NORTHERN ARIZONA UNIVERSITY

Department of Mechanical Engineering
Connor Maldonado
Sean Stone
Andrew Barton
ME476C

To: Jennifer Wade

From: Team D - Generator Dynamometer

CC: Sarah Oman

Date: 2/17/2017

Re: *Background Report*

1. Background

1.1 Introduction

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 motor acting as a small-scale 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-motor electric 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.

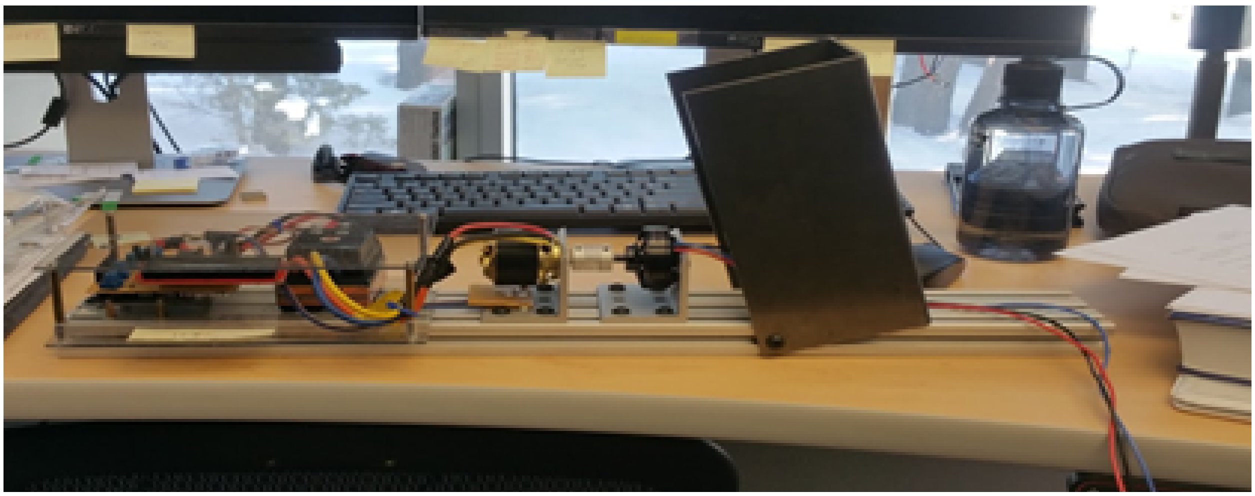


Figure 1: Previous Dyno

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

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, which is accurate enough for the purposes of the dyno, but our team would like to make sure that we are getting accurate readings for RPM for the tested motor. 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 created a few more from the information provided, such as safety, reliability and easily accessible. These needs are essential to the project because we need to be able to count on this to receive accurate measurements from the wind turbines. 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 and reliability were originally rated at 3 but after doing research we changed them to 5. Safety is important to have at 5 because this device will be operated by people, and we do not want them to be at risk of any harm. 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 the dyno 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. After our team created the customer requirements we checked them with our client, and with his approval we began creating the engineering requirements for the HoQ.

2.2 Engineering Requirements

To create the engineering requirements(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, shield thickness and a few more shown 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	Tolerance
Speed range	RPM	7000	>6000
Accuracy/Precision	%diff	<1	<5
Torque resolution	N*m	(+/-)0.01	<0.05
Speed resolution	RPM	0	<5
Torque range	N*m	1	>0.75
Voltage	V	24/40	24/40
Electrical leakage	mA	<10	<5
Shield thickness	in	0.5	>0.25
Wattage	W	150	>100

2.3 House of Quality

Throughout section 2 we are building towards the final house of quality. Now that we have all CRs, weights, and ERs we are able to relate the ERs to CRs and finish the HoQ. We use a 1,3,9 system for correlations from low to high. After taking a weighted average of all the correlations we can find 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 also attached in appendix B for a better visual.

