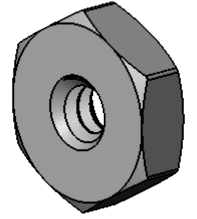
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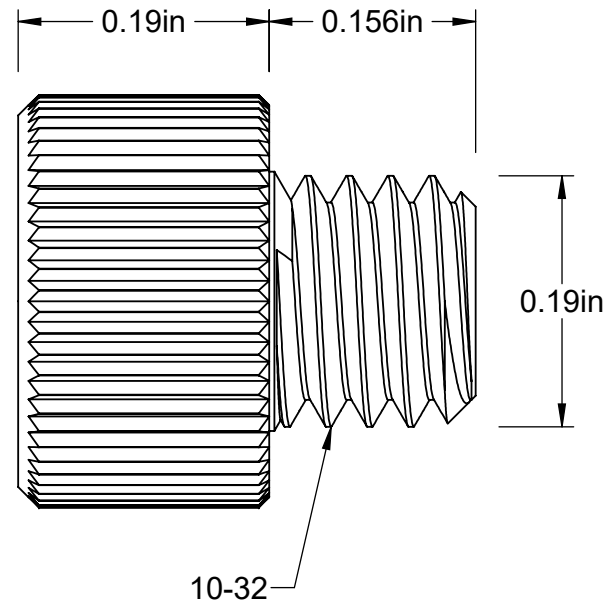
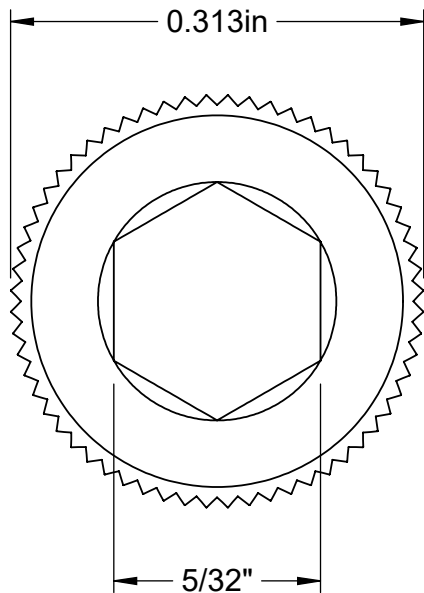
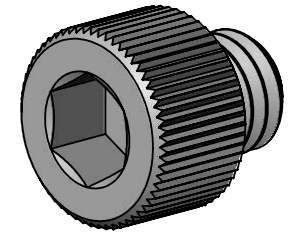
PART NUMBER **91800A056**

18-8 Stainless Steel Narrow
Cheese Head Slotted Screws



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PART NUMBER **91828A003**
18-8 Stainless
Steel Hex Nut



Thread Direction: Right Hand

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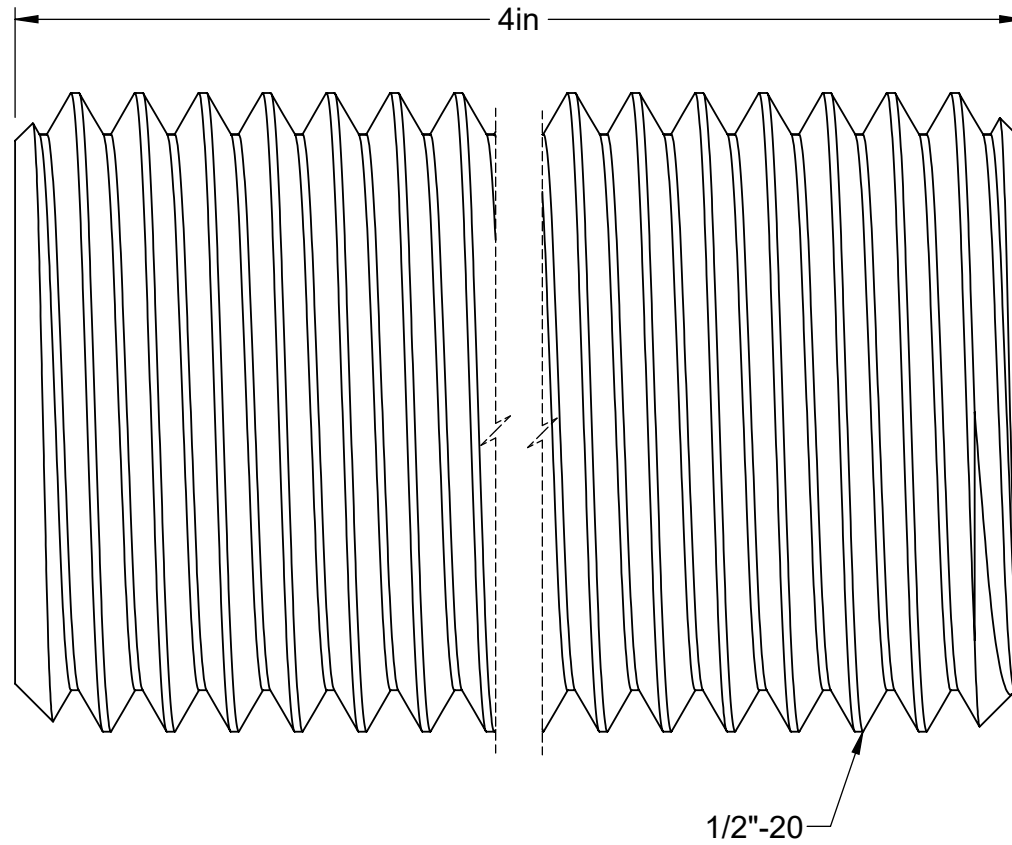
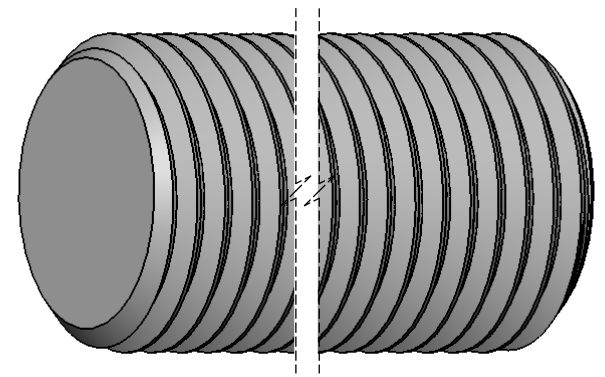
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PART
NUMBER

