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Design and Implementation of a Small Electric Motor Dynamometer for Mechanical Engineering Undergraduate Laboratory

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DESIGN AND IMPLEMENTATION OF A SMALL ELECTRIC MOTOR DYNAMOMETER
FOR MECHANICAL ENGINEERING UNDERGRADUATE LABORATORY

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering

By

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University of Arkansas
Bachelor of Science in Mechanical Engineering, 2001

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ABSTRACT

This thesis set out to design and implement a new experiment for use in the second lab of the laboratory curriculum in the Mechanical Engineering Department at the University of Arkansas in Fayetteville, AR. The second of three labs typically consists of data acquisition and the real world measurements of concepts learned in the classes at the freshman and sophomore level. This small electric motor dynamometer was designed to be a table top lab setup allowing students to familiarize themselves with forces, torques, angular velocity and the sensors used to measure those quantities, i.e. load cells and optical encoders. The data acquisition concepts learned in the first lab can be built on with this experiment. The dynamometer also allows the introduction of electric motor theory and methods of braking rotational loads.

The dynamometer was developed using SolidWorks as a design tool and the data acquisition utilizes both LabVIEW and LabJack devices found in the market today. The data collected during the development of the dynamometer shows that the measurements of torque and speed can have less than 10% error to the manufacturer supplied data.

The recommendations at the end of this thesis are provided to help the Mechanical Engineering Department with ideas on how to implement this dynamometer in the lab setting. There are also recommendations on how to develop a larger similar dynamometer for use with the Solar Boat senior design project.

This thesis is approved for recommendation to the Graduate Council.

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Most importantly I would like to thank my wife Alecia for her constant love and support throughout this process and throughout our lives together. She is mostly responsible for the closure of this work as she urged me to return and finish. I hope she always knows how thankful I am for her in my life.

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CHAPTER 1
INTRODUCTION

Project Purpose and Need

The Mechanical Engineering Department at the University of Arkansas has been working to revamp the three undergraduate labs by introducing newer technology and systems that the students will most likely come into contact with when they graduate and enter the work force. The second lab in the three lab sequence is dedicated to mechanical systems and data acquisition. The goal of this second lab is to teach the students the fundamentals of data acquisition and its role in measuring some of the most basic mechanical engineering quantities. The students are to be introduced to items that produce mechanical forces and torques. These include springs, elastomers, pneumatics, hydraulics, engines and electric motors.

Electric motors can be found everywhere in the world today. They are used in homes, vehicles, industry, and even toys. An electric motor is the most common electro-mechanical device that acts as a prime mover. There are two general types of electric motors: AC motors and DC motors. AC motors use alternating current in order to power the motor whereas DC motors utilize direct current. The types of DC motors are permanent magnet, series wound, and shunt wound motors.

Mechanical control motors are typically permanent magnet DC motors. Therefore, that is the motor that was selected to be the test motor for this dynamometer. In the past, University of Arkansas mechanical engineering students have had no exposure to electric motor theory, except for those that take the junior level elective Control Systems course.

Goals

The main goal of this experiment is to introduce electric motor theory to the students and give a hands-on experience with what electric motors are and can do. It will also introduce the concepts and hardware needed for data acquisition for a dynamometer.

Once this electric motor dynamometer experiment is in rotation in the labs, the Lab II course could become a prerequisite for the Control Systems course. This should allow the Control Systems course to be more productive for the students and the professor. This experiment will also benefit the solar boat senior design project with recommendations provided at the end of this thesis.

An additional goal of this experiment was to have several table top units using power sources readily available in the Mechanical Engineering Laboratory setting. Having several units allows the opportunity for a greater number of students to get the hands-on experience needed.

Dynamometer Theory

Dynamometers are used to measure the performance of a prime mover, such as an internal combustion engine or an electric motor. The typical measured output of a dynamometer is a torque versus speed curve, power versus speed curve, or both. Typical curves are shown below in Fig. 2.1 and Fig. 2.2.
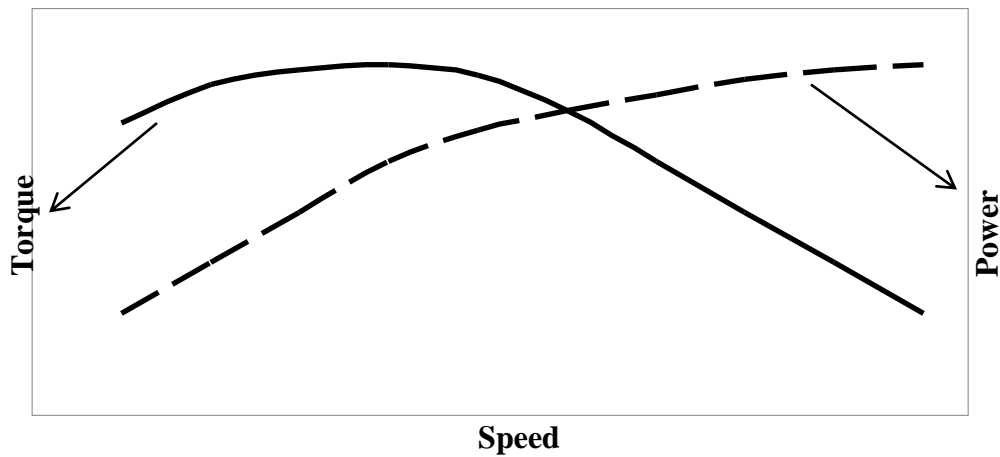
Figure 2.1. Power and torque curves for a typical internal combustion engine
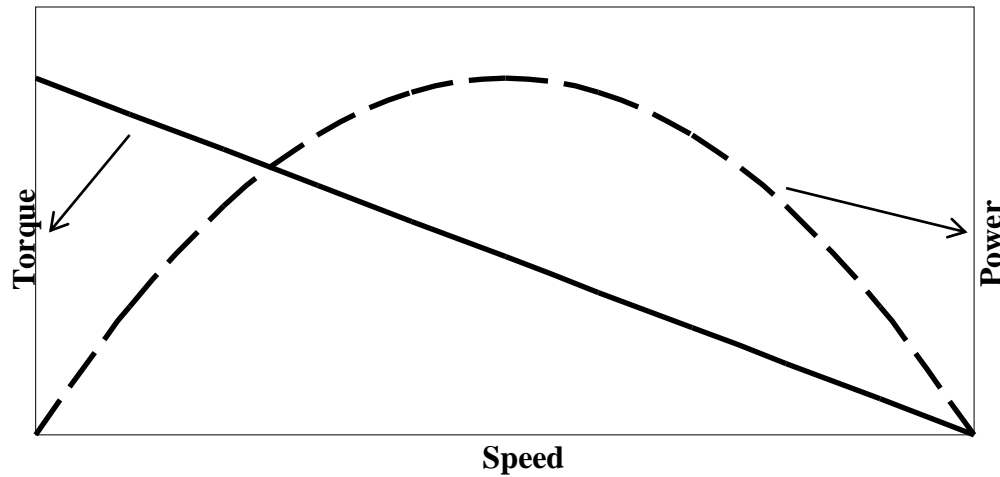
Figure 2.2. Torque curves for a DC electric motor

Dynamometers place a load on the engine or motor in order to measure the amount of power that can be produced against this load. Power is not directly measured though; it is a product of the torque and speed measurements. The most important characteristic of a dynamometer is that it measures torque and speed simultaneously. Power of a device is defined in Eq. (2.1):

$$P = T\omega \tag{2.1}$$

where

P = power

T = torque

ω = angular velocity

Another equation often used is Eq. (2.2):

$$P = T * S / 5252 \tag{2.2}$$

where

P = Power in horsepower

T = Torque in foot-pounds

S = Speed in revolutions per minute (rpm)

The constant 5252 is the speed at which the torque and speed curves cross with these particular units. This constant has units of foot-pounds times revolutions per minute divided by horsepower.

The load on the engine or motor can be applied using several different methods such as an inertial load or some type of brake. A brake can be a rotor with a caliper, a water pump, an eddy current brake, or a magnetic particle brake. All of these examples are used in

dynamometers today and each has its own pros and cons for a specific application. Most of these brakes are a rendition of the classic Prony Brake.

Gaspard Clair Francois Marie Riche De Prony was the first person to figure out how to measure the torque on a rotating shaft. This measurement has proven to be a complicated venture. Torque is easy to measure in a static situation. Imagine using a torque wrench to tighten a bolt to a specific value. This is done every day in many different industries. If, however, the torque is being measured on an object that is moving, the measurement process becomes much more difficult. De Prony, a French engineer in the early 19th century, invented the Prony Brake by using two symmetrically shaped timber beams that were clamped to the shaft of a rotating engine on one side and extended as an arm on the other. This clamp still allowed the shaft to rotate inside it. The force of this clamp on the shaft could be increased by tightening the nuts on the bolts that held the two pieces of timber together. A weight was moved along the arm until the beams were horizontal and the desired speed of the engine was obtained. This weight allowed for a torque measurement to be made since the distance could be measured and the weight was known. There have been several modifications since Prony's original brake. Anything that can slow the speed of the rotating shaft while measuring the torque can be considered a Prony brake.

The dynamometer used in this project is a Prony-brake style dynamometer. The brake is a magnetic-particle brake is shown in Fig. 2.3. Normally a magnetic-particle brake would be mounted with the housing stationary, but in this project, the shaft is pressed into bearings which allow the brake housing to rotate. As the brake slows down the motor, it will try to rotate. A small arm is attached to the housing and rests on the load cell. As the brake rotates, a force is applied down on the load cell. The load cell is offset at a specified distance allowing for a torque

measurement of the motor. A more detailed description of the particle brake can be found in the equipment section.
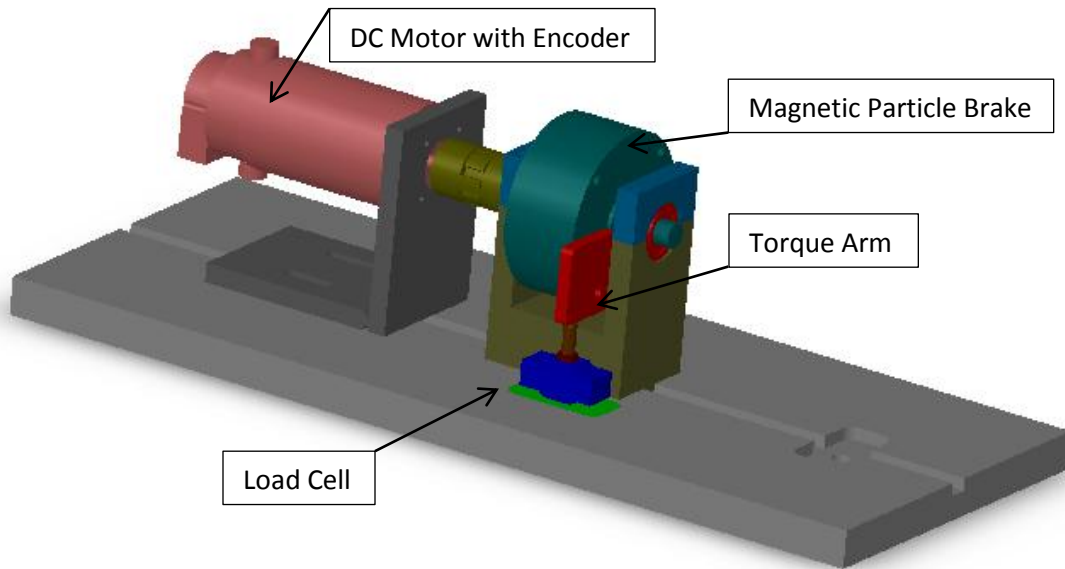
Figure 2.3. Physical dynamometer picture

