Hobby Dynamometer
Final Proposal

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DISCLAIMER

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EXECUTIVE SUMMARY

Northern Arizona University participates in the annual Collegiate Wind Competition hosted by the U.S. department of energy, where teams are challenged to build an efficient small scale wind turbine. Competing teams' turbines are placed in a wind tunnel and tested in various wind conditions to determine who can harvest wind energy most efficiently along with a variety of specific challenges [1]. By competing in this event, teams can bring recognition and potential sponsorship to NAU, while helping to spark innovation and advancement to wind energy technologies.

Currently, wind competition teams at NAU do not have a reliable way to characterize the generators that are used in their turbine design. The dynamometer designed in 2014 by a previous capstone group is lacking torque acquisition, precise motor control, and an electronic load that can be precisely adjusted. Due to these limitations, it is difficult to assess the accuracy of data obtained using the current dynamometer and the data usefulness is relatively low. In designing a new dynamometer system, our team's goal is to provide future wind competition teams with the means to accurately characterize generators for use in their turbine design.

Through information gathered by interviewing our client, Mr. Willy, it was determined that torque acquisition, RPM measurement, DC drive motor, and a variable load were to be considered in the next generation dyno. After reviewing several system-level dynamometer configurations, our team determined that an electric generator dynamometer is the most practical solution to complete this project. By individual analysis conducted by the team, it was decided that with our budget of $1,000, combinations including different subsystems for the final design would need to be considered.

The design selected for development consists of a reaction torque sensor, a DC drive motor, an infrared sensor for speed measurement, the original coupler, T-slots for the base, and L brackets for mounting. The total cost of this design including hardware is approximately $850, leaving extra money for unforeseen purchases and material shipping costs.

Additionally, the client has informed us that the Collegiate Wind Competition rules may soon change, requiring our design to be flexible until the new competition rules are known. The design will be constructed in such a way that components can be interchanged to account for possible new competition rules. The team is expecting to know the scope of possible new rules during this summer

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1 BACKGROUND

1.1 Introduction

In recent times with climate change and limited fossil fuels, the development of clean renewable energy is as important as ever. While wind power only provides 1.9% of total energy in the U.S., developments in energy storage and turbine efficiency are helping to raise the competitiveness of wind energy [2].

The purpose of our capstone project is to design and build a hobby-scale dynamometer (dyno) capable of accurately measuring torque outputs and RPM of the driving motor, and wattage outputs of a wind turbine generator. The energy difference between these outputs is used to create efficiency and power curves of the motors of interest. Once completed, this dyno will help future Northern Arizona University (NAU) wind turbine teams to accurately test designs under different scenarios to create the most efficient designs possible. This dyno will build upon and replace the previous dyno completed by a capstone team of electrical engineering students in May 2016. With demand for renewable energy sources increasing, this dyno could help to design wind turbines capable of generating clean electricity for a more sustainable future.

1.2 Project Description

The main sponsor/client of this capstone project is David Willy from the mechanical engineering department of NAU. The project description stated by Mr. Willy reads "design, build, and test a hobby scale (~50-500W, ~200-2000KV rating) generator dynamometer. This dyno will be used for all future hobby scale generator characterization for designs in areas such as renewable energy conversion and energy harvesting."

1.3 Original System

The original dyno was designed and built in the 2015-2016 academic year. The dyno was successful in that it was able to measure the RPM and voltage. Improvements to the accuracy of these readings as well as the acquisition of torque must be implemented. The previous design used a Rimfire .32 AC outrunner motor with a rated output of 1480 Watts and a KV of 380 as the driving motor. KV ratings refer to the number of revolutions per minute the motor can sustain when 1 Volt is applied [1]. Figure 1 below shows the motor-generator dyno created by the previous capstone team. The far left of the picture shows the Arduino controller as well as the three-phase AC power supply, which is attached to the AC generator. The generator and motor being tested, on the right side, share a shaft that runs through a coupler to reduce misalignment of concentricity. The generator is wired to a "dumb" resistance load(not shown in the picture). The motor and generator are attached to an Aluminum T-bar frame by machined motor mounts specific to each motor. A solid metal shield covers the system while testing to reduce the risk of injury.

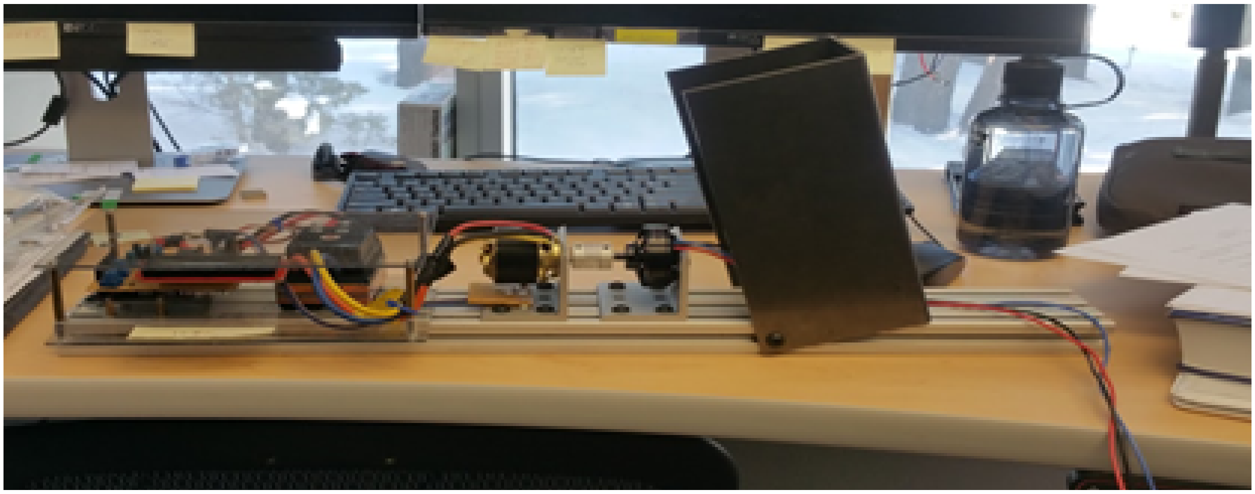


Figure 1: Previous Dyno

2 REQUIREMENTS

The team gathered the customer needs through meetings with our client, Mr. Willy, and developed the House of Quality (HoQ). For this report we were tasked with creating the customer requirements as well as weighting them. To complete this, the team reviewed previous capstone team reports to see what they needed to test. The previous dyno teams report, the wind competition teams report, and a report recommended to us by the client done by Penn State were all important to finding what the requirements for this design would be. After review the team started to create customer requirements, the first step to creating a HoQ, the team's process is detailed in this section.

2.1 Customer Requirements (CRs)

After meeting with our client, we formed a list of customer needs. Mr. Willy made it clear that his top priority was to get torque measurements from the dyno, as the current one has no way of measuring mechanical torque. To do this, our team has to get an accurate torque sensor and add it to the dyno. The current dyno measures RPM through an infrared sensor, our team would use a similar design and check our results with a tachometer. Another need that Mr. Willy expressed was getting a DC motor, for its low KV rating. These DC motors come in much larger sizes than AC so our mounting system will have to change to accompany this larger motor. Along with these needs, we identified additional quality criteria such as safety, reliability and easily accessible. Safety and reliability are important for our project because the dyno will be operated by students, and we will assure this by designing for long lifespans in the bearings and shaft. Low cost is important because we have a limited budget. With all of this knowledge we started to build the HoQ, by turning our customer's needs into requirements. The first step of the HoQ is to gather customer needs and then translate them into customer requirements(CRs) with weights. Our team completed this and created table 1 below, which shows the CRs and the corresponding weights. Our weighting system is 1,3,5 with 1 being lowest priority and 5 being highest.

Table 1: Customer Requirements and weight

Customer Requirements	Weight
1. Accurate Torque reading	5
2. Accurate RPM reading	5
3. Capable driving motor	5
4. Safety	5
5. Reliability	5
6. Adjustability for motor size	3
7. Low cost	3
8. Easily accessible	3
9. Adjustable Load	1
10. Variable power supply	1

The most important requirements of this project would be accurate torque and RPM readings, as those are essential for a dyno to operate. Having a driving motor capable of our load is also very important to the design, as the design needs to be able to handle multiple different tester motor characteristics. Safety is rated at 5 because this device will be operated by people, and any potential harm from the device must be minimized. Reliability was changed because we want our system to provide consistent accurate results. Adjustability, accessibility and cost are all weighed at 3 because they are fairly important to the design but are not the most important factors of the dyno. DC variable load and adjustable power supply are rated lowest, and although they would be helpful to wind turbine designers, our team decided to focus on key functions before worrying about power supplies. The client has stated that he has a dumb load that we can use, but our results would be more realistic with a variable load. This is because a variable load is similar to a real life load, able to fluctuate to different Wattages, a dumb load is stuck at one single wattage. After our team created the customer requirements with client approval, we created the engineering requirements for the HoQ.

2.2 Engineering Requirements (ERs)

Engineering requirements (ERs) are the measurable requirements that we can relate to the customer requirements. To create the ERs the team thought of the requirements needed to measure the CRs. Our team first created ERs to correspond with the highest rated CRs: accurate torque reading, accurate RPM reading, capable driving motor, safety, and reliability. To start we created requirements based on measurable needs that the client expressed. Speed range, torque range, voltage, and wattage were all derived from needs given by the client. The targets and tolerances were all either given by the client or derived through calculations. Other important requirements that we thought were important were Accuracy/precision, torque and speed resolution, electrical leakage, and shield thickness are in the next section with the full HoQ. Units, targets, and tolerances are all listed for the top ERs below in table 2.

Table 2: Dynamometer Engineering Requirements with Units, Targets, and Tolerances

Engineering Requirements	Units	Target	Constraint
Speed Range	RPM	7000	>6000
Accuracy/Precision	%diff	<1	<5
Torque Resolution	in-lb	0.01	<0.025
Speed Resolution	RPM	0	<5
Torque Range	in-lb	15	>10
Voltage	V	0-48	0-48
Electrical Leakage	mA	<10	<5
Shield Thickness	in	0.25	>0.125
Wattage	W	150	>100

2.3 Testing Procedures (TPs)

Testing procedures (TPs) are the methods we will use in order to measure our engineering requirements. These tests or tools will be used to take measurements off our system and through that we can determine the system's performance through several metrics. Each ER needs a TP but some can share TPs if they are measured with the same device. Each section is a different TP for our design, designated by the corresponding ERs and numbered the same as the HoQ.