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	Passive Emergency Shutoff	Wattage	Time to setup	Motor Width Accomodation	Motor Depth Accomodation	Shaft Size Accomodation	Max Dimension of Driving Motor	Max Dimension of System	Weight
1. Accurate torque reading	5		9	9	9		9													
2. Accurate RPM Reading	5		9			9														
3. Capable driving motor	5		9					9					3					1		
4. Safety	5								9	9	9	9								
5. Reliability	5			9	9	9	9													
6. Adjustability for motor size	3														3	3	3			
7. Easily Accessable	3													9					1	1
8. Low Cost	3			9	3	1							1							
9. Variable load	1			9				9					9							
10. Adjustable power supply	1							9					9							
Absolute Technical Importance (ATI)			**135**	**126**	**99**	**93**	**90**	**63**	**45**	**45**	**45**	**45**	**36**	**27**	**9**	**9**	**9**	**5**	**3**	**3**
Relative Technical Importance (RTI)			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**7**	**7**	**7**	**11**	**12**	**13**	**13**	**13**	**16**	**17**	**17**
Units			**RPM**	**%diff**	**N-m**	**RPM**	**N-m**	**V**	**mA**	**in**	**Y/N**	**Y/N**	**W**	**min**	**in**	**in**	**mm**	**in**	**in**	**lb**
Target			**7000**	**<1**	**(+/-) 0.01**	**0**	**1**	**24/40**	**<10**	**0.5**	**Y**	**Y**	**150W**	**<2**	**0.5<W<2.5**	**0.1<D<3**	**4<D<8**	**<5**	**<12**	**<1**
Tolerance			**>6000**	**<5**	**<.05**	**<5**	**>0.75**	**24/40**	**<5**	**>.25**	**Y**	**Y**	**>100W**	**<5**	**1<W<2**	**0.3<D<2.5**	**5<D<7**	**<10**	**<36**	**<20**

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 General Information

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 [2].

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.

3.2.2 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 [3]. 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.

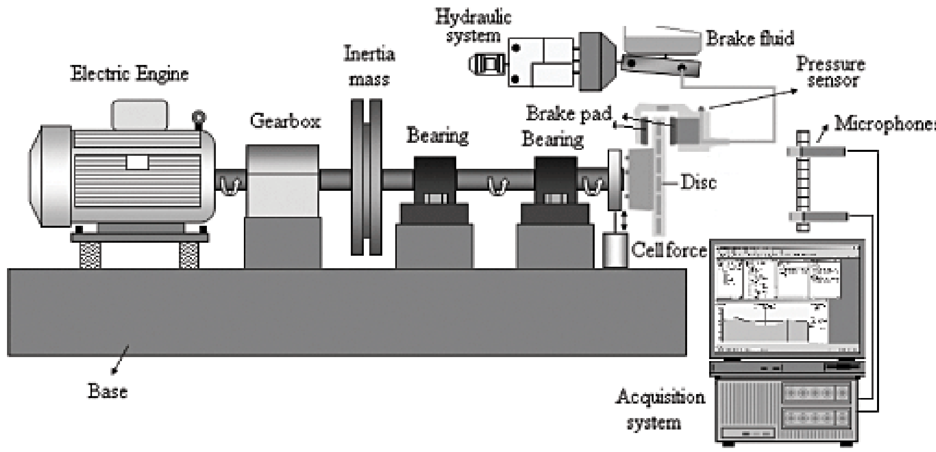


Figure 2. Components of an inertial dynamometer. [4]

3.2.3 Water Brake Dyno

Water brake dynos (also know as water brake absorbers) work 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.

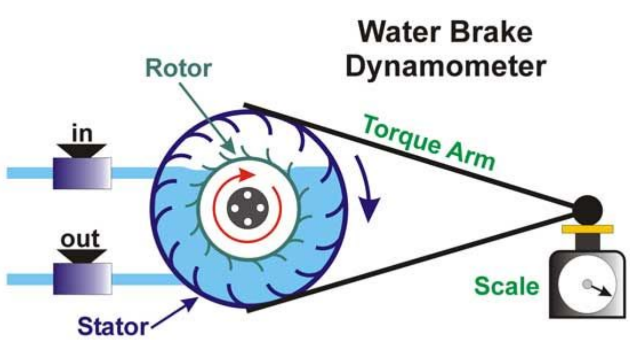


Figure 3: Water Brake Dynamometer [6]

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.