Electric Motor Theory

This section reviews the theoretical concepts of electric control motors. A mechanical control motor is normally a DC permanent magnet motor. These motors have permanent magnets attached to the inner diameter of the outer housing of the motor. The casing remains stationary in normal operation of a motor and is therefore referred to as the stator. The rotor, or rotating part, of the motor has laminations attached to a shaft. These laminations have open slots in them forming pole faces around which copper wires are coiled. The number of slots in the laminations correlate to the number of poles that the motor has, usually 2, 4, 6, or 8. Wires around each pole are connected to individual plates on a commutator. Brushes are fitted into the housing and ride on these commutator plates. Fig. 2.4 is a picture of the commutator section of the motor used in this lab experiment.
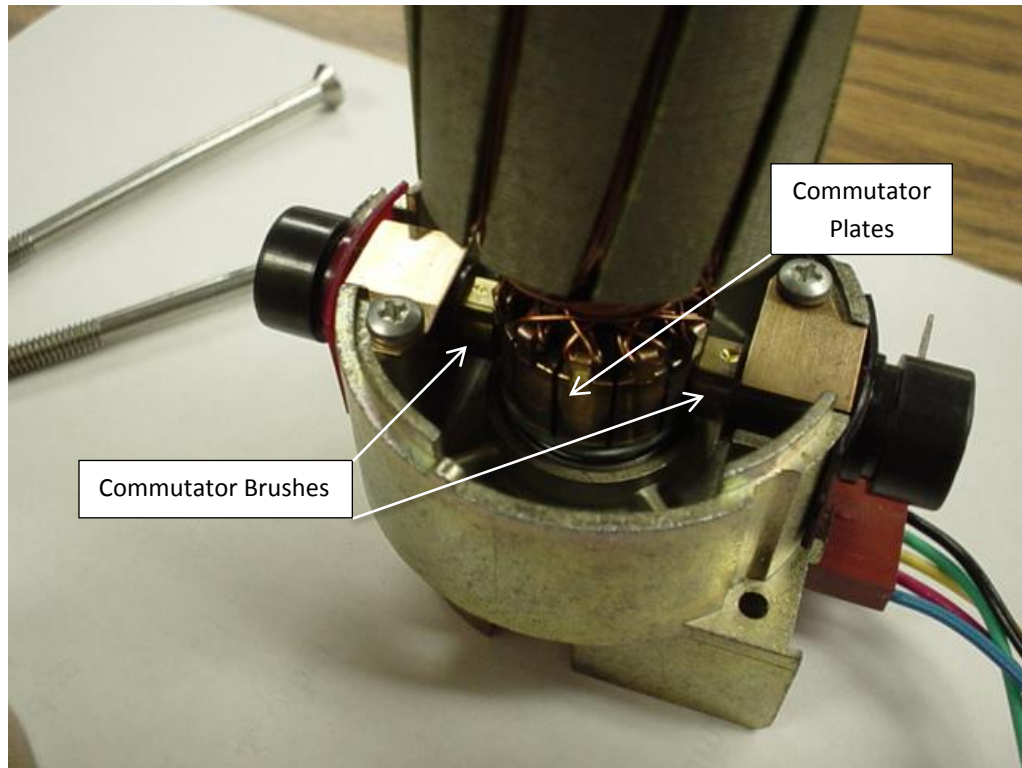
Figure 2.4. Commutator of Brushed DC Motor

Current passes through the brushes to the plates and to the sets of wires. This current movement produces a magnetic field which interacts with the field of the permanent magnet and in turn causes the rotor to rotate. As this rotation occurs, the commutator spins underneath the brushes and the power is transferred from one set of wires to another.

Figure 2.5 shows the equivalent circuit of this particular type of electric motor. There are four elements in this circuit: a voltage source (V_s), the armature resistance (R_a), the armature inductance (L_a) and an induced back voltage (e) due to the rotation of the magnetic field. This back voltage is known as the back electromotive force or emf. This voltage is proportional to the angular velocity (ω) of the rotor as shown in Eq. 2.3.

$$e = emf = v_{emf} = K_e\omega \qquad\qquad (2.3)$$

The electric emf constant, K_e, for DC electric motors has units of volts per radians per second.
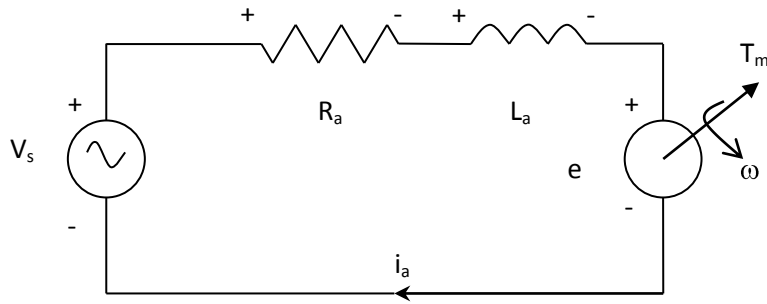
Figure 2.5. Equivalent circuit for a permanent magnet DC motor

The torque of the motor, T_m, is directly proportional to the current.

$$T_m = K_{t*}i_a \tag{2.4}$$

Eq. (2.4) is considered to be the "Law of Electric Motors". DC motors also have another

constant associated with them called the torque constant, K_t in Eq. (2.4), with units of Newton

meters per amp.

Two ordinary differential equations determine the characteristics of this particular type of

motor, one of which corresponds to the electrical circuit and another which is derived from the

summation of torques on the shaft.   Eq. (2.5) is obtained by using Kirchoff's Voltage Loop

(KVL) principle on the circuit in Fig. (2.4). Eq. (2.5) is time dependent due to the voltage of the

inductor.

$$R_a i_a + L*di_a/dt + K_e\omega - v_s = 0 \tag{2.5}$$

Eq. (2.6) shows the summation of torques on the shaft of the motor. The net torque is the torque

that is produced electrically, T_m, minus the drag torque, T_{drag}.

$$T_{net} = \sum T = T_m - T_{drag} \tag{2.6}$$

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This net torque is equal to the rotational inertia of the motor, J, multiplied by the angular acceleration, α. The drag torque is the damping coefficient, β, multiplied by the angular velocity of the motor. Knowing these relationships and the torque from Eq. (2.4), Eq. (2.6) becomes Eq. (2.7).

$$T_{net} = J\alpha = K_t i_a - \beta\omega \tag{2.7}$$

Eq. (2.7) is a differential equation as well because the torque due to inertia is proportional to the acceleration of the rotor. Eq. (2.8) is Eq. (2.7) rearranged into the traditional engineering form.

$$J\alpha + \beta\omega - K_t i_a = 0 \tag{2.8}$$

The characteristics of the motor that are of interest in this project are the steady state characteristics. In a steady state system, Eq. (2.5) becomes:

$$i_a^{SS} = v_s/R_a - (K_e/Ra)\,\omega \tag{2.9}$$

The inductance of the armature is irrelevant in a steady state application. With this steady state current, the steady state torque can be found.

$$T_m^{SS} = K_t i_a^{SS} = K_t v_s/R_a - (K_t K_e/R_a)\,\omega \tag{2.10}$$

The torque of the motor can now be shown as a linear graph with respect to the speed of the motor, as in Fig. 2.6. This is the torque versus speed curve that will be measured in this project.
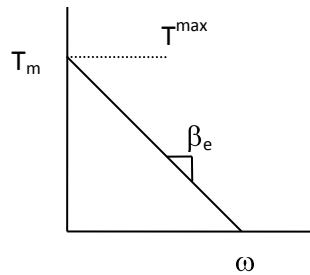
Figure 2.6. Torque versus speed curve for a permanent magnet motor

The maximum torque of the motor occurs (T^{max} in Fig. 2.6) when the rotor is not rotating and is referred to as the "stall torque". The maximum speed of the motor occurs at zero torque and is labeled as the "no load speed". The slope of this line is the rotary viscous damping, β_e, of the motor.

$$\beta_e = K_t K_e / R_a \qquad (2.11)$$

This damping is electrical in nature and is purely due to the inherent emf induced in the armature coil as the electromagnetic field rotates.

Data Acquisition Overview

Introduction

Data acquisition is the automatic collection of data from sensors, instruments and devices with the use of a computer. This data comes from equipment in a factory, in a laboratory, or in the field and is converted into electronic signals by the sensors that the computer can interpret. A sensor is a device that "senses" a mechanical property (force, torque, temperature, pressure, etc.) and converts this quantity into an electronic signal (usually a very small voltage signal). After the signal leaves the sensor, it passes through any hardware signal conditioning (amplifiers, filters, etc.) that might be present. After this signal conditioning if any, the signal enters the

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DAQ (Data AcQuisition) system through a screw terminal block which can also be referred to as the junction box or signal connector block (SCB), as shown in Fig. 2.7.
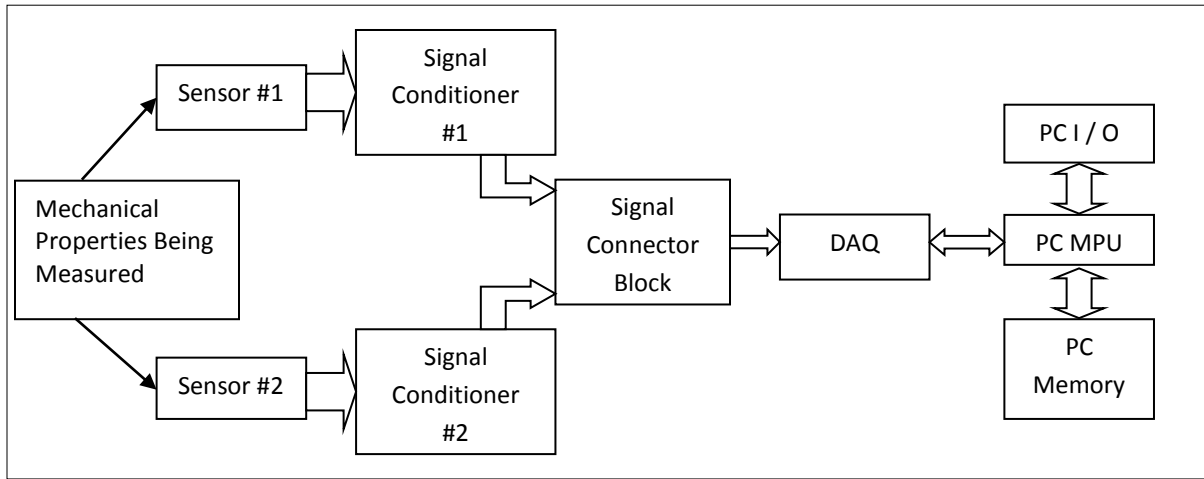
Figure 2.7. Data acquisition system

After the SCB, the signal enters the actual DAQ card in the back plane of the computer. This card is a printed circuit board that plugs into the mother board of a computer just like extra memory or modem. Figure 2.8 shows the path of the signal inside the DAQ card where it is digitized into data for the computer to interpret.
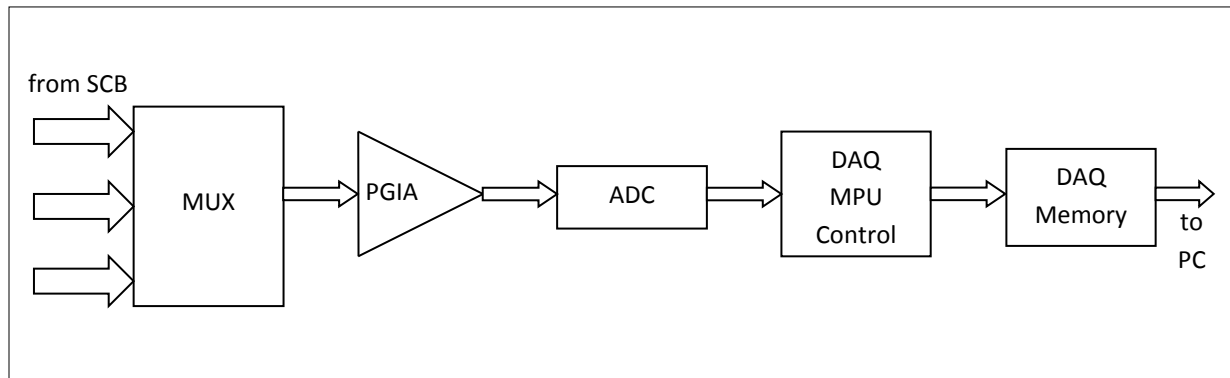
Figure 2.8. Signal path through DAQ

DAQ Concepts

Once the signals pass through the signal connector block, they pass into the multiplexer. The signal path becomes known as a channel once the signal enters the SCB. In order for the

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DAQ card to complete the circuit, the ground or return must be determined. The input mode is how the DAQ card handles this "ground reference". There are three different channel modes.

- Non-Referenced Single-Ended

- Referenced Single-Ended

- Differential

These different modes allow for different applications and sensors. Non-referenced single-ended refers to a system where the sensors are grounded, but they do not share the same ground as the DAQ board. For instance, when taking measurements on an automobile, the sensors would be grounded to the vehicle, but this ground is only a chassis ground, it isn't "earth" ground. Referenced single-ended (or ground referenced, as it is commonly known) is designed for a system that shares the same ground as the DAQ board. The problem that occurs when using ground-referenced signals is that sometimes the ground plugs vary slight in their voltages, not necessarily being 0 volts. When these ground voltages vary, a ground loop is produced. Current flows from the slightly higher voltage to the lower. This potential could be as small as 1 millivolt, so unless the grounds can be verified to be exact then ground referenced channels should be avoided because when ground loops occur in produces noise in the system, which can cause major headaches with data acquisition.