<u>Speed Range; Speed Resolution (1)</u>

To ensure that the speed of the drive motor is within the needed range, a RPM sensor will be used. The sensor to be used will be the existing infrared light that is currently fixed to the current dyno. A piece of reflective tape will be fixed to the shaft of the drive motor. The sensor will measure the time between "hits" on the reflective piece of tape to calculate the rpm of the shaft.

<u>Accuracy/Precision (2)</u>

Precise and accurate torque measurements are vital to wind teams that will be operating the dyno. Three TPs will be used to ensure the validity of torque measurements from the torque sensor. The first will be recording the torque output of the drive motor using a digital torque wrench. The wrench will be fixed to the torque sensor and torque will be applied. The output of the torque wrench will be compared to that of the torque sensor. The torque wrench will need to be calibrated to ensure that its' outputs are as accurate and precise as well. The second TP for ensuring accuracy and precision of torque measurements will be using the manufacturer's tolerances. From the resolution engineering requirement, a torque sensor will be acquired that can measure torque increments down to less than 0.05 N*m. This sensor will come calibrated from the manufacturer with supporting documentation. A final way that torque measurements will be tested is through the comparison of multiple test results. Under the same testing conditions, torque readings will be compared for precision.

<u>Torque Resolution; Torque Range (3)</u>

Torque range and resolution will be tested under the same procedure. Manufacturer tolerances for the selected torque sensor will be analyzed to ensure that the sensor will produce outputs for the necessary range of torque measurement and within the necessary resolution requirement.

<u>Voltage; Wattage (4)</u>

The same testing procedure will be utilized for measuring voltage and wattage. A digital multimeter will measure the voltage and wattage into the drive motor of the dyno. This multimeter will need to be calibrated to ensure that its outputs are valid. We will access the multimeter hopefully through the thermal fluids lab.

<u>Electrical Leakage (5)</u>

Electrical leakage will be measured be a hipot tester. A hipot tester works by applying a high voltage through the object under analysis. The current that runs through the insulation is monitored by the tester. This test will ensure that the risk of electric shock under normal operating conditions is non existent.

<u>Shield Thickness; Max Diameter of Driving Motor; Max Dimension of System (6)</u>

Shield thickness, max diameter of driving motor, and max dimension of system will all be measured by a caliper. The required thickness of the shield was determined through a technical analysis of the impact force of the coupler breaking off the shaft. Max dimension of driving motor is the diameter and is determined by the bracket the motor is mounted to. Max dimension of system is the length of the T-Slots that everything is mounted too and can be adjusted to fit all parts sufficiently.

<u>Manual Emergency Shutoff (7)</u>

Manual emergency shutoff is tested by use of a switch that shorts the circuit attached to the driving motor. This is a pass or fail test, with a simple switch design.

<u>Time to Setup (8)</u>

Time to setup the system would be measured with a stopwatch and includes how long it takes to attach a tester motor to the shaft, wire the tester motor to the load, and attach the shield to the T-Slots.

<u>Max Diameter of Tester Motor; Shaft Size Accommodation (9)</u>

All of these ERs are also measured with a ruler and by attaching different tester motors and making sure they fit.

<u>Weight (10)</u>

To accomplish this TP we will use a scale and determine the overall weight of the system with all parts attached. The dyno needs to be heavy enough to not face any lift from the spinning of the shaft, which should be around 15 lbs.

2.4 Design Links (DLs)

Design Links (DLs) ensure that the design to be built will satisfy all ERs. DLs are the validation that the dyno will meet the ERs from the measurements gathered through TPs and the manufacturer specifications. Each ER has a specific DL that shows how the design will meet the targets and constraints. Each DL is numbered according to how they are presented in the HoQ.

<u>Speed Range (1)</u>

The ER of a driving motor capable of at least 6,000 rpm with a target of 7,000 rpm is met by the AmpFlow F30-150. This motor is capable of 6,900 rpm which will be ideal for testing conditions.

<u>Accuracy/Precision (2)</u>

A target of consistency between measuring techniques of 1 percent of difference between recorded values with a constraint of below 5 percent difference between recorded will be met by our design. Through TPs, values will be recorded and analyzed to ensure they are within the stated engineering requirement.

<u>Torque Resolution (3)</u>

To calculate the torque resolution needed, inputs of 2 Watts and 6,000 rpm are used in the equation in Appendix 9. A value of 0.025 in*lbs is obtained. This is how fine the units of the torque sensor must be. The Transducer Techniques RTS-200 sensor utilized in the design can measure values at .1% of full scale nonlinearity. With the sensor's range of 0 to 12.5 in*lbs, its resolution is 0.0125 in*lbs which fulfills our torque resolution requirement.

<u>Speed Resolution (4)</u>

The digital tachometer selected for our design is capable of measuring rpm on the scale of 1. This meets our ER of resolution less than 5 rpm.

<u>Torque Range (5)</u>

Transducer Techniques reports that the RTS-200 can report torque measurements between the range of 0 and 12.5 in*lbs. With an expected torque range of 0 to 9 in*lbs in the system, the torque sensor will be able to measure all torque values needed.

<u>Voltage (6)</u>

The drive motor to be used will be powered by 24 or 40 volts of direct current. A rectifier is needed to transform the AC power supply to usable DC power, meeting the engineering requirement of 24 or 40 volts DC.

<u>Electrical Leakage (7)</u>

TP 5 indicates that a hipot tester will be used to measure electrical leakage of the system. The engineering requirement of current leakage less than 10 mA indicates that the design is safe for use under normal conditions.

Shield Thickness (8)

Equation 8 presented in section 5.2.3 calculates that the minimum slow down distance needed for our design is 0.003. A polycarbonate tube with a thickness of 0.00635m will serve to protect the users of potential projectiles in the event of breakage of rotation parts.

Manaul Emergency Shutoff (9)

The dyno accomplishes this through the use of a switch that shorts the circuit applied to the driving motor which causes the entire system to lose power. The system has no brakes, so it will slowly stop spinning based on the friction in the shaft.

Wattage (10)

The variable load we currently have selected is capable of dissipating up to 300W. This is much higher than the target for our ER, which is 150W. This allows the dyno to have an adequate factor of safety even at higher loads.

Time to Setup (11)

The easy to setup T-Slots and brackets use 8 screws to attach the tester motor to the slots and then attaching to the shaft would be another few screws, depending on the motor being tested. The shield slides on and off with ease and locks in place with a few simple screws on the side of the T-Slots. This should make our design able to meet our target of under 2 minutes to set up the entire system.

Max Diameter of Tester Motor (12)

The L-bracket design of the dyno allows for various sizes of motors to be attached to the shaft with a max diameter of 4 inches allowed until interference is occurred with the T-Slots. Our target was between 0.5 and 2.5 inches which is more than accomplished by this solution.

Shaft Size Accommodation (13)

Shaft size accommodation is accomplished through the use of a coupler, allowing the shafts to be different diameters and still be compatible. The length of the shaft is accomplished by using the T-slots to adjust for whatever size is necessary.

Max Diameter of Driving Motor (14)

The driving motor is attached the same way as the tester motor, through L-brackets attached to the T-slots and because of this the max diameter of the driving motor would also be 4 inches to avoid interference with the T-slots.

Max Dimension of System (15)

This ER is dependent on the length of the motor controller, power supply, driving motor, shaft, coupler, torque transducer and tester motor. The length is easily controlled by ordering a more than long enough T-slot and then cutting it to size once the final design is assembled.

Weight (16)

By using a polycarbonate shield, as opposed to the steel being used now, the dyno will become much lighter while still maintaining a large factor of safety.

<u>Low Cost (17)</u>

The total cost of the proposed dyno is $850, which is a subtotal not including shipping costs and tax. This is more than enough room for the project budget of $1000 and allows for a little flexibility in the component choices.

2.5 House of Quality (HoQ)

Throughout section 2, we are building towards the final house of quality (HoQ). We use a 1,3,9 system for correlations from low to high. A weighted sum of all the correlations gives the absolute technical importance (ATI) for each ER. Ranking them from high to low gives the relative technical importance (RTI). The ATI and RTI show us which ERs are the most important to our design. Our highest ATI is in speed range, because it is affected by 3 of our highest rated CRs. Accuracy/precision is our second highest ATI, which makes sense because we want our design to consistently give accurate results. Torque and speed resolution are rated roughly the same, because they play a role in all the same categories. The only difference between them is that higher torque resolution would be much harder to obtain because of the prices for the more precise torque measurement systems discussed later in the report. Below is table 3, which shows the full HoQ for the hobby dynamometer system.

Table 3: Dynamometer House of Quality

House of Quality (HoQ)																				
Customer Requirement	**Weight**	**Engineering Requirement**	Speed Range	Accuracy / Precison	Torque Resolution	Speed Resolution	Torque Range	Voltage	Electrical Leakage	Shield Thickness	Manual Emergency Shutoff	Wattage	Time to setup	Max Diameter of Tester Motor	Shaft Size Accomodation	Max Diameter of Driving Motor	Max Dimension of System	Weight	Low Cost
1. Accurate torque reading	5		9	9	9		9												9
2. Accurate RPM Reading	5		9			9													
3. Capable driving motor	5		9					9				3				1			3
4. Safety	5								9	9	9								3
5. Reliability	5			9	9	9	9												3
6. Adjustability for motor size	3													3	3				
7. Easily Accessable	3												9				1	1	
8. Low Cost	3			9	3	1						1							9
9. Variable load	1			9				9				9							3
Absolute Technical Importance (ATI)			**135**	**126**	**99**	**93**	**90**	**63**	**45**	**45**	**45**	**36**	**27**	**9**	**9**	**5**	**3**	**3**	**120**
Relative Technical Importance (RTI)			**1**	**2**	**4**	**5**	**6**	**8**	**9**	**9**	**9**	**12**	**13**	**14**	**14**	**17**	**18**	**18**	**3**
Units			**RPM**	**%diff**	**N-m**	**RPM**	**N-m**	**V**	**mA**	**in**	**Y/N**	**W**	**min**	**in**	**mm**	**in**	**in**	**lb**	**$**
Target			**7000**	**<1**	**(+/-) 0.01**	**0**	**1**	**24/40**	**<10**	**0.5**	**Y**	**150**	**<2**	**0.5<W<2.5**	**4<D<8**	**<5**	**<12**	**<15**	**<900**
Constraint			**>6000**	**<5**	**<.05**	**<5**	**>0.75**	**24/40**	**<5**	**>.25**	**Y**	**>100**	**<5**	**1<W<2**	**5<D<7**	**<10**	**<36**	**<20**	**<1000**
Testing Procedure (TP#)			1	2	3	1	3	4	5	6	7	4	8	9	9	6	6	10	11
Design Link (DL#)			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

3 EXISTING DESIGNS

To gather background information, the team set up a shared document with sections dedicated to certain parts of the design including: types of dynos, torque sensors, RPM sensors, driving motor, motor controllers, etc. Each team member was tasked to insert info that he gathered into relevant sections. This helped us gather information much faster and have it all in one collective location for the group to look at.