92196A961

18-8 Stainless Steel
Socket Head Screw



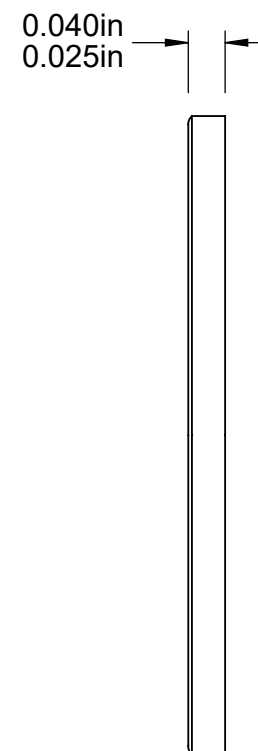
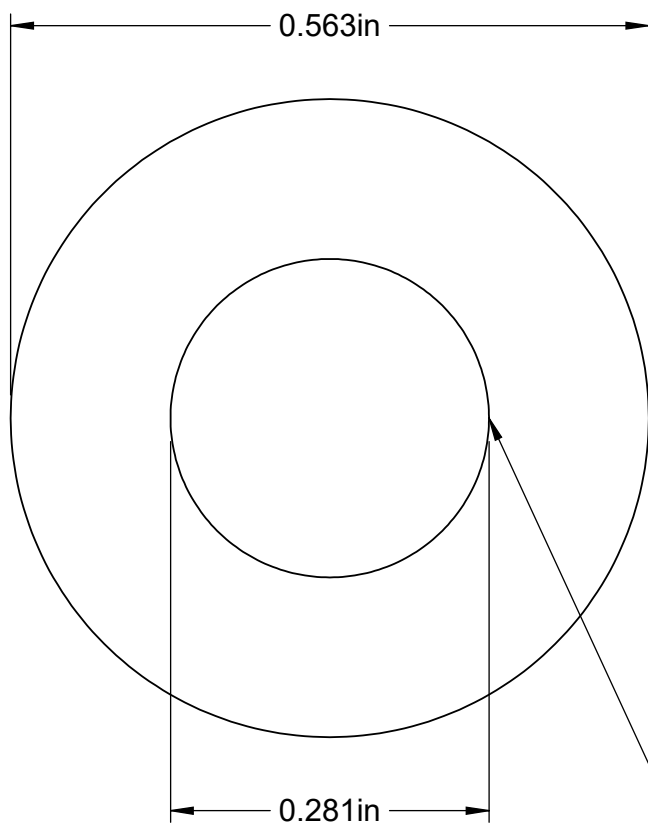
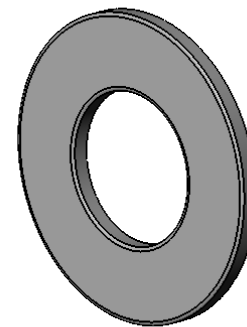
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Information in this drawing is provided for reference only.

PART NUMBER **98750A483**

Grade B7 Medium-Strength
Steel Threaded Rod



For Screw Size: No. 14

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PART
NUMBER

92141A223

18-8 Stainless
Steel Washer