To avoid ground loops, differential channels should be used. Differential channels do not reference ground at all and are considered floating. The DAQ board takes the difference between the two floating inputs instead of taking the difference between the positive voltage and zero as with ground-referenced channels. Since the inputs are floating, ground loop interference is eliminated. A difference between the two inputs is calculated negating any noise that is introduced from any source as long as both wires travel through the same environment.

When a channel is set to the differential mode, bias resistors need to be installed in the SCB, shown in Fig. 2.9.
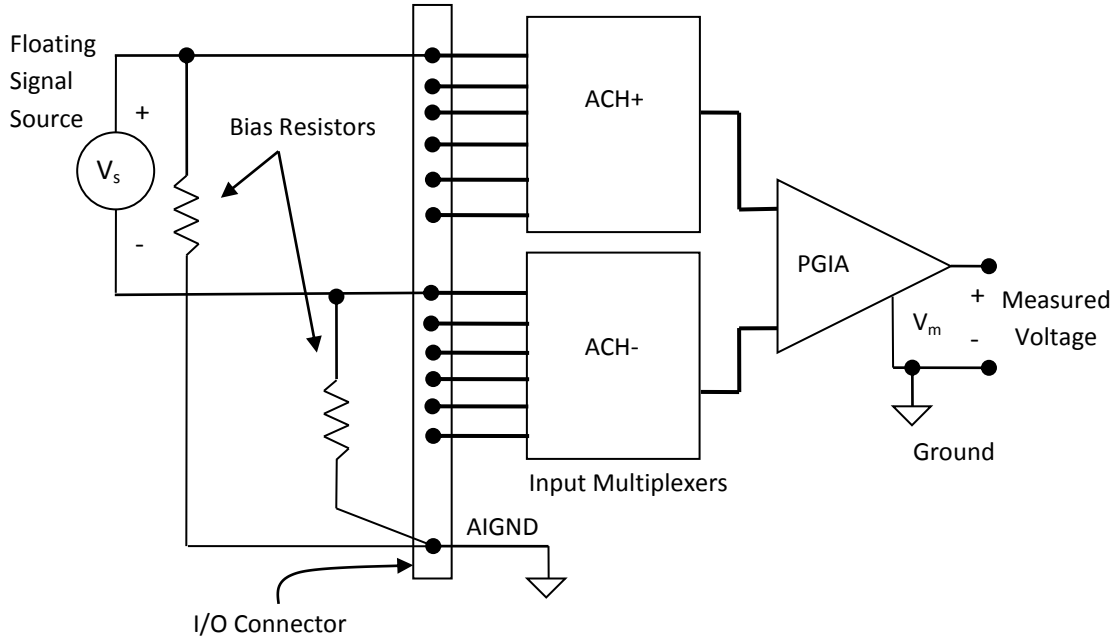
Figure 2.9. Bias resistors for differential mode

Bias resistors are needed with any differential measuring design as the resistors dissipate a charge injection that the DAQ board induces. If these resistors are not present, then the signal tends to drift to the maximum or minimum value of the channel.

The signals pass through the multiplexer (MUX). A multiplexer takes several signals from several different wires and transmits them through a single wire to the amplifier. Once the signals pass through the MUX, they reach the Programmable Gain Instrument Amplifier (PGIA). This device can change its gain to allow small voltage signals to be seen at a high resolution.

After the signal passes through the PGIA, it is digitized by the Analog to Digital Converter (ADC). The ADC has typical resolutions of 12 bit or 16 bit. 16-bit resolution is accurate to one part in 2^{16} or 1 in 65,536, which is about 0.0015%. Once this signal is digitized, it goes into the DAQ microprocessor, the cards memory and then to the PC for the user to see.

CHAPTER 3
EQUIPMENT

Electric Motor

The motor specified for this project is a permanent magnet DC motor; this type of motor normally serves as a mechanical control motor. The DC motor chosen has a high power rating at the 12 volts readily available in the lab. The table-top requirement also helped determine the size. The power rating is approximately ¾ of a horsepower. The motor chosen has an optical encoder that is built in, proving to be most cost efficient. Also the manufacturer provides more information on the performance of the motor than most other manufacturers. This information is beneficial because results can be compared with the manufacturers supplied data. After the motor was selected, the brake and load cell could be specified knowing the performance parameters of the motor. The required bearings were then selected to match the dimensions of the magnetic particle brake.

The motor selected is a Pittman electric motor, model number 14204S004. As stated above, Pittman provides the motor constants in its literature as well as the resistance and inductance of the coil. Table 3.1 shows a list of the pertinent motor specifications. The data sheet from Pittman can be found in the Appendix.

Table 3.1 DC Motor Specifications

Pittman Model Number	14204S004
Supply Voltage	12.0 Volts
Continuous Torque	26 ounce inches (0.1836 Newton meters)
Peak Torque	190 ounce inches (1.3414 Newton meters)
Torque Constant (K_t)	4.33 ounce inches/Amp (0.031 Newton meter per Amp)
Voltage Constant (K_e)	3.20 Volts per krpm (0.031 volts per radian per second)
Terminal Resistance (R_a)	0.27 Ohms
Inductance (L_a)	0.40 milli-Henry's
Max. Winding Temperature	155 °Celsius
Dimensions	2 1/8" diameter by 5" long
Weight	2.3 pounds
Encoder	500 counts per revolution

Optical Encoder

Optical shaft encoders are sensors that provide a logical square wave signal that is relative to the mechanical rotation. In this respect, an optical encoder can be considered as an analog to digital converter. The two types of encoders that are widely used in automation and industry today are incremental encoders and absolute encoders. Incremental and absolute encoders differ in their design and their internal electronics. Incremental encoders are most common due to lower cost and simpler application. An incremental encoder with 500 CPR is part of the electric motor used in this experiment.

An incremental encoder consists of a light source, a disc mounted on a shaft, a stationary photocell, and processing electronics to covert the signal from the photocell to a logical output. The rotating disc has concentric holes in it that allow light to pass through onto the photocell. The number of holes in the disc varies depending on the resolution. The resolution has units of counts per revolution. Most incremental encoders are quadrature encoders. The quadrature name comes from having two sets of concentric holes on the disc that are offset from each other. The second set of holes provides another channel; the channels are usually labeled Channel A and Channel B. The offset holes produce two signals that are 90° out of phase with each other.

This allows for the direction of rotation to be determined. Normally, with clockwise rotation, Channel A leads Channel B. Also, there is another channel, called the index, which provides just one pulse per revolution. This single pulse is typically used to mark a specific location in the rotation known as the home position.

The logical signal provided by an incremental encoder is a square wave as shown in Fig. 3.1. Figure 3.1 shows the time phase difference between the pulses of the different channels. In Fig. 3.1, the channels are offset vertically to illustrate this time difference. There is no voltage difference between the three channels. When the photocell receives light through a hole, the resulting signal is a high or a logical one. When the light is blocked, a low or a logical zero is produced. By counting the pulses of the square wave, the shaft position, velocity and/or acceleration can be determined.
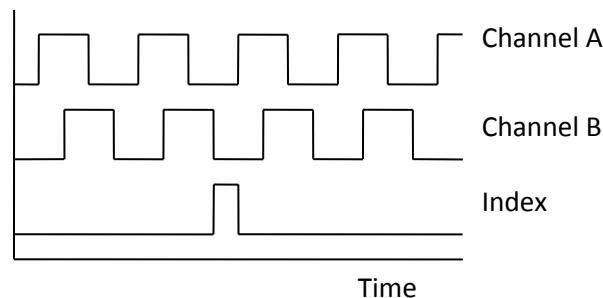
Figure 3.1. Square wave output of a quadrature optical encoder

The encoder being used for this project is a 500 CPR quadrature encoder that is part of the motor manufactured by Pittman. This encoder has five leads for connection: Channel A, Channel B, Index, Ground, and V_{cc}. The designation for the 5-volt excitation of the encoder is V_{cc}. Figure 3.2 is a picture of the Pittman encoder.

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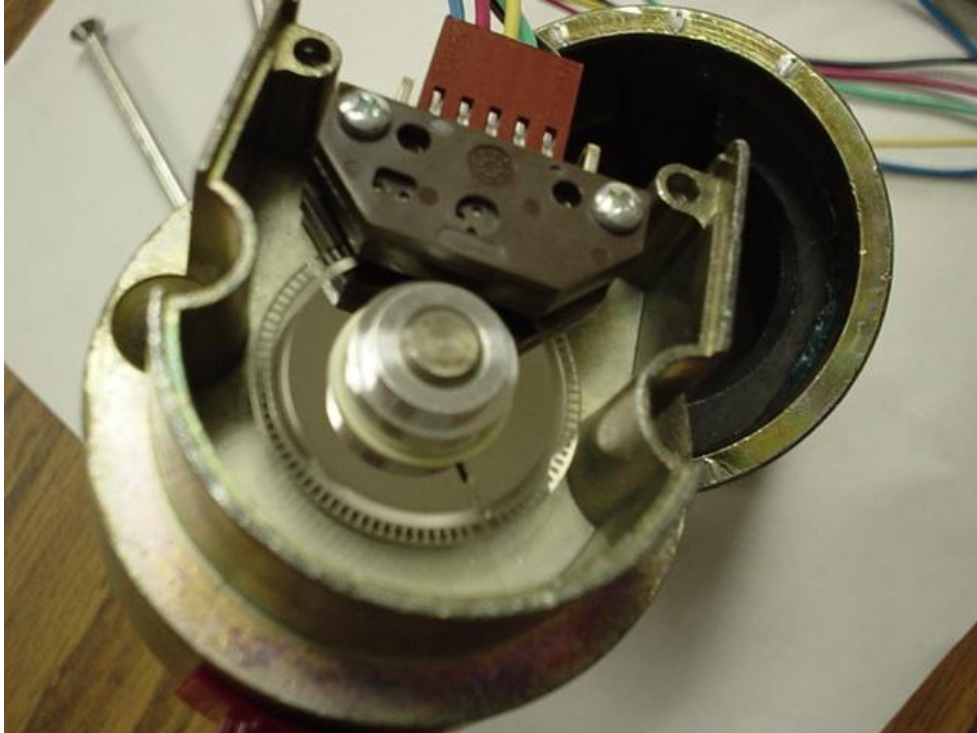
Figure 3.2. Pittman 500 CPR encoder

Power Supply

Every electronic piece of equipment in this project requires a power supply ranging from 5 to 12 volts. The load cell and optical encoder require an excitation voltage of 10 volts and 5 volts respectively. The electric motor and the particle brake both require a 12-volt input in order to operate. Except for the electric motor, all of these pieces of equipment only require a minimal current, on the order of milliamps.

At first the power supplies available in the mechanical engineering department were thought to be adequate. These are Heathkit Tri-Power Supplies, Model # 1P-2718. These power supplies have three outputs two of which are 0-20 volts with a maximum current of 3 amps and one constant 5-volt, 1.5-amp output. These power supplies provide enough power for each piece of equipment by themselves, but when the assembly was put together, the particle brake had so

much internal friction that the motor couldn't spin the particle shaft. It was then discovered that

these power supplies only provided a maximum current of 3 amps at 12 volts. The manufacturer

of the electric motor states that it pulls 40 amps at 12 volts when it is in full stall. Therefore, a

search was begun for a power supply that could provide 40 amps at 12 volts and had a variable

voltage. After a long search, an adequate power supply intended for the HAM radio industry

was found. The power supply selected is a MFJ Switching Power Supply, Model # MFJ-

4245MV, with a 9-15 volt variable voltage with maximum amperage of 45 amps. The power

supply specifications are summarized in Table 3.2.

Table 3.2 Power Supply Specifications

Manufacturer	MFJ	Heathkit
Model	MFJ-4245MV	1P-2718
Maximum Voltage	15 Volts	20 Volts
Maximum Current	45 Amps	3 Amps

Magnetic Particle Brake

Magnetic-particle brakes are mechanical brakes used mostly for torque control in

tensioning, load simulation, and motor testing applications. In tensioning industry applications,

brakes provide smooth variable torque for use in unwinding film, fabric, or wire. Brakes can

also be used for load simulation by providing an adjustable load torque for performance and life

testing of gear trains, drives, and mechanisms. In this project, the brake is used as a load for a

small electric motor. This brake provides a variable load to allow the measurement of electric

motor characteristics such as stall torque, torque versus speed curves, and acceleration.