3.1 Design Research

The purpose of a dynamometer is to test various characteristics of a motor. Based on measurements taken of inputs and outputs to and from the motor, attributes can be directly or mathematically obtained. A typical dyno will measure torque at a given rpm, then based upon the voltage and current input from an electric drive, torque and efficiency curves can be mapped along with characteristics such as dynamic and static drag. For the purposes of our project, we will need to do this process in reverse, since we are concerned with how the motors that are tested function as a generator. While any electric motor can function as both a generator, where mechanical energy is converted to electrical, or a motor, where electrical energy is converted to mechanical, the efficiency will be slightly different due to back emf (electromagnetic force). When an electric motor functions as a 'motor', rotation of the armature through the magnetic field induces a counter field that opposes the rotational motion. Functioning as a generator, the e.m.f. produced is essentially what drives the rotation, so there is no back e.m.f. This difference, although slight, could affect the characterization of a motor to be used as a generator or vice versa [3].

3.2 System Level

Dynamometers come in various forms, including motor-motor electric generator, inertial, or a variety of braking such as friction, hydraulic or fan. While our client has made it apparent that for this project, an electric generator dyno will likely be the best option, we give an overview of the types of dynamometers below. We also considered the possibility of constructing a small wind tunnel for testing turbine efficiencies, however it wouldn't be practical due to the size required. In order to produce an uniform airstream as would be experienced in the open air, the wind tunnel diameter would have to be several times larger than the turbine blade diameter because of fluid drag (no-slip) on the tunnel walls.

3.2.1 Electric Generator Motor Dyno

Motor-motor or electric generator dynos function by coupling the shaft of two motors together. The 'driving' motor is electrically powered, in turn mechanically powering the motor to be tested. The resulting electricity produced by the testee can then be measured to interpret its characteristics. In order to determine the magnitude of mechanical energy the testee is receiving, input rpm and torque must be known. This can be accomplished either through electrical input monitoring and electrical calculations with a known driving motor efficiency, or through a torque sensor (aka torque transducer) as well as a rpm measuring device. Generally, the latter method is easier and more accurate due to changes in efficiency of the driving motor as a result of torque, rpm, or temperature during extended test periods [3].

3.2.2 Inertial Dyno

Inertial dynos work on the principle of rotating a relatively heavy cylindrical mass. With the moment of inertia of the mass known, motor characteristics can be interpreted based upon the rotational acceleration and deceleration of the mass from a given electrical input. An appropriate mass is selected based upon the operating range of the motor(s) to be tested. A couple of the most important benefits of an inertial dyno is that tests can be conducted within a matter of seconds, and are very repeatable due to design simplicity [4]. Figure 2 below shows a diagram of an inertial dyno. While useful for testing electric motors as a 'motor', an inertial dyno would not work for our application, wherein the motors being tested need to be tested as a generator.

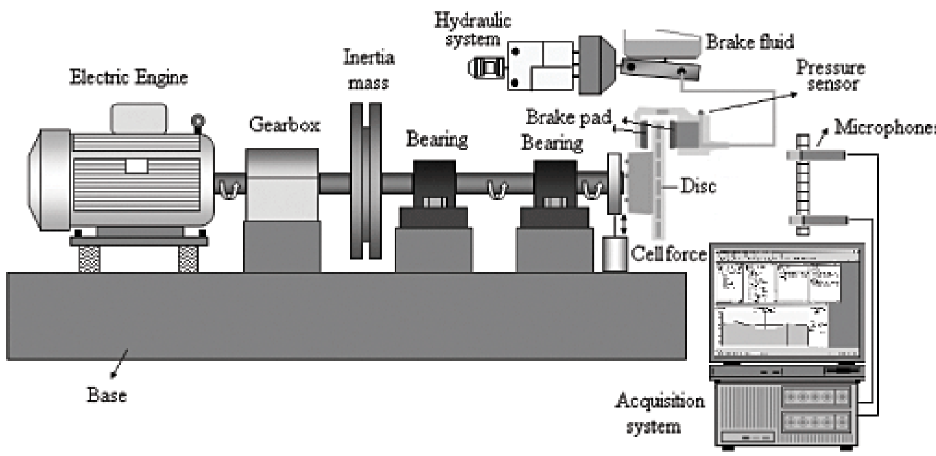


Figure 2: Inertial Dyno [4]

3.2.3 Water Brake Dyno

Water brake dynos (also known as water brake absorbers) work as a result of the rotational resistance of a pump full of water. A typical water brake dyno has one or more vaned rotors that spin between stators. The amount of load output by the dyno is controlled by the amount of water inside and the size of the inlets and outlets. When more water is added to the system, more resistance is applied to the motor being tested. The water within the dyno becomes extremely hot during use. This clean, hot water can either be discarded or cooled and recirculated back into the dyno. Manual or automatic controls are available to control RPM and load experienced by the motor being tested. A major market where water brake dynos are used is the go-kart industry. Many manufacturers and race teams prefer to use these types of dynos because of their "power capacity versus size." These dynos can be fitted directly onto the output shaft of the motor being tested for quick and easy setup. Water dynos are used for testing motors from about 10 horsepower to over 2,000 horsepower. Because the motors we will be testing will be of a much smaller scale, water brake dynos are not a feasible option for use on our project [5]. Figure 3 shows a simplified version of a water brake dyno. Similar to the inertial dyno, a water-brake dyno tests the capabilities and efficiencies of a motor as a 'motor' and would not meet the customer requirements of this project.

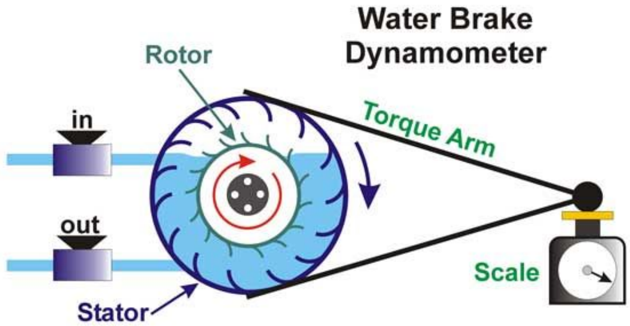


Figure 3: Water Brake Dynamometer [6]

3.3 Subsystem Level

The client requested we create an electric generator dynamometer, therefore we focused our research into this type of dyno. The main functions the client desires are a torque sensor and swapping the AC (Alternating Current) motor for a DC (Direct Current) one. These were our main two subsystems as they were most important to the design. The final subsystem describes how a variable load functions in a motor-motor dyno.

3.3.1 Functional Decomposition

In order to help our team figure out the main purposes of the dyno, we created a functional model. This helped the team to identify which subsystems would be most important to research. Starting with the human energy to mount the motors and interface with the control to set your voltage to the drive. As you input the control to the drive the electricity is applied to the driving motor which converts the electrical energy (E.E.) to mechanical energy (M.E.) in the shaft. From there we measure the RPM and torque going into the tester motor through the shaft and log that data. The shaft rotating causes the tester motor to convert that M.E. to E.E. and that is where we can measure the current and voltage outputs and from there create a power curve. All of this data is logged and will either be saved to a data file or displayed on a small screen attached to the dyno. The final conversion of energy happens with the load, to disperse the energy in the form of heat. Figure 4 below shows the complete functional model.

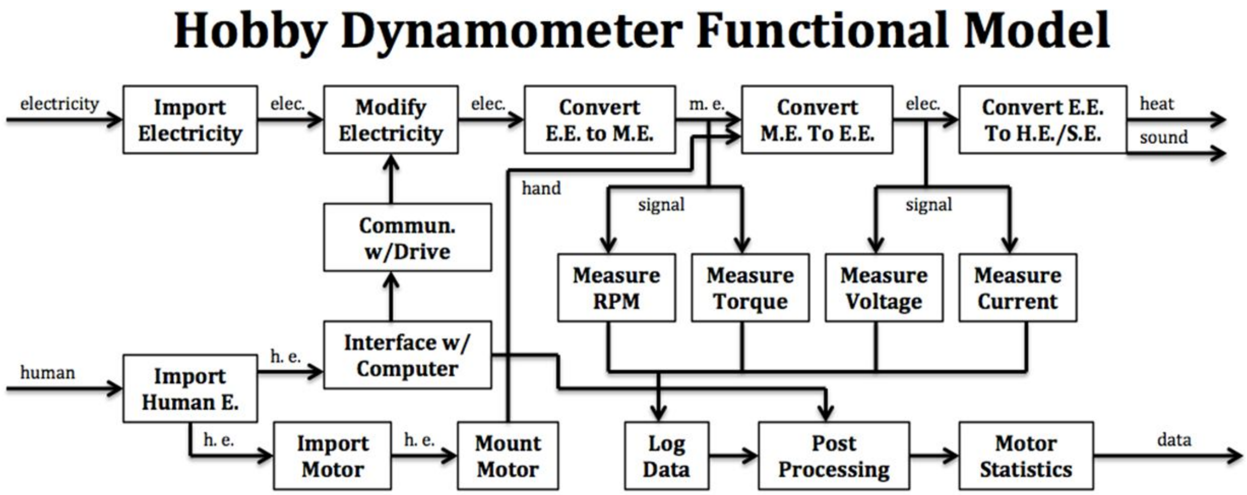


Figure 4: Dyno Functional Decomposition Model

3.3.2 Torque Sensor

There are many different types of torque transducers (sensors) , such as reaction, slip ring, and various rotary sensors. Reaction sensors measure torque through linear strain gauges oriented radially in order to measure the torsion. While they are simple and have a long working life, they are less accurate than other in-line torque sensors and have reduced dynamic response time [6]. Slip ring style sensors use metal brushes to measure torque output. While they are relatively inexpensive, they may have issues with accurate torque readings and require regular maintenance when their brushes begin to wear down over time. Maintenance of slip ring torque sensors consists of taking the sensor apart and cleaning the brushes. After maintenance the sensor must be recalibrated to ensure correct measurements [6]. There are a variety of rotary torque sensors which rely on a strain gauges to interpret shaft torques [6].