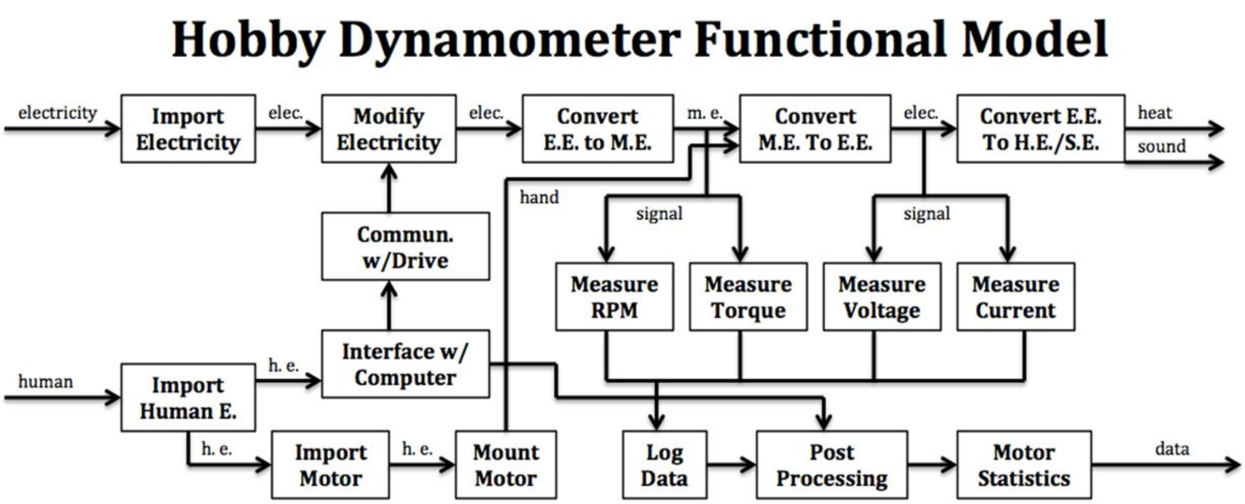


Figure 4: Dyno functional decomposition model

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. 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 maintenance. There are a variety of rotary torque sensors which rely on a strain gauge to interpret shaft torques. [7]

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. Our client has specified that we should look for a driving motor in the range of 1000-1500W if we are to construct an electric generator dyno. Also, because we are likely to use an Arduino as the motor controller for this type of dyno system, it will be easier to use a DC input motor. Most electric motors listed for sale advertise the torque specifications rather than wattage. Calculations to approximate the max torque, shown in Appendix A, will be used to find us a suitable motor.