A magnetic-particle brake is a specific type of mechanical brake. Other possible brakes

are water brakes, friction brakes, or eddy-current brakes. The magnetic-particle brake can

provide precise, reliable torque control, and the torque is proportional to the input current as well

as independent of the slip revolutions per minute (RPM). This precise torque control is not

possible with either the water or friction brakes. Eddy-current brakes must have slip between the rotor and stator in order to generate torque.

A magnetic-particle brake consists of a rotor that is connected to the input shaft riding on bearings. This rotor spins inside a chamber that is filled with a fine, dry stainless steel powder comparable to iron filings. A stationary coil surrounds this chamber. As current is applied to the coil, the free flowing powder begins to form chains along the magnetic field lines, providing a frictional link between the rotor and the housing. The torque provided is proportional to the magnetic field strength, which in turn is proportional to the input DC current. If the input current is high enough, the torque will be great enough to stop or stall the rotor. When the current is at zero amps, the rotor is relatively free to slip.

Since the rotor is always in contact with the powder inside the chamber, a minimum drag torque is always present, even at full slip. Heat is produced due to this constant contact between the rotor and powder. Most brake companies provide a heat dissipation rate based upon the torque output and the speed. With these constraints of minimum and maximum torque and heat dissipation, some thought is needed into what application the brake is to be used, as well as how big and powerful the brake needs to be.

The magnetic particle brake used in this project is a Placid Industries magnetic particle brake, model B35. Table 3.3 lists the specifications of this particle brake.

Table 3.3 Magnetic Particle Brake Specifications

Torque Range	0.4 to 35 in.-lb$_f$
Voltage Rating	12 VDC
Current Rating	0.75 amps
Diameter	3.37 in.
Width	1.47 in.
Shaft Diameter	.4995 in.
Shaft Length	1.12 in
Weight	4 lb

Load Cell

Load cells are force transducers which convert mechanical force or torque into an electrical signal. Force can be determined many different ways; therefore there are many different types of load cells such as hydraulic, pneumatic, strain gauge and piezoelectric. Hydraulic and pneumatic load cells utilize a fluid and its pressure due to an applied force. Strain gauge load cells utilize a change in resistance due to strain. Piezoelectric load cells produce a voltage when the quartz crystal is deformed. The most widely used type of load cell is the strain gauge load cell.

There are several different styles of strain gauge load cells. These load cells can be used in weighing systems, dynamic force measurements and dynamic torque measurements. These styles are bending beam, shear beam, column, canister, helical, "S or Z", etc. The load cell used in this experiment is a bending-beam load cell, more specifically a binocular-shape bending-beam load cell. Binocular refers to the internal shape of the load cell as shown in Fig. 3.3.
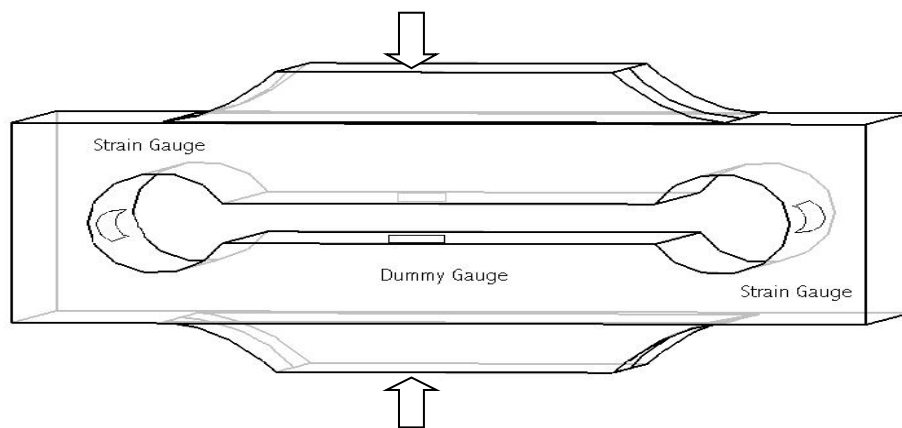
Figure 3.3. Internal view of binocular load cell

The strain gauges are located in the curvature of the holes as indicated in the figure. The strain gauges are bonded to the metal, usually stainless steel, and sense the strain of the metal caused by the external force or torque. Normally a strain gauge utilizes a Wheatstone bridge to convert

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the material strain into a small DC voltage signal. Figure 3.4 illustrates a divided bridge circuit

used for measuring electrical resistance, known as a Wheatstone bridge circuit. R_4 is equal to the

strain gauge R_g.
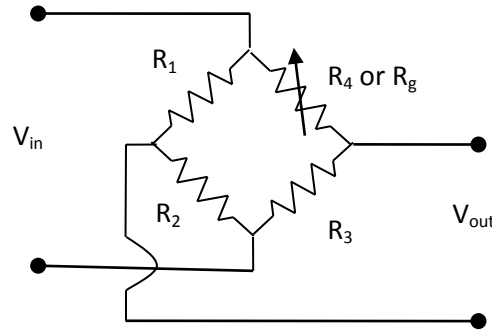
Figure 3.4. Wheatstone bridge

The use of a bridge is needed because the change in resistance is so small. This is because it is

proportional to the strain in the material and the strain is very small. A strain gauge can be set up

as a full, half or quarter bridge depending on the application. An excitation voltage, usually 10

volts, is applied to the bridge. The output of the strain gauge is on the order of millivolts.

Equation 3.1 shows how the output voltage is obtained.

$$V_{out} = V_{in}\left[\frac{R_3}{R_3 + R_g} - \frac{R_2}{R_1 + R_2}\right]$$
(3.1)

All strain gauges must be calibrated if this millivolt signal is to be converted into the force or

torque that is applied. Calibration is a simple process. For this, a known weight is placed on the

load cell to obtain the corresponding voltage value. Most load cells can be calibrated in both

tension and compression.

Another aspect of strain gauges that is important is the idea of temperature compensation. Temperature compensation is used to counteract the apparent strain due to temperature effects on the resistors. To remedy this, a "dummy gauge" is placed in the load cell where no strain or minimal strain is present in the material. This "dummy gauge" is on the same arm as the working gauge and therefore has the same apparent strain due to temperature and in turn cancels the apparent strain due to temperature measured by the acting gauge.

The load cell used in this experiment is a Transducer Techniques Model MLP-25. This load cell is a binocular style and has temperature compensation. This load cell is approximately 1.5 in. by ½ in. and ¾ in. tall and is calibrated in compression to a maximum load of 25 pounds. The exact internal shape and locations of the load cell is not known because this information is proprietary technology to Transducer Techniques. Therefore, Figure 3.3 is just an example of what the load cell might look like.

DAQ Hardware

There were two different DAQ hardware set-ups used for the development of this dynamometer project. Initially a signal connector block and enclosure, NI SCB-68 and CA-1000, from National Instruments were used to develop and improve the design of the dynamometer. Later, a LabJack U3-HV was implemented to in order to represent what was to be presented to students.

SCB-68 and CA-1000

The NI SCB-68 and CA-1000 are both available from National Instruments. The SCB-68 is a signal connector block for DAQ devices with 68-pin connectors. The CA-1000 is a metal enclosure that the SCB-68 circuit board is mounted in. The CA-1000 provides protection against

electronic interference due to the Faraday Effect.   The CA-1000 also has interface panels to allow quick connection of standard I/O connectors.
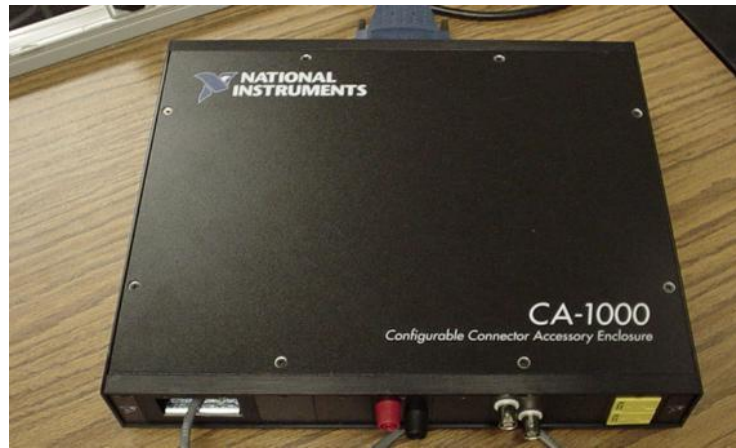
Figure 3.5. National Instruments CA-1000 SCB Enclosure
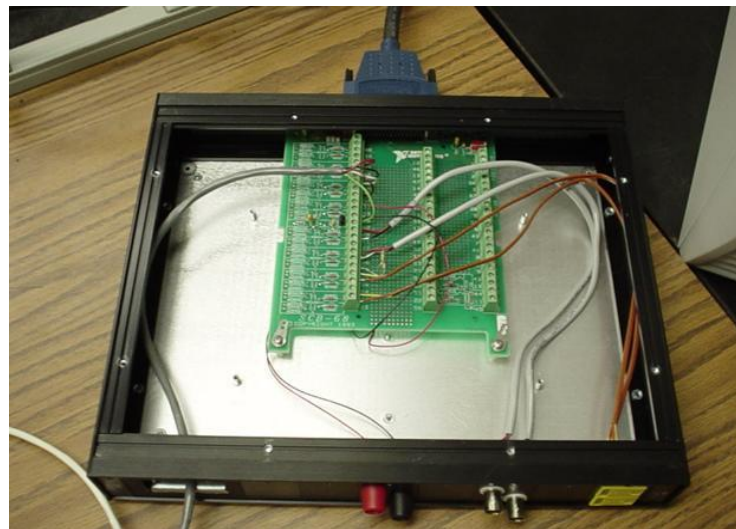
Figure 3.6. Inside view of CA-1000 Enclosure showing SCB-68

LabJack U3-HV

The LabJack U3-HV is measurement device that provides analog and digital inputs and outputs as well as timers and counters. The LabJack devices connect to a PC through USB or Ethernet and allow for a less expensive interface for data acquisition than the National Instruments DAQ cards. The inexpensive LabJack data acquisition device is attractive to a

teaching environment because any mistakes made in connecting to the device by the students

would not be detrimental to the Mechanical Engineering Department's budget.

The LJTick-InAmp is a signal conditioning module provided by LabJack that is designed

to plug directly into the U3. This module provides two amplifiers to the user ideal for bridge

circuits such as the signal from the load cell used in this dynamometer.
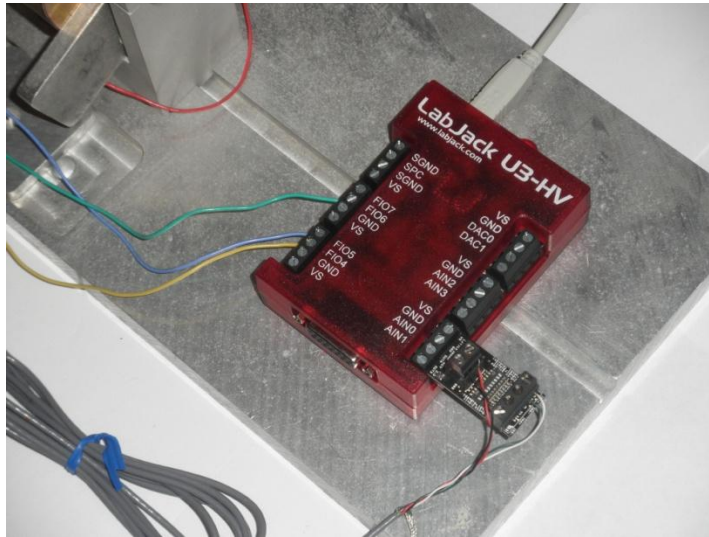
Figure 3.7. LabJack U3-HV with LJTick-InAmp Installed
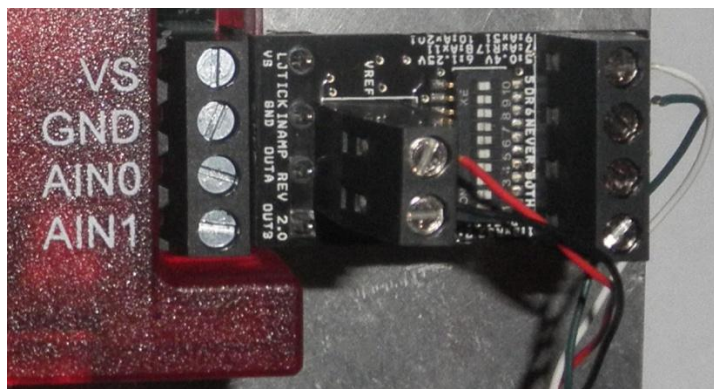
Figure 3.8. Close up of LJTick-InAmp

LabVIEW Software

LabVIEW is a National Instruments data acquisition package that has been designed for use in almost every industry. LabVIEW software utilizes a graphical programming language, now known as G; to obtain and send data from the DAQ card to the computers monitor or another program (PC I/O in Fig. 2.7). LabVIEW is software that is designed to acquire data in the DAQ board, manipulate it, and display it to the user. LabVIEW is a graphical programming language or visual programming language since the programs are designed/written using icons. The programmer must use a mouse to place icons and wire them together. These wires are virtual wires that allow data to flow from icon to icon. Many other programs use this visual programming technique such as: SolidWorks or AutoCAD Inventor. Visual Basic is a software package that is half and half; it utilizes the placement of icons with a mouse, but still requires command line text input. The predecessor to LabVIEW, LabWindows, was strictly command line based.