3.3.3 DC Driving Motor

It is important that the driving motor be powerful enough to handle a range of hobby motor output capabilities. Although it is likely that the maximum input to the testee motor needed will be in the range of 100-200W, our client has specified that we should look for a DC driving motor in the range of 1000-1500W to provide a generous factor of safety. This factor of safety will ensure that the driving motor can supply sufficient torque regardless of RPM. DC motors work off direct current which can be controlled through a programmable Arduino microcontroller.. Most electric motors listed for sale advertise the torque specifications rather than wattage. Calculations to approximate the max torque, shown in Appendix A, along with a technical analysis performed on the driving motor will be used to find a suitable motor.

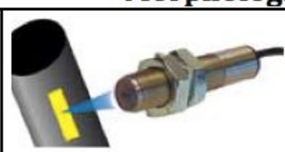
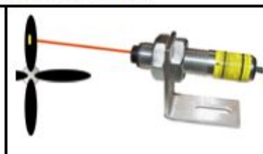
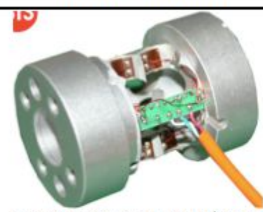
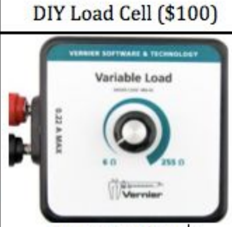
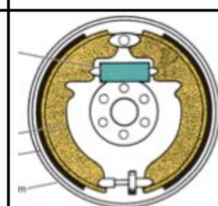
3.3.4 Load

An electrical load as used in an electric generator dyno functions as the simulation of a battery by consuming generated electrical energy and converting it to heat energy generated by resistors. A “dumb” load, as used in the current dyno setup, is just a single resistor. They are a good choice for testing motors of the same size where is is not necessary to precisely modify the load. On the other hand, commercial variable loads can change resistance values instantaneously through the use of multiple resistors, allowing for constant current/voltage operating conditions to be simulated. Variable loads can be used to test motors with different outputs under different load conditions quickly [7]. According to the competition rules, teams are free to operate their load at anything below 48V. [8] It is important that our design incorporates a commercial variable load so that future wind competition teams have the ability to match the efficiency and power curves of turbine generators to an appropriate load selection.

4 DESIGNS CONSIDERED

To develop a comparison of possible dyno configurations, we compared components corresponding to our top ranking customer requirements. The three customer requirements selected for analysis include RPM measurement, torque measurement, and conversion of electrical to heat energy. Descriptions of each considered components are given below in table 4.

Table 4: Dynamometer Morphological Matrix

Component	Morphological Matrix			
Measure RPM	 Magnetic Encoder ($150)	 Infrared ($0/$25)	 Laser ($50)	 Rotary T. Transducer
Measure Torque	 DIY Load Cell ($100)	 Reaction Transducer ($600)	 Rotary Transducer ($1500)	$P_m = \frac{2 \times \pi \times \text{Rotating Speed}}{60} \times \text{Torque}$ Rotating Speed = RPM, Torque = N-m, P_m = Mechanical Power in Watts. Calculations ($0)
Convert E.E. to heat/sound	 Variable ($500)	 Variety of Simple ($0/$100)	 DIY Variable ($200)	 Motor - Frictional ($50)

To measure RPM, magnetic encoders, infrared tachometers, laser tachometers, and rotary torque transducers were considered. Magnetic encoders measure rpm as well as angular position through electromagnetic signals. Encoders are very accurate, even possessing the ability to measure angular position, however this is not a necessary output of the dyno. The current dyno uses an infrared light that reflects off a strip on a rotating component to measure rpm. While a laser tachometer works under the same principle of the infrared light at a higher cost, it can provide higher accuracies across larger shaft-tachometer distances or in environments where IR interference may be an issue. The last option considered for measuring RPM is through output from a rotary torque transducer.

The next sub-function considered is torque measurement. Our first option for measuring torque is building our own device that would work off of a moment arm attached to the drive motor. The drive motor would be restricted to 1 degree of freedom. When the drive motor supplies torque to the shaft, a force is applied to the moment arm. Knowing the size of moment arm and force, the torque produced is calculated. This is the cheapest option, but given the fabrication skill of the team, this option is not as accurate as a sensor bought from a distinguished manufacturer. The next option is to use a reaction torque transducer. This transducer utilizes strain gauges to measure the electrical resistance experienced within the sensor. Through knowledge of the material properties of the sensor, a torque value is then outputted. The last type of torque sensor considered is the rotary torque transducer. Rotary torque transducers are accurate, but could potentially cost a majority, if not all, of our allotted budget. Rotary torque transducers are mounted in-line of the shaft being analyzed. Strain gauges mounted in the shaft measure dynamic torque and the signal is transmitted to the stationary part of the transducer. This way of measurement is considered to be the most accurate, but is the most expensive with most models out of range of our budget.

Our last considered customer requirement for design components is converting electrical energy to heat/sound. A variable load would allow for multiple load scenarios to be tested quickly with minimal modification needed. Load scenarios consist of constant voltage and constant current, constant voltage and variable current, variable voltage and constant current, and variable voltage and variable current. This would allow for wind power teams to test their designs under multiple conditions efficiently. Although a variable load would reduce testing time, multiple “dumb” loads could produce the same results for a cheaper price. “Dumb” loads are essentially resistors to dissipate electrical energy. They could be used to test generators under different load conditions, but these loads would take much more time and modification for each test compared to a variable load. A relatively cheap option for saving time for testing could be to create our own variable load. This would work in the same way a purchased variable load would, but would need to be tested to confirm the desired loads are correct. The last option for dissipating electrical energy would be to run another motor from the power output of the generator. This motor could also be attached to a frictional brake to aid in dissipation of energy from the generator.

4.1 Top Choices

After reviewing several possible combinations of components in the morphological matrix, and considering our limited budget, we came up with three top choices listed below:

1: Infrared RPM Sensor, DIY Load Cell, Variable Load $600
2: Infrared RPM Sensor, Reaction Transducer, Variable Load $1100
3: Magnetic Encoder, Reaction Transducer, DIY Variable Cell $950

The prices indicated for each option only include the rpm sensing, torque sensing, and variable load components, where the cost of other components is assumed to be equal. Differences in cost may arise from mounting requirements, and future analysis will provide us with this information for our final proposal. The relevant customer requirements are compared between these options in a decision matrix shown in Table 2 below.

Table 5: Component Combination Decision Matrix

Customer Requirement	Weight	Combination 1		Combination 2		Combination 3	
	Weight	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score
Meas. Torque	3	2	6	3	9	3	9
Meas. RPM	3	2	6	2	6	3	9
Cost	1	3	3	1	1	2	2
Adjust. Load	2	3	6	3	9	2	4
Reliability	3	2	6	3	9	2	6
Total			27		34		30

Reliability, Torque and RPM measurements were given the highest weight, because they are ranked highest in our customer requirements and are associated most closely with engineering requirements. The adjustable load was given a lower weight because of the customer requirement rank and engineering requirements correlation. Similarly, cost was given the lowest weight in addition to all of these options being close to our budget.

Combination two and three which contain the reaction transducer ranked higher in torque measurement, assuming that pre-bought component to be more accurate than one we fabricate ourselves. A future analytical analysis on torque measurement will provide us with the knowledge to decide whether the differences in accuracy or data acquisition is significant.

Combination three ranked better in RPM measurement, because magnetic encoders can achieve higher accuracies than infrared sensors. The client and customer expressed concern about the current IR sensor accuracy, which will need to be investigated. We may find that a different mounting setup can improve any issues with the IR sensor accuracy.

Scores for the adjustable load and reliability were appropriated similarly to the torque measurement scores. We assume that fabricating components ourselves will result in lower accuracies and reliability. Combination two scored the best in the decision matrix, followed by three and one. Currently, our team will pursue this combination, however our analytical analysis will provide more substance with which to compare our options. Also, because our budget is $1000, we had to seek out lower priced components.

5 DESIGN SELECTED

While the team's limited budget demands a relatively inexpensive design, component costs for mounting are also relatively small. Results from this analysis will aid the team in developing a cost effective mounting solution, determining sizing tolerances for the driving motor and torque transducer, as well as validate the installation requirements of these components. The results of several calculations will be presented to validate the structural integrity of the shaft and frame, bearing life, and safety considerations. A bill of materials (excluding the driving motor, torque transducer and variable load) for the proposed design will be presented afterwards. Finally a detailed drawing of the proposed design will follow.