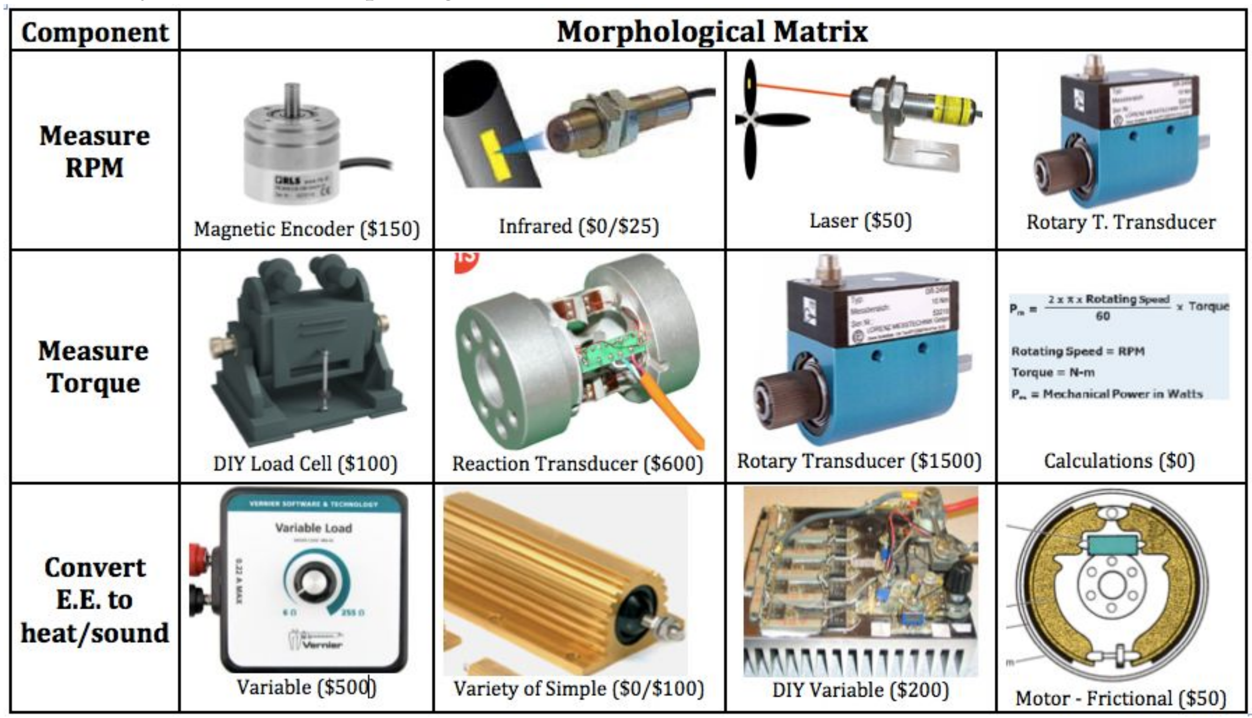
3.3.4 Load

An electrical load is a part of an electrical circuit that consumes generated electrical power. When used in a motor-motor dyno, the load absorbs the power created by the generator and releases this energy through heat. A "dumb" load is essentially a resistor that is able to dissipate all the energy. Advantages of a dumb load are that they are simple and relatively cheap to construct. They are a good choice for testing motors of the same size where is is not necessary to change the amount of load. A variable load is able to change its level of resistance instantaneously through the use of multiple resistors. Variable loads can be used to test motors with different outputs under different load conditions quickly and efficiently. A major disadvantage of variable loads is a high cost. For a hobby scale, price can range from $600-$1,500. Although variable loads provide more adaptability to the system being used, our team will have to factor in cost if it is decided to design a motor-motor dyno. [8]

4.0 Designs considered

To create possible dyno designs, the customer requirements were assigned weightings (Section 2.2). The customer requirements with the highest weightings were selected and researched to learn all possible ways to complete each necessary task. The three customer requirements that have been selected for analysis are RPM measurement, torque measurement, and how to convert electrical energy to heat or sound. Converting E.E. to heat/sound was selected over a capable driving motor because at this time further analysis and information is needed to determine the exact driving motor requirements. 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)	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 and laser measuring, and rotary torque transducers were considered. Magnetic encoders measure RPM as well as angular position through electromagnetic signals. Encoders are accurate, but this increased accuracy comes with in increased cost. Since angular position is not a necessary output of the dyno, this extra cost may not make the encoder a feasible option. The current dyno uses an infrared light reflecting off of a reflective strip to measure RPM. This system is the cheapest option, but this cheap cost comes at the expense of accuracy. A laser works under the same principle of the infrared light RPM measurement. This way of measuring is slightly more accurate at higher RPM than the infrared light. The last option considered for measuring RPM is the output from a rotary torque transducer. This transducer could output a reading directly from the rotating shaft passing through it. This is the most accurate option, but also the most expensive.

The next customer requirment considered is torque measurement. Our first option for measuring torque is building our own torque transducer. This transducer 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 strain gauge would measure the change in position. This is the cheapest option, but not the most accurate. The next option is to use a reaction torque transducer. This transducer utilizes a strain gauge to measure the change in angular position. Rotary torque transducers are accurate, but could potentially cost a majority of our allotted budget. The most accurate and most expensive option is the rotary torque transducer. Rotary torque transducers work by measuring the strain between two couplings attached to the shaft. 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 resistances to be tested quickly with minimal modification needed. This would allow for wind power teams to test designs in multiple scenarios efficiently. Although a variable load would reduce testing time, multiple resistors of different sizes 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 resistors would take time and modification for each test. A relatively cheap option for saving time for testing could be to create our own variable load. This work 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 be attached to a frictional brake to aid in dissipation of energy from the generator.

5.0 Designs Selected

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. At this point in time, 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.

5.1 Design Selection Rationale

Combination two scored the best in the decision matrix, followed by three and one. Currently, our team will pursue this design, however our analytical analysis will provide more substance with which to compare our options. Also, because our budget is $1000, we need to either seek out lower priced components, or investigate whether our budget can be slightly increased.

Conclusion

Now that our team has settled on several combinations of the most expensive components in our design, we can focus our efforts on analyzing specifics of our design. We have divided the necessary analytical analysis into three main sections which will be individually completed by the team. Andrew will analyze torque acquisition, Connor will analyze the driving motor, and Sean will analyze the mounting setup. Conducting these analyses will provide our team with the necessary information to choose a final design.

Appendix A - Calculations for approximate max torque [9]

Requirements:
0-6000rpm
DC, 1000-1500W=2HP
24/40V

E - Motor efficiency (guess 50%)
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

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

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

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

$\tau = (1500W * 0.5 * 60)/(6000rpm * 2\pi)$

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

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