LabVIEW consists of three major interfaces that allow the user interact with software. These interfaces are in the form of windows and are called the front panel, the block diagram, and the palettes.

The front panel consists of controls and indicators that the user can manipulate and view while the program is running and taking data. The front panel is intended to resemble the control panel on any piece of electronic equipment. It has virtual knobs and buttons as well as graphs and digital readouts.

The block diagram is very similar to a circuit diagram for a piece of electronic equipment. In a circuit diagram, current flow can be traced, whereas on the block diagram, the flow of data signals can be traced. The data flows through the icons from left to right, the far left

being the data acquisition from the channel the sensor is wired to, to the far right that is the final

output of the desired values. The output can be an indicator on the front panel or a spreadsheet

or other program. The block diagram has nothing on it that the user manipulates while the

program is running. This manipulation can only be done on the front panel.

The palettes are items used to build the program; these palettes are the tools, controls, and

functions palettes. The tools palette allows the user to change the mouse cursor into different

things such as: a pointer, a probe, text, etc. The controls palette contains the different indicators

and controls that can be placed on the front panel. The programmer simply clicks on the icon of

the control wanted and places it in the front panel. Then the size, font, and different aspects of

that particular control or indicator can be changed. The functions palette contains all of the icons

that can be placed on the block diagram. Functions, as National Instruments calls them, can be

mathematical operation icons, logical loop icons, data acquire icons, icons that write to

spreadsheets, and many other possibilities.

LabJack Software

Control Panel

The LabJack website (www.labjack.com) provides many software download options for

viewing and storing the data collected with the LabJack devices. The LJControlPanel.exe

program allows the user to configure and test the LabJack device. Figures 3.9, 3.10, 3.11 and

3.12 below are screenshots of the LJ Control Panel. By clicking on the U3 – USB-1 device in

Figure 3.9, the user gains access to the LabJack device connected to their computer through

USB. Figure 3.10 is a screenshot of that device's interface that allows the user to select

Configuration Defaults shown in Figure 3.11. Once the user has selected the channel settings

desired, those values can be written to the U3 device and tested. The test screen is shown in Figure 3.12.
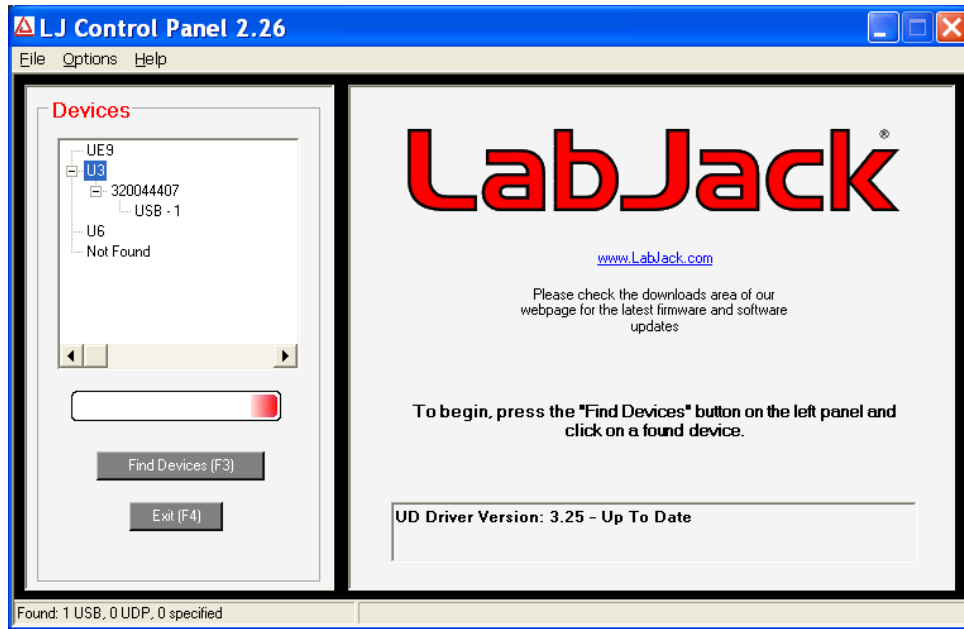
Figure 3.9. LabJack Control Panel screen shot
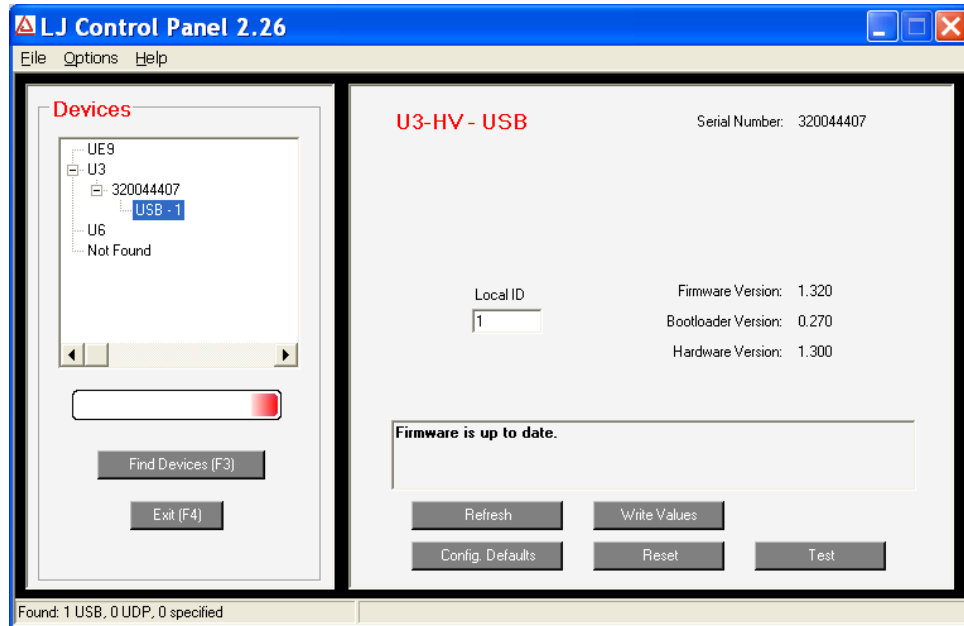
Figure 3.10. LabJack Control Panel U3-HV-USB interface screen shot
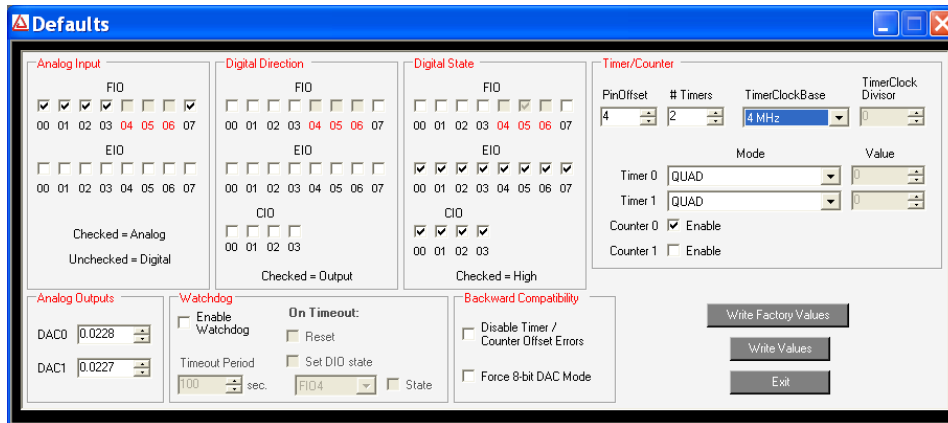
Figure 3.11. LabJack configuration default screen shot
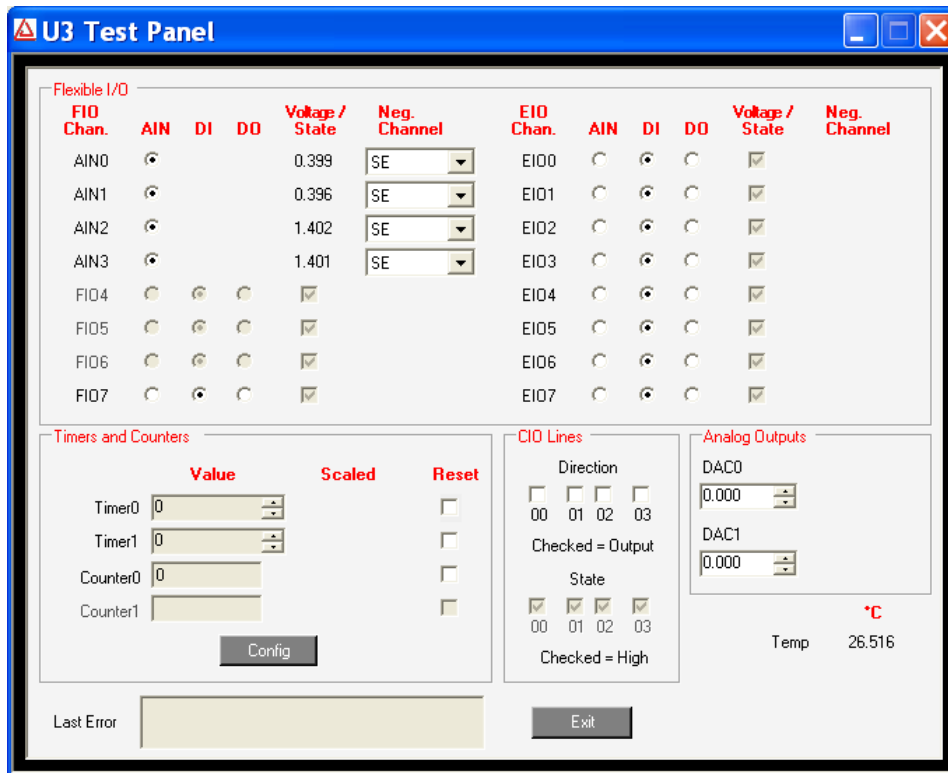
Figure 3.12. LabJack test panel screen shot

The test panel allows the user to verify that the device is set up correctly and allows the

signal values to be viewed.