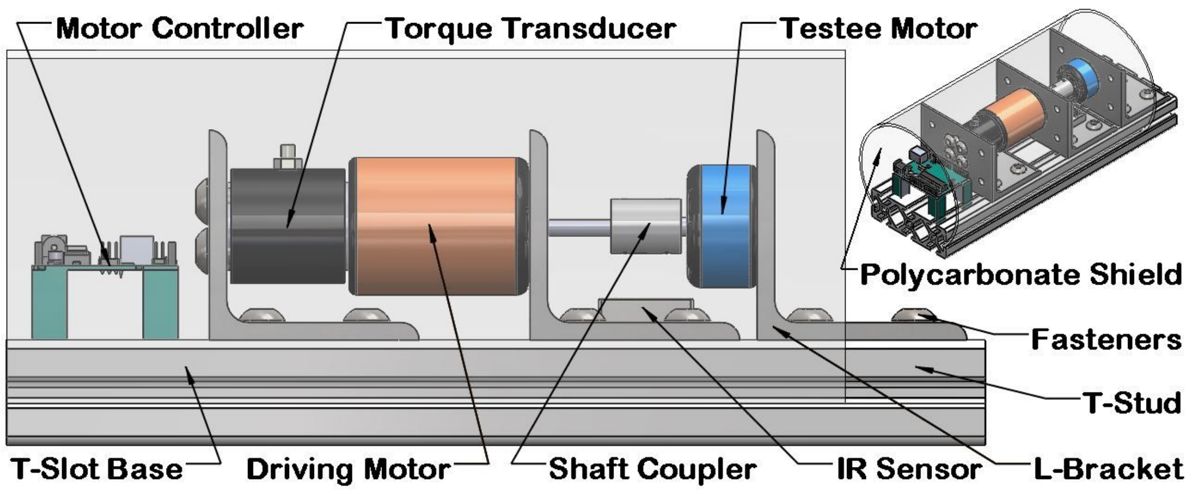


Figure 5: Selected Design

5.1 Rationale for Design Selection

The reaction transducer is fixed between the driving motor and support structure in order to measure the torsional strain resulting from the moment reaction at the support. The motor is mounted with one degree of freedom (rotation about the axle axis), constrained by the transducer. In order to maintain alignment and stability during high speeds, a bearing encased in a corner bracket will support the shaft of the driving motor. The testee motor will be secured to an additional corner bracket by use of four button-head socket screws. The T-slot frame allows for this angle bracket to transverse along the length to accommodate different shaft lengths. The polycarbonate shield will be fixed to the base by use of T-studs, allowing for it to be removed easily during setup.

Due to ease of assembly, adjustability, and affordable cost it was decided that continuing with the use of 80/20's T-Slotted framing as in the previous dynamometer would be the most appropriate option. The existing T-nuts will be replaced with self-aligning T-nuts to support axle concentricity. Design for axle concentricity is important not only for maintaining accurate torque measurements, but also to extend operating life.

5.2 Design Description

This section contains all of the technical analysis performed to determine the components needed to fulfil the customer requirements.

5.2.1 Stress Analysis

A shear and bending moment diagram was evaluated using a scale model of the design presented at the end of this report in Appendix A. Bending stress was found to be the most significant contributor to stress within the shaft. A summary of post calculations performed is detailed below. Table 6 lists the symbols and values used in the calculations. Because the reaction forces are so small, the standard L-Brackets and accompanying fasteners will be of more than sufficient strength for this project.

Table 6: Shaft Stress Variables

Symbol	Description	Value	Units
D	diameter of rod	0.007	m
A	area of rod	3.8×10^{-5}	m^2
I	area moment of inertia	1.2×10^{-10}	m^4
J	polar moment of inertia	2.4×10^{-10}	m^4
V	max shear in rod	6.5	N
T	torque in rod	100	N*cm
M	max bending moment in rod	2	N*cm
c	max y-distance from center axis	D/2	m
σ_T	torsional shear stress	0.007	MPa
σ_B	bending stress	3.8×10^{-5}	MPa
σ_s	shear stress		MPa
σ_{xy}	transverse shear stress		MPa
σ_1	maximum stress		MPa

$$\sigma_T = \frac{T*r}{J} = 14.58 \text{ MPa} \quad \text{(Eqn. 1)}$$

$$\sigma_B = \frac{M*c}{I} = 58.33 \text{ MPa} \quad \text{(Eqn. 2)}$$

$$\sigma_s = \frac{F}{A} = 171.05 \text{ kPa} \quad \text{(Eqn. 3)}$$

$$\sigma_{xy} = \frac{4*V}{3*A} = 228.07 \text{ kPa} \quad \text{(Eqn. 4)}$$

$$\sigma_1 = \frac{\sigma_B}{2} + \sqrt{\left(\frac{\sigma_B}{2}\right)^2 + (\sigma_S + \sigma_T)^2} = 61.85\text{MPa} \quad \text{(Eqn. 5)}$$

Results from stress calculations show that stress due to bending dominates the overall stress experienced by the shaft. Bending stress is at a maximum at the outside of the shaft while zero at the center, and transverse shear stress is at a maximum at the center of the shaft while zero at the outside. Because the bending stress is more than 300 times greater than transverse shear stress, maximum stress will occur at the outside of the shaft and transverse shear stress can be ignored.

The max stress was found to be 62MPa from Equation 5, which is far below the yield strength of all common steels. Because the endurance limit (equal to half the yield strength) is above the stress experienced by the shaftBecause the endurance limit is equal to half of the ultimate tensile strength (which is 300+ MPa for common steels), the client does not need to worry about the driving motor's shaft failing from variable loading fatigue [1].

5.2.2 Bearing Life Analysis

Using the reaction forces found in the stress analysis, and operating time information received from the client, an equivalent C_{10} (Load Rating) was calculated for ball bearings shown in Equation 6 below [1]. After reviewing SKF's bearing catalog, it was found that most supplied bearings with a 7mm bore meet or exceed this rating. SKF Product #618/7 was found to meet the size constraints of the L-bracket that the bearing will be mounted in, allowing for sufficient material to create a seat. Using a bearing with a sufficient load rating will ensure the bearing does not fail or contribute to inaccuracies during its lifetime.

C_{10} - manufacturer dynamic load rating (kN)
a = 2 - ball bearing coefficient
Fd = 6.5N = 0.0065kN – radial force experienced by bearing (reaction force)
$L_r = 10^6$ revolutions – manufacturer rated life
L_d - desired life

$$L_d = \frac{150hr}{yr} \text{ x } 10yr \text{ x } \frac{60min}{hr} \text{ x } \frac{6000rev}{min} = 5.4 \text{ x } 10^8 \text{ rev} \qquad \text{(Eqn. 6)}$$

$$C_{10} = F_d * \left(\frac{L_d}{L_r}\right)^{\left(\frac{1}{a}\right)} = 0.053 \text{ kN} \qquad \text{(Eqn. 7)}$$

5.2.3 Safety Considerations

In order to maintain safe operation, an emergency shutoff button will be installed in line with the power supply with easy access. A 1/4" (.00635m) thick polycarbonate shield will surround the dynamometer to prevent harm from electrical shock or the possibility of the shaft coupler being ejected from the system. Polycarbonate tubing was selected for the purpose of the safety shield due to its high impact strength and transparency for viewing purposes.

An impact force estimation was completed to verify safety during the fastest angular speed that the shaft will experience (6000 rpm). First, the slowdown distance was calculated with Equation 8 below to determine the minimum thickness required from the polycarbonate to resist failure.

ω – angular velocity (rad/s)

$$\omega = \frac{6000rev}{min} \text{ x } \frac{1min}{60sec} \text{ x } 2\pi \text{ x } \frac{2\pi rad}{rev} = \frac{630rad}{s}$$

r - shaft coupler midline radius (0.00655m)
v – impact speed (m/s)

$$v = \omega r = 4 \text{ m/s}$$

m - Approximate weight of shaft coupler (0.1 kg)
F_i – Impact strength of polycarbonate (267 N*m/m) [10]
s = slowdown distance (m)

$$F_i \, s = \frac{1}{2} mv^2 \qquad \text{(Eqn. 8)}$$

S_{min} = 0.003m

The slowdown distance solved for can be thought of as the minimum thickness required by the shield to resist fracture from impact. The factor of safety is calculated by dividing the shield thickness by the minimum thickness required to resist impact in Equation 9 below.00

$$FS = \frac{s_{shield}}{s_{min}} = 2.08 \qquad \text{(Eqn. 9)}$$

A more thorough calculation would involve completing a time-dependent 2-D stress analysis in a finite element program such as ANSYS to evaluate the actual deformation and stress during impact. Because of the generous factor of safety resulting from this basic calculation, it seems reasonable that the selected polycarbonate tube will be appropriate to maintain safety.

5.2.4 Driving Motor Considerations

There are many benefits to using an AC motor but the client stressed the importance of a DC driving motor for the dyno. AC motors typically are lower cost and smaller in size than DC drive counterparts, requiring less maintenance as there are no brushes or commutators. DC motors are easier to control using an electronic speed controller, which can be programmed into an Arduino microcontroller. This is the main reason that the DC motor is preferred for our application. The client wants something that can be easily programmed to run at constant speeds. This can be accomplished in DC motors by using either an armature voltage control or a shunt field control.

An armature voltage control allows the DC motor to output constant torque at rated armature current. When voltage increases or decreases the current adjusts in order to meet the power required for the load. This allows for constant torque operation occurs independent of speed, which is beneficial to our project as different motors will be tested. Shunt field control works by adding a rheostat in series with the shunt field circuit, which allows control of the voltage applied by adjusting the resistance of the rheostat. This in turn reduces the field flux which allows the speed of the motor to increase [9]. There are ways to control the AC driving motor as well, but require specific controllers to alternate the current applied to the motor. Table 1 below lists major advantages and disadvantages of DC vs AC for the driving motor.

Table 7: Advantages and Disadvantages of AC & DC Motors [10]

	AC	**DC**
Advantages	● Work better in high speed applications (over 2500RPM) because no brushes ● Low cost ● High power factor	● Single power conversion (AC to DC) ● High starting torque ● Constant torque over rated speed range ● Speed control over wide range
Disadvantages	● Creates back emf, which slows the motor down ● Poor starting torque ● Fails in low speed, high torque	● High maintenance ● High initial cost ● Vulnerable to dust

There are two main types of DC motors: brushed and brushless. Brushed DC motors all share similar characteristics. Armature windings, made of current carrying conductors such as copper, are connected to a commutator which is set between carbon brushes. A DC voltage is applied to the brushes which causes the armature to rotate as it is set between permanent magnets. Figure 6 below illustrates the basic DC motor layout.