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CloudDot Grounded

The CloudDot Grounded is a downloadable application from LabJack that allows the user
to configure the device as well as log data from the device. Figure 3.13 below is a screenshot of
the CloudDot Grounded application showing the U3-HV device connected. This application
uses an internet browser window. Once the user clicks on the device screen shown in Figure
3.14 appears. In this screen you can see the streaming signals from the sensors connected to the
device. This screen also allow for the logging of each channel simultaneously. The logs created
are comma separated values (.csv) files which can be opened in Microsoft Excel or similar
program to apply calibration factors if any and graph the data.
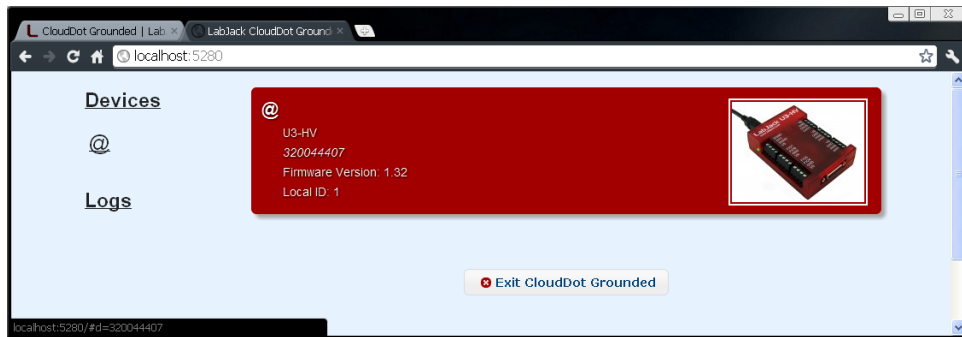
Figure 3.13. CloudDot Grounded screen shot
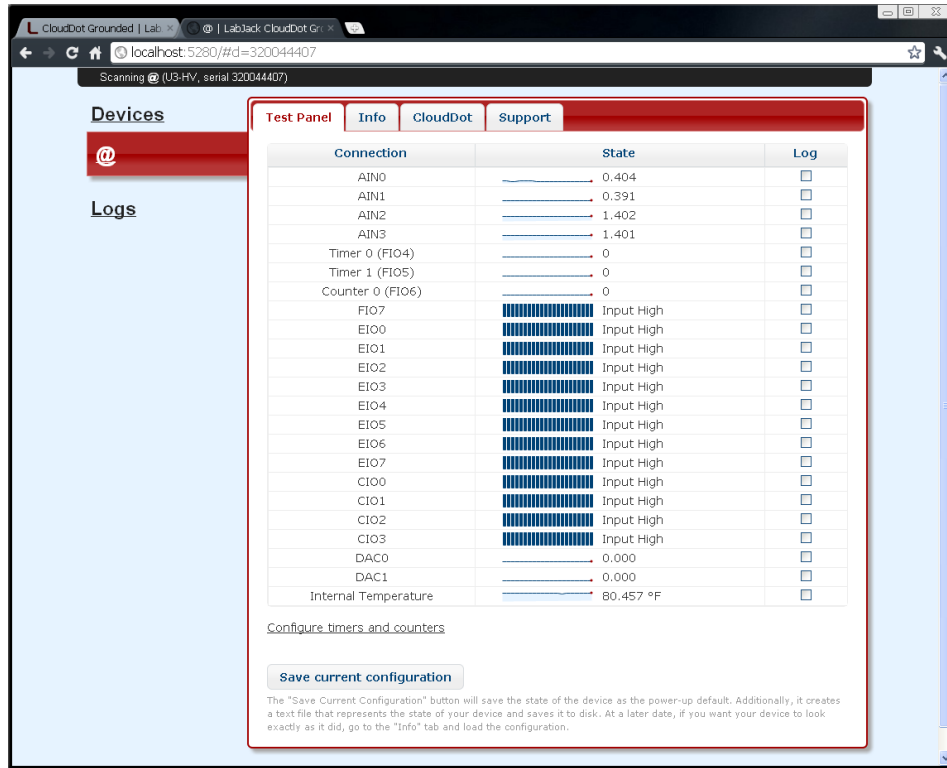
Figure 3.14. CloudDot Grounded device test panel

CHAPTER 4
DESIGN

Design Goals

Several goals were associated with the design of this project. The main goal for this project is to expose the students to the operation concepts and theory of electric motors. The motor that the students will most likely come into contact with is a mechanical control motor, a permanent magnet DC motor, with the linear torque-versus-speed curve. Several dynamometer units are needed, on the order of five or six, so more students could get exposure at a time. These dynamometers needed to be sized so that the motor could provide a torque that the students could actually feel and quantify, but they also needed to be small enough so that they could be used as table-top experiments as well as be easily stored. Another major goal was that everything needed to be fabricated within the Mechanical Engineering machine shop to help reduce the overall cost of the project.

Some other goals helped specify the dynamometer base. The whole thing needed to be easy to assemble and disassemble with minimal use of tools. Also there is space allowed for expansion, so that the dynamometer can be modified in the future to allow for bigger motors or different optical encoders. Another major goal for the design of the base is to allow room for calibration of the load cell on board. This would ensure a neat, compact unit.

Teaching of sensors and data acquisition is also an important goal. This experiment will allow for the introduction and exposure to some basic sensor concepts as well as the requirements for those sensors to be connected to a data acquisition system.

The design goals are summarized below as:

- Mechanical Control Motor

- Table Top / Easy Storage and 5 – 6 Units

- Fabrication in Mechanical Engineering Machine Shop

- Expansion Ability and Allowance for Load Cell Calibration Onboard

- Ease of Assembly / Disassembly

- Teach Basic Sensor Concepts & Data Acquisition

Design Constraints

Some of the limiting factors in this project are the motor itself. The motor has to be a

permanent magnet motor to provide the correct torque curve. Since a table-top dynamometer is a

goal; both the size and the power of the motor must be limited. The system power was limited to

12 volts due to availability of power in the laboratory as well as safety concerns for the students.

This 12-volt limitation also determined the braking component to be used in the dynamometer.

As always, with any project, cost was a major constraint.   Each dynamometer unit needed to

cost less than $2000.00. A suitable motor with the most torque and the lowest cost had to be

located, which in turn determined the size of the other components. The constraints are

summarized below.

- 12 Volt System

- Small Permanent Magnet Motor

- Cost: < $2000.00 per unit

Mechanical Design

Mechanical Assembly

There were several design goals for the mechanical design. First of all; the motor, brake, load cell, and bearings had to be specified. Then the aluminum base, supports, and moment arm had to be designed. The main goal of the mechanical design was to design a dynamometer that was easy to fabricate, as well as easy store and setup. The material is aluminum due to its availability and machine-ability, as well as weighing much less than steel does. The motor provided only C-face mounting, therefore the motor stand was designed as an L-bracket. The brake stand was originally designed the same way to try to maintain the ease of production and shaft alignment. A groove was machined in the center of the base to help provide alignment. Each L-bracket has a nub on the bottom that fit into this groove. Since the particle brake stand was an L-bracket, the brake could only be captured on one side. A flexible coupling, purchased from Love Joy, connected the motor to the brake to allow for misalignment. Love Joy couplings allow for different size shafts to be coupled together as long as the shaft diameters are close to the same dimensions.

SolidWorks Software

SolidWorks, a 3-D CAD program, is a program that runs on the Windows operating system which was installed on a typical Intel PC computer. This program was used to design the aluminum pieces. Due to the capability of SolidWorks and its assembly features, it was possible to completely design the structure first and check for alignment and tolerances before anything was ever built. Once everything was drawn in SolidWorks, it was simple to check for the ease of assembly and disassembly which was another goal of this project. Also plenty of room was

allowed for any additional pieces of equipment to be added for future projects, as well as space for the load cell to be calibrated. Machine shop drawings were generated from SolidWorks.

Design Issues

After the prototype was built and testing was performed, it was discovered that some redesign was needed. The original particle brake stand design, being an L-Bracket just like the motor stand, only captured the shaft of the brake on one side. Apparently the bearings that had been selected allowed for too much play. Therefore the run-out (wobble) of the motor's shaft was transferred directly into the shaft of the brake. This caused a major vibration in the rotating assembly, which in turn caused the moment arm to bounce on the load cell. This bouncing caused the force signal to be erratic. To remedy this vibration, the brake stand was redesigned. This redesign incorporated a stand that held the particle brake on both ends of the shaft. This permitted the particle brake to rotate only allowing the flexible coupling could do its job by allowing for any slight misalignment where before it was acting as a direct hard coupling.

When the stand for the particle brake had been redesigned, it allowed more room for the load cell. The load cell base size was decreased and it was moved closer to the brake. This increased the amount of force on the load cell due to a smaller moment arm. With a larger force on the load cell it produces a larger signal for the data acquisition system. A larger signal is better, when referring to a load cell, because most load cells have a signal that is very small, on the order of milli-volts.

LabVIEW Program

Load Cell Data Acquisition

The load cell that is being used in this project, the Transducer Techniques MLP-25, has an output signal of about one millivolt per pound of force. The size of the output signal determines the ranges needed in the channel setup of the DAQ board. The load cell channel is an analog input channel that is set up in the differential mode. There is no hardware amplifier being used because the PGIA with its highest gain of 100 is adequate. The maximum output of this particular load cell is 25 millivolts with the specified 10-volt excitation.

An example of a LabVIEW program that can acquire data from a load cell is shown in Fig. 4.1. There are several icons used to manipulate the signal once it has been acquired. Initially the signal is acquired using the Analog Input Multi-Point icon. The sample rate and number of samples are set to 1000 and 200 respectively. This signal is then displayed on the front panel in graph form. Since there is still a little oscillation in the signal, a DC Estimator icon is used in order to find the average DC value. This signal is now a single average value that is displayed every time the program runs through its loop. After this average voltage is established, the signal is manipulated with calibration and conversion factors to obtain the force on the load cell.
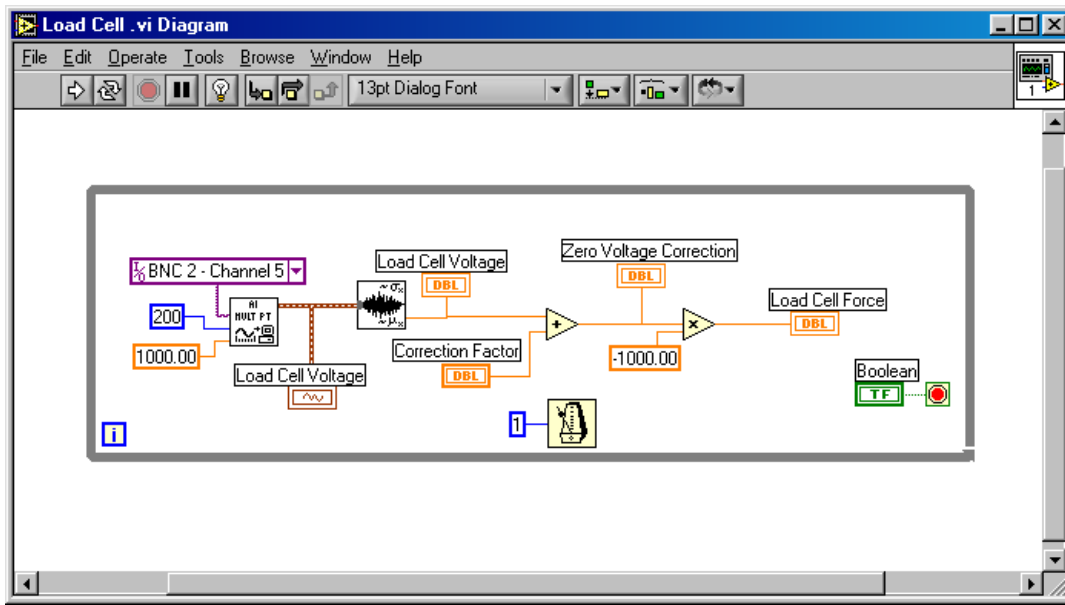
Figure 4.1. Block diagram of load cell program

Optical Encoder Data Acquisition

The optical encoder is built into the electric motor. The square wave logical signal from the encoder is converted by the US Digital ETACH unit into a steady analog voltage signal that is proportional to the speed of the rotating shaft. This voltage signal has a 10-volt span. Therefore, the channel of the encoder signal has a 10-volt span as well. This span sets the internal gain of the DAQ board to 1. The channel mode for the encoder is a referenced single-ended mode due to the fact that the ETACH is powered separately with an AC adapter plugged into an outlet. This power shares a ground with the DAQ board's ground.

The LabVIEW program for the encoder, Fig. 4.2, is very similar to that of the load cell. It uses the same multi-point analog input; the same sample rate, the same number of samples, and the same DC estimator. The only difference between these two programs is the calibration and conversion factors that are applied to the signal. These conversion factors convert the voltage signal into a speed with units of revolutions per minute (RPM).
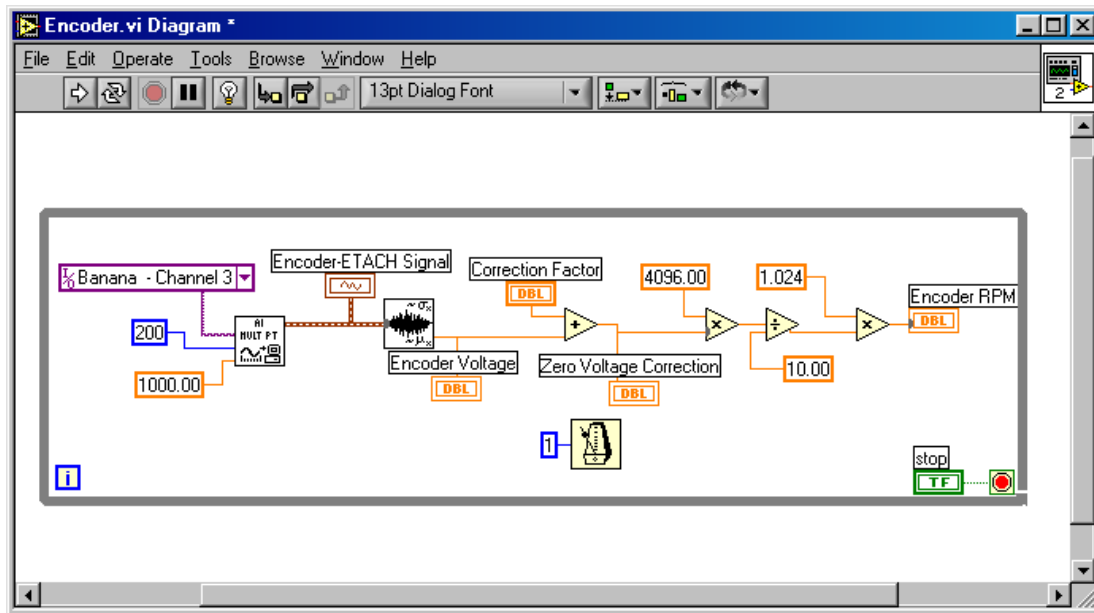
Figure 4.2. Block diagram of optical encoder program

Main Program Block Diagram

The load cell program and the optical encoder program discussed above are programs that deal with each sensor individually. These two programs are combined in the main program to obtain the data needed to produce the torque versus speed curve. See Fig. 4.3. The force and speed are obtained from the load cell and optical encoder programs. To obtain torque, the force from the load cell is multiplied by the moment arm. This torque value is displayed on the front panel. Once the values for torque (in.-lbs) and speed (RPM) are obtained, they are placed into arrays using the build array icon. These arrays are now 1 by "X "arrays, where "X "is the total number of samples taken. These two arrays need to be placed into a single 2 by "X" array. To accomplish this, the reshape array and replace array subset are used. This array is then written to an Excel spreadsheet file so that the torque versus speed curve can be generated. Since the data is in an array, it is connected to the 2D data in the "Write to Spreadsheet" icon. The data is transposed and written to the hard drive of the computer.
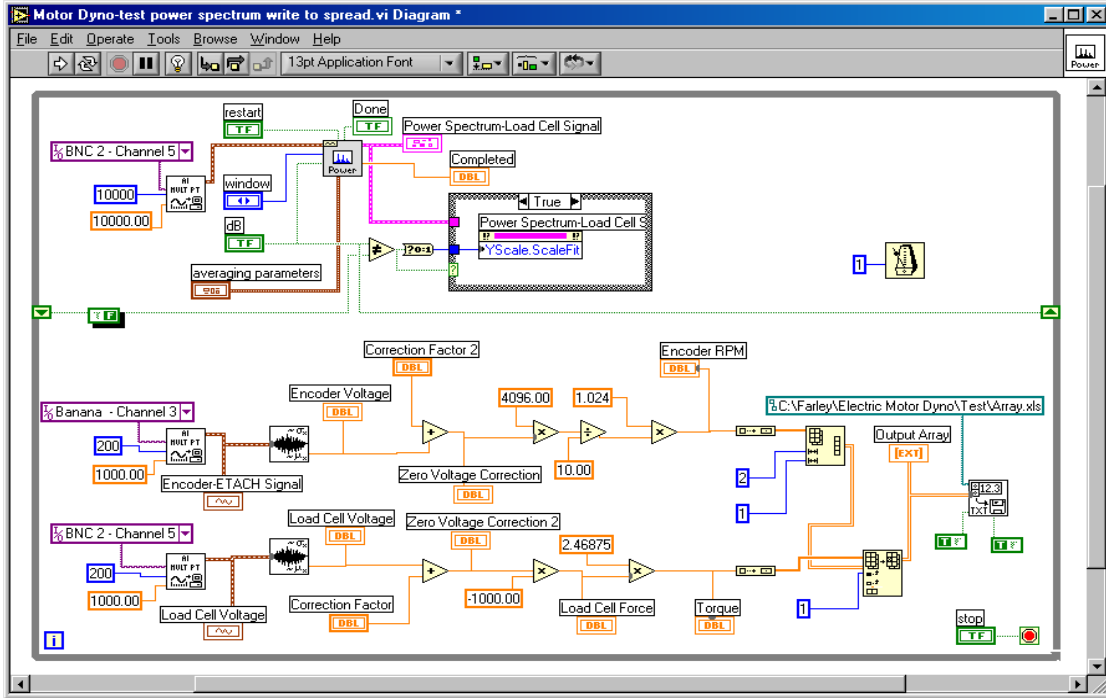
Figure 4.3. Main program block diagram

A power spectrum is performed on the load cell signal. At first the power spectrum was used to determine the amplitude of vibration before the particle brake stand was redesigned. Once the vibration was fixed, the power spectrum continued to be useful as an indicator of the frequency and amplitude of the electrical noise. The power spectrum helped determine what level the white noise was, as well as the EMI and ground loop noise. It appears that the system itself has a small ground loop causing a little noise. Now this noise is on the order of -100 dB. This noise level is very small, but it is still there.

Main Program Front Panel

The front panel of this program was used to observe the output as changes were made to the physical apparatus. Therefore, there were no controls except for a stop button. Several indicators including graphs and digital indicators showed the voltage, speed and torque values.

The indicators showed the average value of both the encoder and load cell signals and the values

after calibration factors are applied.

CHAPTER 5
RESULTS

Data was collected to show that the experiment will work as intended for use in the

Mechanical Engineering Lab 2. The data was collected using both LabVIEW and LabJack. The

software used during a given semester will be up to the Mechanical Engineering department and

the individual instructors. An example of the output of the optical encoder using the LabJack

CloudDotGrounded is shown in Figure 5.1. The data was graphed in Microsoft Excel. Channel

A of the encoder was connected to the flexible input/output channel 4(FIO4) on the U3-HV

device.
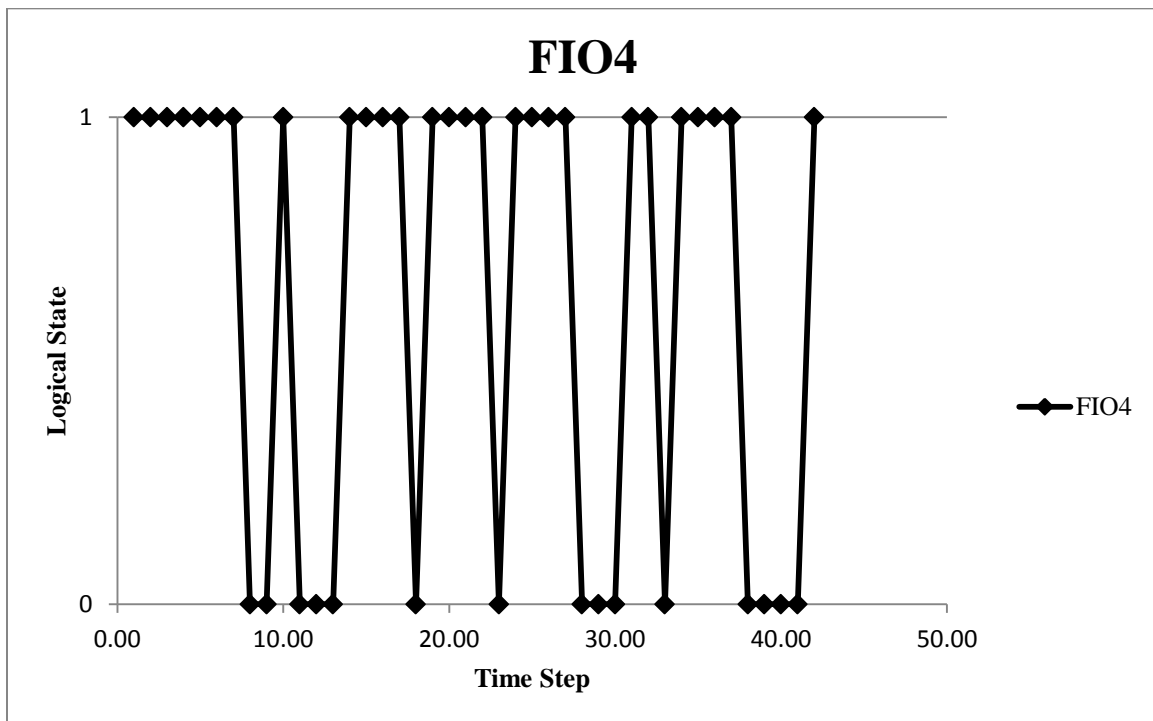
Figure 5.1. Example data of optical encoder

Figure 5.2 is an example of the data taken when testing the motor. This figure was

produced in Microsoft Excel with the spreadsheet file output from the "Write to Spreadsheet"

icon in the LabVIEW program shown in Fig. 4.3.

Torque vs. Speed Curve
Pittman #14204S004

$y = -0.0465x + 133.72$
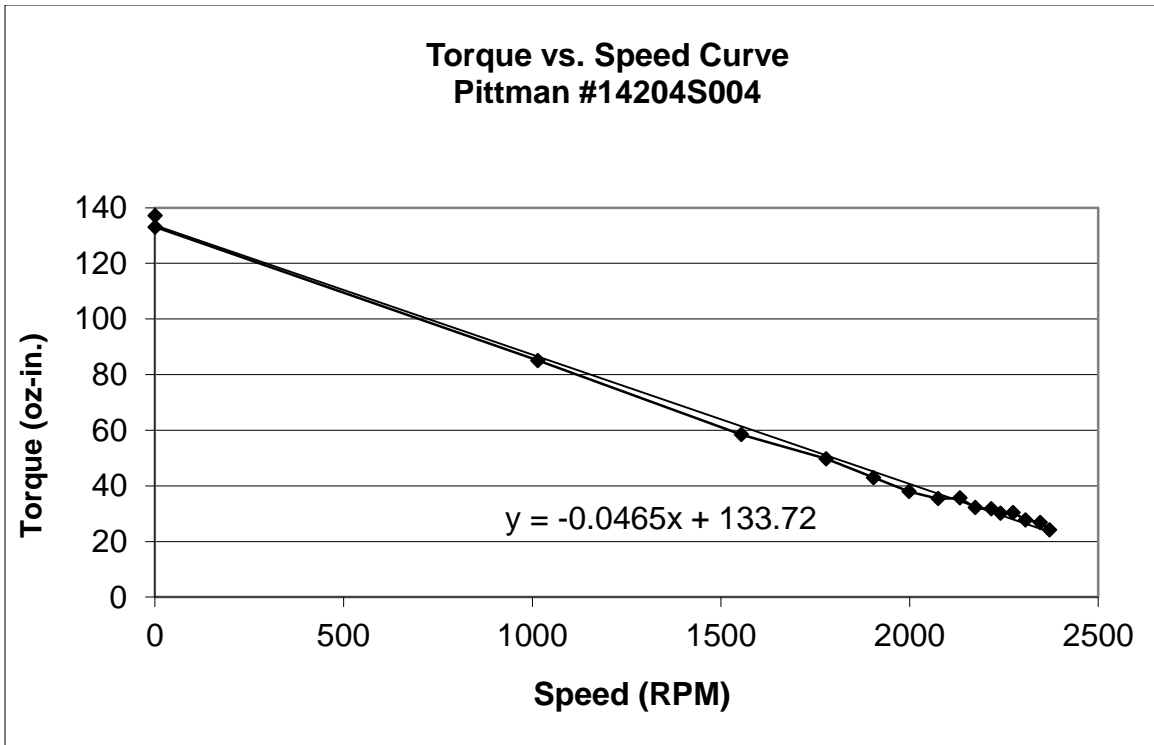
Figure 5.2. Torque versus Speed curve for the Pittman motor

The results shown in Fig. 5.2 and their comparison to the manufacturer's supplied data are discussed in the following chapter.