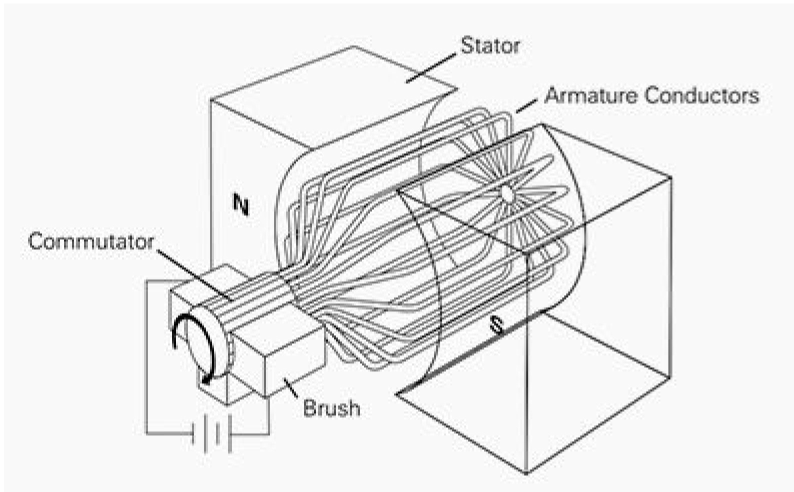


Figure 6: Basic DC Motor layout [11]

Permanent magnet motors are the most basic DC motor and function as described above. In smaller scale applications, it is most common to use permanent magnet DC motors because of availability and cost. This type of motor would be able to satisfy all requirements needed by the dyno and is easily found online. One major disadvantage of brushed motors is the replacement of the brushes over time, with life spans around 2,000-5,000 hours. Equations below estimate the required hours needed from the motor over the span of 10 years. Assumptions are 150 hours of operation per years and 3,500 hours of brush life from the brushes. This is influenced by a lot of distinct factors such as load, time, temp, RPM, and commutator speed. Estimating on the low end would still provide us will over 10 years of life, which is more than enough for what we need, though it would be nice to have a longer life. [12]

$$150\ \frac{hr}{yr} \times 10\ yr\ =\ 1,500\ hr$$

$$3,500\ hr\ \div\ 150\ \frac{hr}{yr}\ =\ 23.33\ yr$$

Brushless DC motors have multiple advantages over brushed. They have much longer lifespans and higher efficiencies because they do not have brushes. The brushless DC motor has two main parts, the magnets and the stator. The stator is made up of multiple coils connected across the diameter. When a DC current is applied to the coils it attracts the opposite pole and causes rotation. It is also possible to program an electronic controller to send a current through the other pairs of coils (B and C in Figure 7) that is the same polarity as the magnets to repel them, increasing the torque and RPM dramatically. Brushless DC motors have much higher efficiencies as well, typically around 85-90% compared to brushed motors 75-80%. The biggest disadvantage is the high initial cost. They also need a dedicated electronic controller that sends the current through specific coils to rotate the magnets. These controllers can be very expensive and hard to program. Figure 7 below shows a basic diagram of a brushless DC motor with the stators on the inside, although it is also possible to have the stators on the outside and the magnets inside.

Figure 7: Brushless DC Motor Diagram [13]

To decide which motor type would be best suited for the dyno, the customer requirements were related to each type in a decision matrix. The customer requirements that were relevant to the DC motor were torque measurement, RPM measurement, safety, maintenance (reliability), low cost, and easy control was added specifically for the motors. With weights assigned to the requirements the matrix shows that brushed DC is most suitable for the project, mainly because of its ease of control and large range of torque. The only downfall of brushed DC is the maintenance, through because the dyno sees such little use it will have a long lifespan regardless. The chosen DC motor is the AmpFlow F30-150.

Table 8: Driving Motor Decision Matrix

Driving Motor Reqs.	Weight	***AC***		***Brushed DC***		***Brushless DC***	
	Weight	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score
Torque Range	5	4	20	5	25	5	25
RPM Range	5	5	25	5	25	5	25
Safety	5	3	15	3	15	3	15
Easy Control & Measurement	3	3	9	5	15	1	3

Maintenance	3	5	15	3	9	5	15
Low Cost	3	1	3	5	15	1	3
Total			**87**		**104**		**86**

5.2.5 Torque Transducer Selection

After considering many types of torque transducers, it was determined that the best option for our design would be a reaction torque sensor. Rotary torque transducers are not a realistic option for this project because of their substantial price. Most rotary sensor prices start at around $1,000 which is our entire allocated budget. Although building our own torque measuring device would be the cheapest option, it would be very difficult to achieve the accuracy and reliability of a transducer produced by a reputable manufacturer. Reaction torque sensors are the most cost-effective option and will be easy to mount within the layout of the selected design. The torque sensor that will be pursued for purchase is the Transducer Techniques RTS-200. As discussed in section 2.4, the RTS-200 operates within the necessary engineering requirements and constraints. Sensors manufactured by Honeywell and Futek were also considered, but they were not able to compete with the RTS-200 when it came to price. The RTS-200 can be purchased for $189 which allows a substantial portion of the budget to be allocated to other subsystems. One side will be mounted and fixed to the drive motor and the other side will be mounted and fixed to a L-bracket. The torque operating on the shaft will be measured by the equal and opposite reaction torque measured by the sensor.

6 PROPOSED DESIGN

Our team plans to order all parts over summer break so that we can begin construction immediately upon the start of fall semester. One month of lead time will allow room for shipping delays or return needs. First, required fabrication processes are discussed, in 6.1 followed by final assembly processes in 6.2.

6.1 Fabrication Processes

Our team plans to complete fabrication processes within the first month of fall semester, allowing time for unforeseen adjustments and confirmation of engineering requirements. Because most of the components used in our design have been selected to fit together appropriately without modification, little fabrication is required to build our design. Several fabrication processes are detailed below.

Polycarbonate Shield

The polycarbonate tubing used as the shield will be cut longitudinally so that the inside chord of the cylinder is equal to the distance spanning the inner faces of the side t-slots of the base. Four pilot holes will be drilled (2 each side) normal to the inner angled face of the side t-slots with sufficient material surrounding the hole. Precise location of the holes is important to allow for clearance of the thumb screws through the t-slot opening as shown in Figure 8 below. Tapping the holes will be unnecessary, as metal threads will self-tap with minimal force. Once the correct locations of the holes are marked on the polycarbonate, an electric hand drill will suffice to create the holes. The customer will be able to easily slide the shield to the desired position with the thumb screws backed out slightly. Once the shield is in the desired position, tightening the screws will compress the polycarbonate material below the screws against the lower t-slot rail, securing the shield in place.

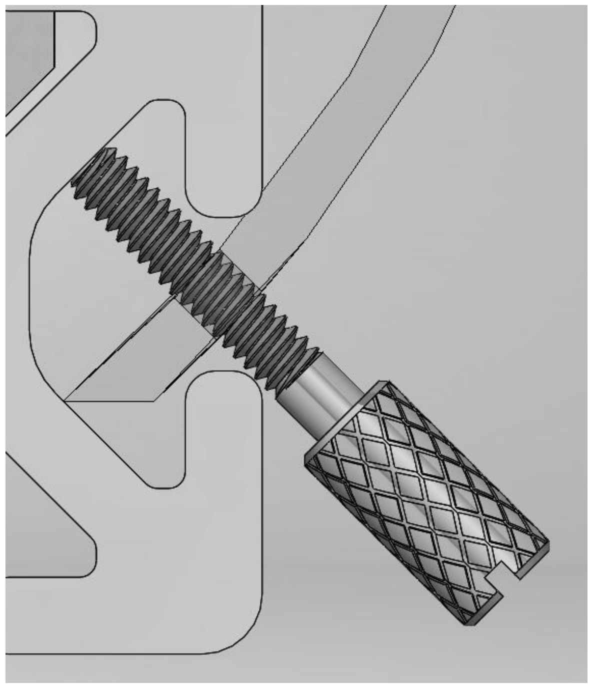


Figure 8: Shield Fastening Detail

Motor Mounting Holes

Both the reaction transducer and testee motor require through-holes to be drilled into the L-bracket supports to be mounted in the system. Precise location of these holes is of utmost importance to ensure concentricity within the system. Use of a CNC to drill these holes will allow us to achieve the tightest tolerances.

Bearing Mounting Hole

Proper fabrication of the bearing hole with respect to normality to the axle as well as location in regards to the axle axis is also important to ensure concentricity of the system. Additionally, precision of the diametral size of the hole is crucial to ensuring a proper press fit. Similar to the motor mounting holes, a CNC will be used for this process to ensure tight tolerances. A press tool will need to custom fabricated from plastic to the correct dimensions using a lathe so that force is exerted through the outer race of the bearing.

6.2 Final Assembly

Final assembly will occur after completion of fabrication processes, requiring tools that are readily available at the NAU machine shop. Dimensions and mounting points of the motor controller are unknown at this point in time. Mounting of the motor controller can be accomplished in the future with general hardware available at local stores. Details of assembly processes are explained below.

Bearing Press Fit

The bearing will be press fit into the mounting hole using a hydraulic hand press. It is important to ensure proper alignment of the press, tool and bearing during this process to prevent damage to the bearing.

Remaining Components

All other components in the system will be fastened together using hex keys to tighten the button head socket screws. The L-bracket mounts are attached to the T-slot base with self-aligning studs to support concentricity.

6.3 Bill of Materials

The bill of materials for mounting components is presented in Appendix C. Our total system cost is under budget at $860.02 with room for shipping and unforeseen costs. Product links can be found in a separate reference section and are identified in the table.

CONCLUSION

Our team is tasked with producing a dyno that will help to improve testing of Northern Arizona University's Collegiate Wind Competition teams. From improved testing processes, these teams will have the ability to be more competitive at competitions, potentially bringing revenue and sponsorships to NAU. Through meetings with our client, Mr. Willy, the team converted customer requirements into engineering requirements and constraints. A morphological matrix was created to aid in the decision making process and three potential designs were selected. Individual analysis were conducted on certain subsystems of the designs with a final design was selected. Methods of procuring necessary parts and material for construction of the dyno have been researched along with the creation of a bill of materials and a preliminary budget. With the rules of the Collegiate Wind Competition potentially changing for the next event, the design must be flexible and able to adapt to possibly different size components. The team will hold off on purchasing materials until the rules and regulations for next years competition are released. With clean energy becoming more of a priority worldwide, construction of our motor-motor dyno will help the next generation of engineers to create the most efficient designs possible.

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[16] McMaster [product description]. Avaliable: https://www.mcmaster.com/#6208k461/=17ilmdn

APPENDIX A - Calculations for approximate max torque [9]

Requirements:
0-6000rpm
DC, 1000-1500W
24/40V

E - Motor efficiency (assume 100%)
Pout - Power output from motor (Watts)
PIn - Power input to motor
τ - torque (Newton*Meters)
I - current (Amps)
V - Voltage (Volts)
ω - rad/s

Pout = Pin * E

E = Pout / Pin

$\tau * \omega = I * V * E$

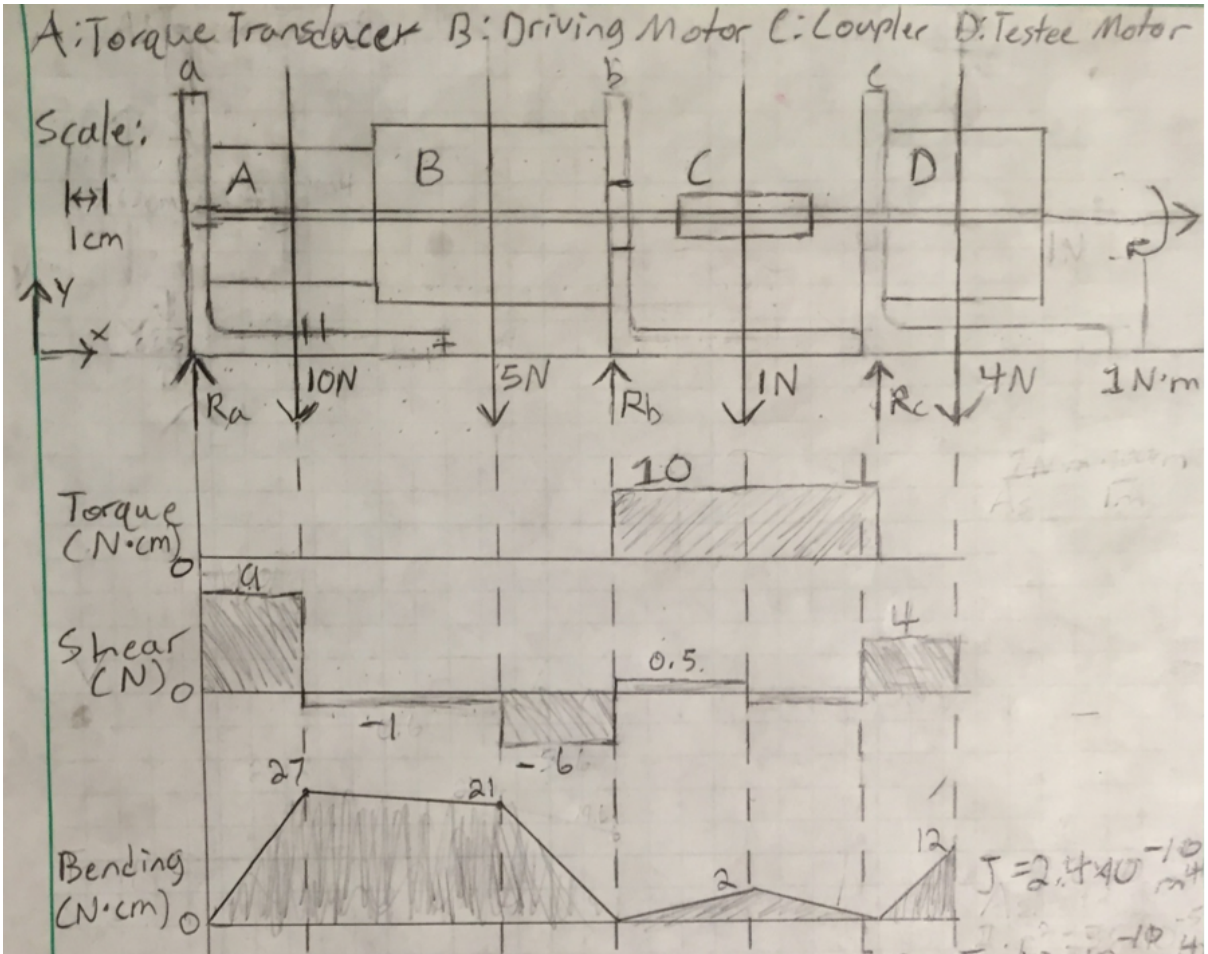
$\tau * rpm * 2\pi / 60 = I * V * E$

$\tau = (I * V * E * 60) / (rpm * 2\pi)$

$\tau = (1500W * 1 * 60)/(6000rpm * 2\pi)$

Approximate max torque = 1.19N-m ~ 1 N-m = 0.75 ft-lb = 144 oz-in = 9 in-lb

APPENDIX B - Shear and Bending Moment Diagram



Stress in shaft: $D = 0.007m$ $A = 3.8\times10^{-5} m^2$ $I = 1.2\times10^{-10} m^4$

Center of shaft: Bend = 0 $\sigma_T = 10N\cdot cm \cdot \frac{1m}{100cm} \cdot \frac{D/2}{J} = 1.48MPa$

Outer shaft: $\tau_{xy} = 0$ $\sigma_{bend\,max} = \frac{2N\cdot cm \cdot D/2}{I} \cdot \frac{1m}{100cm} = 58.33MPa$

τ_{xy} due to transverse shear negligible

$\sigma_s = 6.5N/A$ $= 171.05kPa$

$\sigma_1 = \frac{\sigma_B}{2} + \sqrt{\left(\frac{\sigma_B}{2}\right)^2 + (\sigma_s + \sigma_T)^2}$ $\tau_{max} = \frac{4\cdot 6.5N}{3\cdot A} = 228.07kPa$

★ Max Stress = 58.37MPa

$\circlearrowleft +)\ \Sigma M_a = 0 = -10N\cdot 3cm - 5N\cdot 9cm + R_{b_1}\cdot 12.5cm$ $\therefore R_{b_1} = 6N$

$+\uparrow\ \Sigma F_y = 0 = R_a + R_b - 10N - 5N$ $\therefore R_a = 9N$

$+\uparrow\ \Sigma F_y = 0 = R_{b_2} + R_{c_1} - 1N$ By Symmetry $\therefore R_{b_2} = R_{c_1} = 0.5N$

$+\uparrow\ \Sigma F_y = 0 = R_{c_2} - 4N$ $\therefore R_{c_2} = 4N$

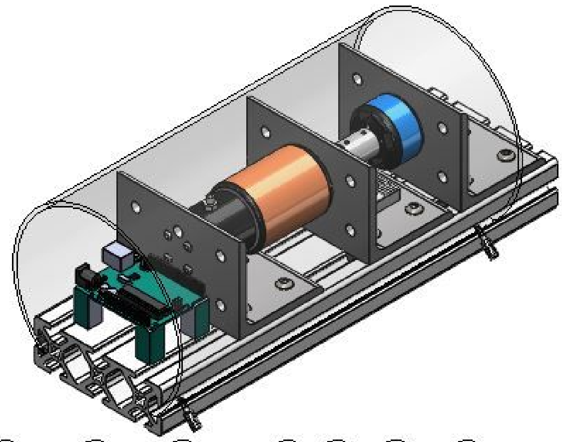
$R_b = R_{b_1} + R_{b_2} = 6.5N$ $R_c = R_{c_1} + R_{c_2} = 4.5N$

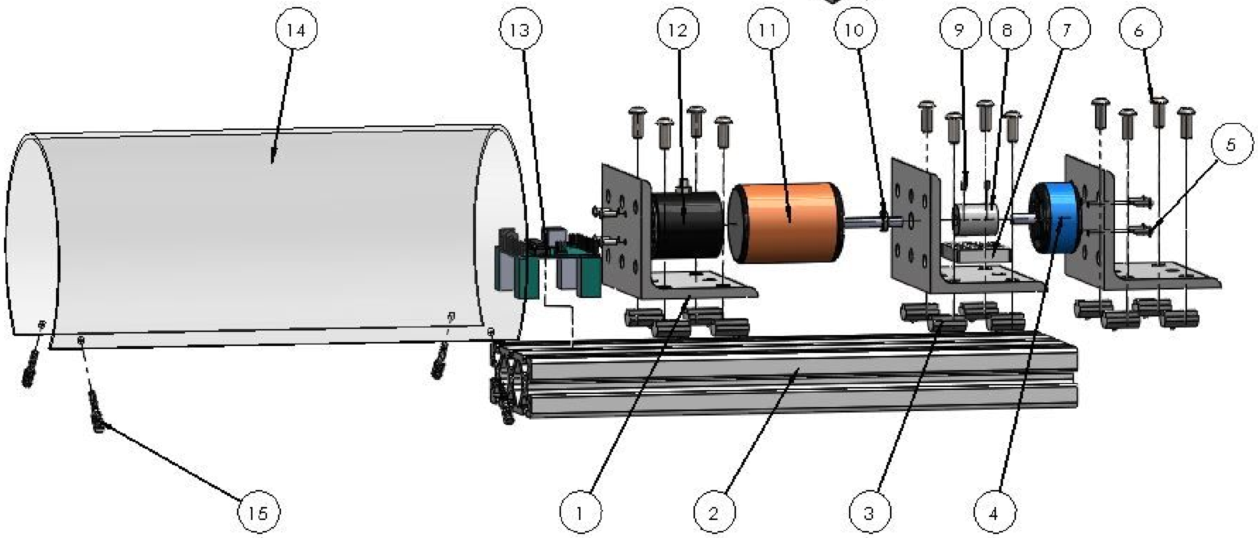
APPENDIX C - Bill of Materials

Part #	Component Description	Quantity	Total Cost	Ref.
1	15s Triple T-slot	1	$27.75	[1]
2	15s 12-hole Corner Bracket	3	$26.40	[2]
3	Self-Aligning T-nut	12	$24.00	[3]
4	6 -32 Socket Screw	4	$2.00	[4]
5	3mm Socket Screw	4	$2.00	[5]
6	¼-20 x .625 Socket Screw	12	$1.60	[6]
7	7x14x3.5mm Bearing	1	$6.98	[7]
8	6” Polycarbonate Tube	1	$36.01	[8]
9	Thumb Screws	4	$12.72	[9]
10	Emergency Shutoff	1	$8.00	[10]
11	Torque Transducer	1	$189	[11]
12	Transducer Digital Display	1	$125	[12]
13	AmpFlow F30-150 Motor	1	$209	[13]
14	IR Arduino Sensor	1	$3.56	[14]
15	300W Variable Load	1	$186	[15]
16	Shaft Coupler	1	$0 (reuse)	[16]
	Total		$860.02	

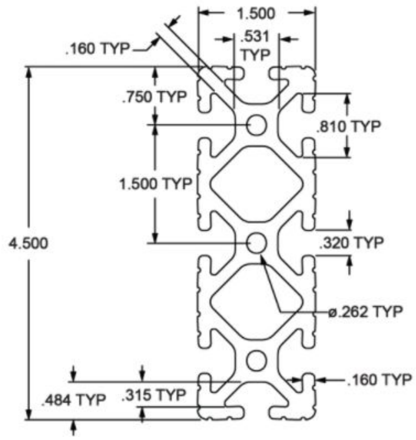
APPENDIX D - Exploded View

Bill Of Materials		
Item Number	Description	Quantity
1	12-Hole L-Bracket	3
2	T-Slot Base	1
3	Self-Aligning T-nut	12
4	Testee Motor	1
5	6-32 Socket Screw	8
6	1/4-20 Socket Screw	12
7	IR Sensor	1
8	Shaft Coupler	1
9	Set Screw	2
10	Bearing	1
11	Driving Motor	1
12	Reaction Transducer	1
13	Motor Controller	1
14	Polycarbonate Shield	1
15	Thumb Screw	4



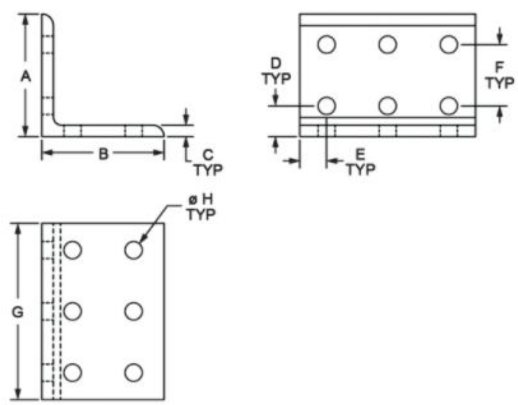


1



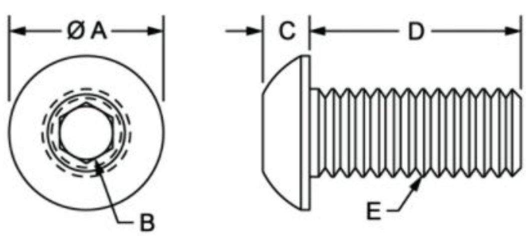
Length	per inch
Material	Aluminum
Grade	6105-T5
Finish	Anodize #204-R1
Color	Clear
Drop Lock	2°
Moment of Inertia - IX	0.710"^4
Moment of Inertia - IY	5.688"^4
Surface Area	3.002 Sq. in.
Yield Strength	35,000 psi.
Modulus of Elasticity	10,200,000 Lbs / Sq. In.
Weight lbs	0.2927 per inch

2



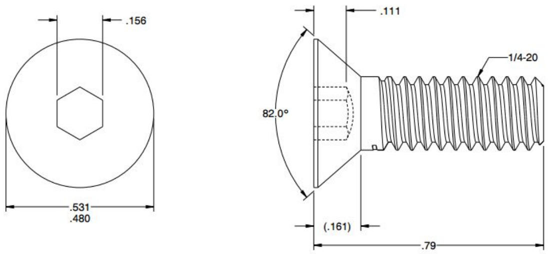
Material	Aluminum
Grade	6105-T5
Finish	Anodize
Color	Clear
A	2.000"
B	2.000"
C	.188"
D	.500"
E	.438"
F	1.000"
G	2.875"
H	.281"
Weight lbs	0.1780

3



Material	Steel
Finish	Zinc
Color	Black
A	.428"
B	5/32
C	.127"
D (Length)	.625"
E (Thread)	1/4-20
Weight lbs	0.0100

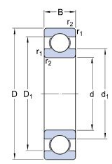
6



Item	Socket Flat Head Cap Screw	Thread Style	Fully Threaded
Screw Style	Socket Head Cap Screw	Thread Direction	Right Hand
System of Measurement	Inch	Thread Length	5/8"
Screw Head Type	Flat	Head Height	1/4"
Basic Material	Steel	Thread Dia.	1/4"
Material Grade	Alloy Steel	Vented Hole Size	Not Vented
Dia./Thread Size	1/4"-20	Head Dia.	3/8"
Length	5/8"	Temp. Range	-65 Degrees F to 300 Degrees F
Fastener Finish	Black Oxide	Rockwell Hardness	C38 to C43
Fastener Thread Type	UNC	Min. Tensile Strength	180,000 psi
Drive Type	Hex Socket	Screw Industry Standards	ASME B18.3
Drive Size	5/32"		

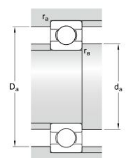
7

Dimensions



d		7	mm
D		14	mm
B		3.5	mm
d_1	≈	9	mm
D_1	≈	12	mm
$r_{1,2}$	min.	0.15	mm

Abutment dimensions



d_a	min.	7.8	mm
D_a	max.	13.2	mm
r_a	max.	0.1	mm

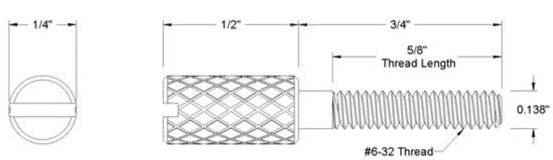
Calculation data

Basic dynamic load rating	C	0.78	kN
Basic static load rating	C_0	0.26	kN
Fatigue load limit	P_u	0.011	kN
Reference speed		100000	r/min
Limiting speed		63000	r/min
Calculation factor	k_r	0.015	
Calculation factor	f_0	7.2	

Mass

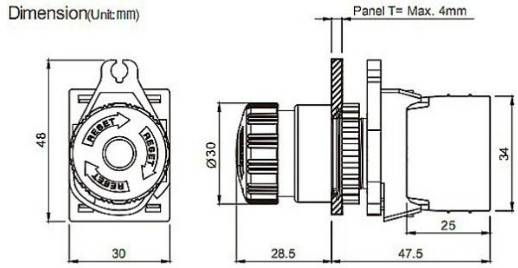
Mass bearing	0.0022	kg

9

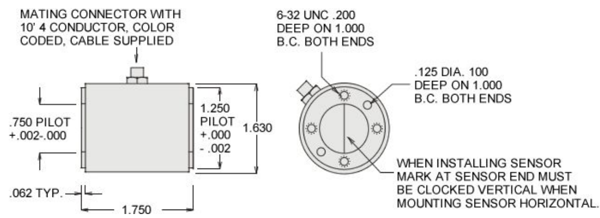


Material	18-8 Stainless Steel
Thread Size	6-32
Length	3/4"
Threading	Partially Threaded
Thread Length	5/8"
Head	
Diameter	1/4"
Height	1/2"
Tensile Strength	80,000 psi
Hardness	Rockwell B85
Screw Size Decimal Equivalent	0.138"
Thread Type	UNC
Thread Spacing	Coarse
Thread Fit	Class 2A
Thread Direction	Right Hand
Drive Style	Slotted
Head Texture	Knurled
Head Type	Thumb
Thumb Screw Head Shape	Round
Round-Head Thumb Screw Profile	Narrow
System of Measurement	Inch
RoHS	Compliant

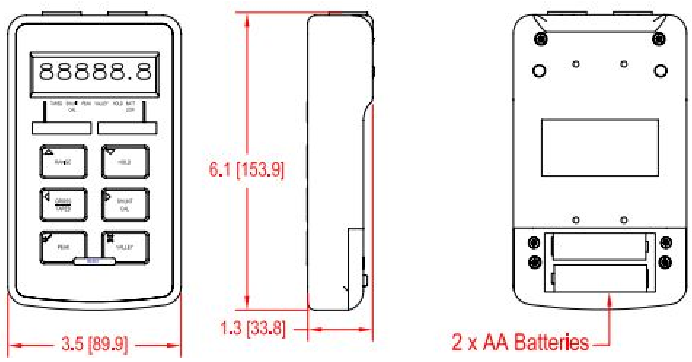
10


Dimension(Unit:mm)
Panel T= Max. 4mm
48
30
Ø30
28.5
47.5
34
25

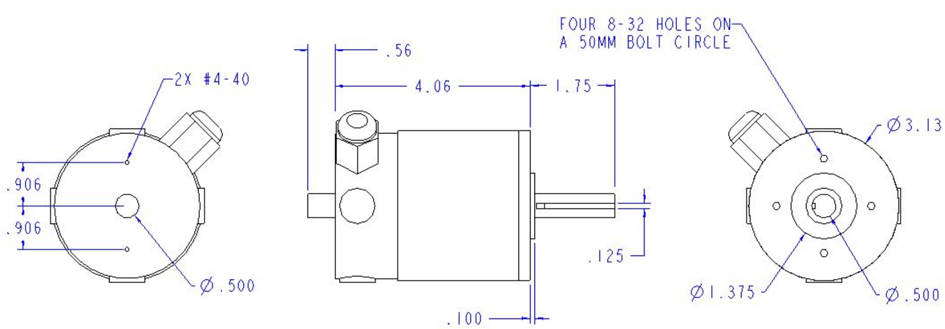
11


MATING CONNECTOR WITH
10' 4 CONDUCTOR, COLOR
CODED, CABLE SUPPLIED
6-32 UNC .200
DEEP ON 1.000
B.C. BOTH ENDS
.125 DIA. 100
DEEP ON 1.000
B.C. BOTH ENDS
.750 PILOT
+.002-.000
1.250
PILOT
+.000
-.002
1.630
WHEN INSTALLING SENSOR
MARK AT SENSOR END MUST
BE CLOCKED VERTICAL WHEN
MOUNTING SENSOR HORIZONTAL.
.062 TYP.
1.750

12


88888.8
6.1 [153.9]
3.5 [89.9]
1.3 [33.8]
2 x AA Batteries

13


FOUR 8-32 HOLES ON
A 50MM BOLT CIRCLE
.56
4.06
1.75
2X #4-40
Ø3.13
.906
.906
Ø.500
.125
Ø1.375
Ø.500
.100

15

16