CHAPTER 6
DISCUSSION

Design Goals

The design goals of this project were very straight forward and are listed again below:

- Mechanical Control Motor

- Table Top / Easy Storage and 5 – 6 Units

- Fabrication in Mechanical Engineering Machine Shop

- Expansion Ability and Allowance for Load Cell Calibration Onboard

- Ease of Assembly / Disassembly

- Teach Basic Sensor Concepts & Data Acquisition

- 12 Volt System

- Cost: < $2000.00 per unit

Each goal has been met, most of which has been presented already in this thesis. The cost per unit has been achieved as shown in the bill of materials, Table A.1 in the appendix. The cost is less than half of the goal of $2000 each. Even if the cost of the LabJack U3-HV and the LJTickAmp, already available in the mechanical engineering lab, the cost per dynamometer setup is still much less than the goal.
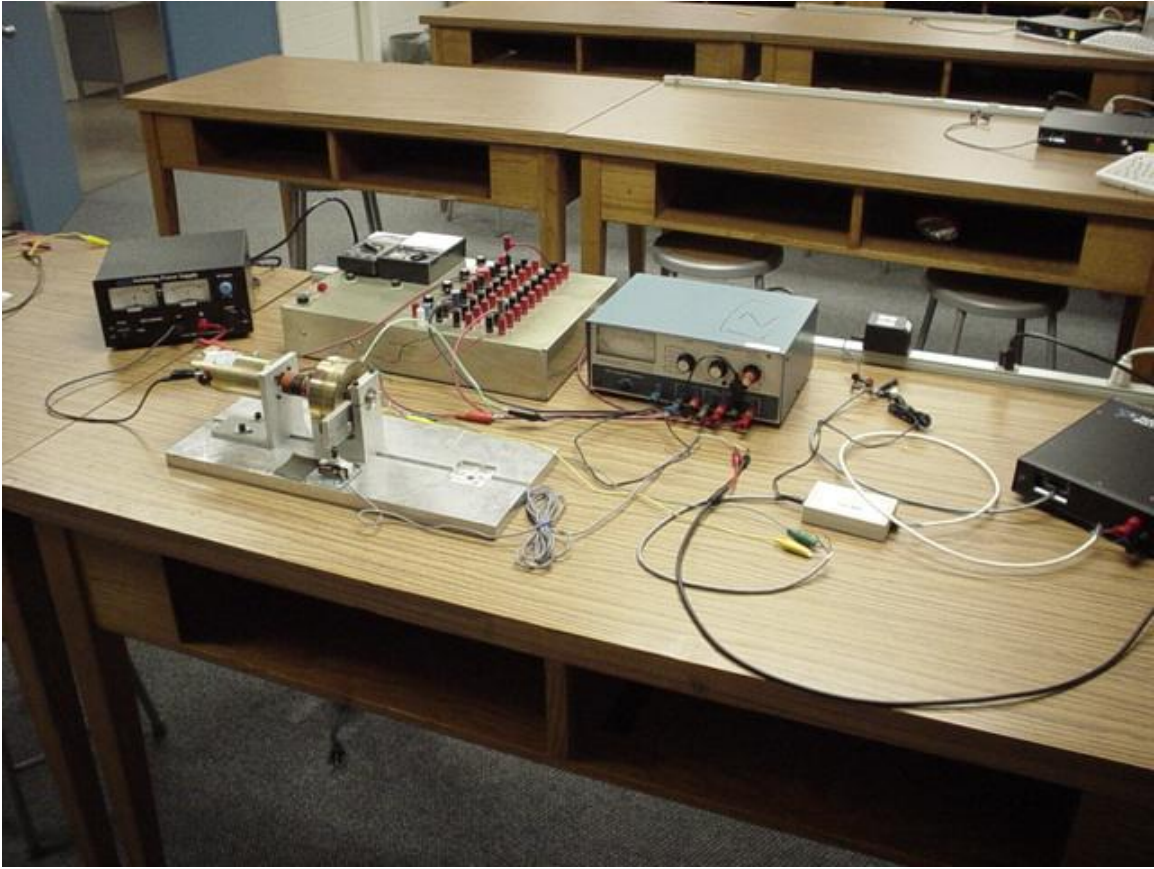
Figure 6.1. Dynamometer Setup with LabVIEW

Figure 6.2. Dynamometer Setup with LabJack

Data Analysis

The data shown in Fig. 5.2 can be compared to the graph on the Pittman data sheet found in the Appendix or to the calculation of the viscous damping using the constants found in the data sheet. Using Eq. 2.11 and the values found in Table 3.1 for the Torque Constant, Voltage Constant and Armature Resistance, the slope of the Torque vs. Speed line or the viscous damping, β_e can be calculated.

$$\beta_e = K_t K_e / R_a \hspace{3cm} (2.11)$$

$$\beta_e = (4.33 \text{ oz.in/A}) (3.20 \text{ V/kRPM}) / (0.27 \text{ } \Omega) \tag{6.1}$$

$$\beta_e = 0.0513 \text{ oz.in/RPM} \tag{6.2}$$

An error can be calculated comparing the 0.0513 oz.in/RPM to the slope of the trend line in Fig. 5.2 of 0.0465 oz.in/RPM.

$$\% \text{ Error} = (0.0465 - 0.0513) / 0.0513 \text{ x } 100\% \tag{6.3}$$

$$\% \text{ Error} = -9.36\% \tag{6.4}$$

The error calculated could be due to noise in the system or errors in calibration of the load cell. The line in Fig. 5.2 does not reach 0 oz.-in. of torque because there is an inherent drag in the particle brake. This drag applies a constant load to the motor of about 20 oz.-in., as shown in graph above.

All in all this small electric motor dynamometer should prove to be very useful to the lab curriculum used by the Mechanical Engineering Department. The students should get a good basic understanding of sensors, data acquisition and electric motors which will prove to be very useful in their careers whether they deal directly or indirectly with them.

CHAPTER 7
RECOMMENDATIONS

The following recommendations are for the faculty of the Mechanical Engineering Department. They include some recommendations for both Lab 2 and for the Solar Boat Design Project.

Proposed Procedure for Lab 2

The experiments currently found in Lab 2 will be covered in one to two weeks depending on the experiment. Each week typically includes a lecture with possibly some homework and a 3-4 hour lab used to run the experiment and collect data. The suggested procedure for this Small Electric Motor Dynamometer experiment is to use two weeks. A partial handout sheet has been provided in the appendix showing where certain LabVIEW functions can be located.

Week One

The first week could include a lecture that reviews the concepts of data acquisition depending on the students' knowledge at that point. If the students have a firm understanding of the data acquisition concepts then the instructor can move right into teaching the concepts of the two sensors used in this dynamometer. The theory and equipment section of this thesis can be used as a guideline as to what concepts to teach. The concepts of strain, Wheatstone bridge circuits and temperature compensation can be reviewed and taught for the load cell as well as the need to amplify such a small signal from a bridge circuit. A load cell could possibly be disassembled to allow the students to see the internal structure used. The same can be done with the optical encoder. Allowing the students to see the actual holes in the wheel while the instructor teaches the concepts of a quadrature signal would be very helpful.

The lab portion of week one should have the students run the electric motor uncoupled from the brake. The optical encoder should be connected to the data acquisition system and the students should vary the speed of the motor by adjusting the power supply output. This will allow the students to focus on just the optical encoder and how the signal varies with speed. The second part of the first lab should be focused on the load cell. The load cell should be moved to the calibration area of the lab set up and connected to the data acquisition system. The students can then be allowed to calibrate the load cell by placing a few different calibrated weights, not exceeding 25 lbs., on the load cell and recording the voltage. The students should also be allowed to the push on the load cell with their finger so they can watch its effect on the signal. The same thing can be done on a de-energized motor so the student can spin the motor by hand slowly to watch the signal. Safety should be the number one concern for the instructor as there are no guards on this dynamometer setup.

Week Two

The second lecture should cover the concepts of a brush commutated permanent magnet motor and a magnetic particle brake. Again the theory and equipment section of this thesis could provide a guideline to the concepts that need understanding by the students.

The lab portion of the second week should cover the entire system of the dynamometer. The students should be familiar with data acquisition and the two sensors in question at this point and should run the electric motor coupled to the brake with the load cell in the correct position. Data from the two sensors should be collected simultaneously while the motor is loaded by the particle brake. The amount of braking the particle brake applies can be adjusted by either a potentiometer or by adjusting its power supply. The students should ramp the load of the motor up and down several times in order to have a chance at the best set of data since the speed at

which they ramp the current on the particle brake will play a large role in the quality of the data. Another method of collecting data for the system would be setting the loading at a specific point, collecting several samples of data and then adjusting that setting. Depending on the noise in the system and the steadiness of the person adjusting the load, this second method may provide better results. The students should then measure the length of the torque arm and use that value and the load cell calibration value they measured from the previous week to modify the data collected to allow them to graph a torque versus speed curve. The slope of this curve can be calculated and compared to the data sheet of the motor.

If a shunt resistor is used in line with the motor power connections, the voltage drop across that resistor can be measure and in turn provide an electrical power. This power can be compared to the mechanical power of the motor using the torque and speed measurement from the sensors. This would then allow the instructor to teach the concept of efficiency.

Care should be used during the running of the dynamometer to ensure that the motor is not stalled for too long because it could be damaged from excessive heat since there is no cooling fan on the motor. The brake however should not be run continuous for too long because due to the friction within the brake, it will heat up as well. The brake can dissipate 30 Watts at its maximum slip condition. If the appropriate attention is not paid during the experiment, the components could be ruined and the students could be burned if they touch the hot motor or brake.

Lab Report

The lab report should include the theory of all of the equipment and sensors including the electric motor, particle brake, load cell and optical encoder. The students should show graphs or screenshots of the signals collected of the sensors as well as a graph of the torque vs. speed curve

and power vs. speed curve of the motor used in the dynamometer. Calculations should be made

of torque, power, efficiency as well as an error calculation compared to the motor data sheet.

Recommendations for Solar Boat Design Project

The IEEE Solar Splash design contest is a senior design competition that allows electrical

and mechanical engineering students to compete with other universities around the United States

and the world. The competition is held every year and the University of Arkansas has

participated in most of the competitions starting in 2000, placing in the top 5 for several years

and placing 1st overall in two year's competitions. The solar boat design project has electrical

engineering student design the electrical system including the solar panel array and battery

system, whereas the mechanical engineering students design and build the boat hull and the

power train.

An electric motor dynamometer designed to characterize the motors used in the solar

boats would be invaluable to the students. They would be able to test different load profiles on

the motor to understand the motors characteristics and allow them to design a power train,

propeller and hull to best utilize the power they will get from the motor.

They Lynch LEM 200 is a permanent magnet DC motor but it is much larger and much

more powerful motor than the one selected for the dynamometer in this experiment. However,

the same concepts can be applied because the characteristics should be similar. Since the Lynch

motor is much larger (ø205.30mm x 180.30mm) the dynamometer base and stand would need to

be designed to accommodate the size. The torque of the Lynch motor is about 15 times that of

the small motor for this experiment at constant torque so it would be best if the structure be made

out of due to the increased power of the motor and since the dynamometer should be a permanent fixture the weight is not a factor.

The most important aspect to consider for the solar boat motor is what method to use to load it. A similar particle brake and load cell design can be implemented, however the largest Placid Industries brake does not quite meet the peak torque rating that the motor can produce. There are many other manufacturers of particle brakes though that certainly could meet that rating. The peak rating may not be needed if the peak current of 400 amps cannot be obtained. Another method of loading would be to use another electric motor as a load motor coupled to the Lynch motor through a torque transducer. A torque transducer is a sensor that measures torque dynamically typically with strain gauges attached to a shaft and the signal from the strain gauge bridge is transmitted through wireless telemetry or slip rings. The shafts of the two motors would connect to the shaft on the transducer and the load motor would be set to spin slightly slower than the Lynch motor in turn producing a torque. A torque transducer capable of measuring the torque on the Lynch motor can be purchased from companies such as FUTEK Advanced Sensor Technology, Inc. or Magtrol Inc.

APPENDIX

Table A.1   Bill of Materials and Cost

Component	Manufacturer/Supplier	Mfr. Part Number	Cost each	Qty.	Ext. Cost
Electric Motor	Pittman	14204S004	$186.96	6	$1121.76
Particle Brake	Placid Industries	B35-12-2	$260.00	6	$1560.00
Load Cell	Transducer Techniques	MLP-25	$295.00	6	$1770.00
Power Supply	MFJ	MFJ-4245MV	$149.95	6	$899.70
Coupling ¼"	Love Joy	10206	$2.71	6	$16.26
Coupling ½"	Love Joy	10210	$2.71	6	$16.26
Coupling Spider	Love Joy	10194	$1.60	6	$9.60
Bearings	NTN	R8ZZC3/5C-1L005	$10.45	12	$125.40
Aluminum	Ryerson Tull	6061 Al. Bar	$74.46	1	$74.46
				Total Cost	$5593.44
				Cost per Unit	$932.24

Table A.2   Partial Lab Handout
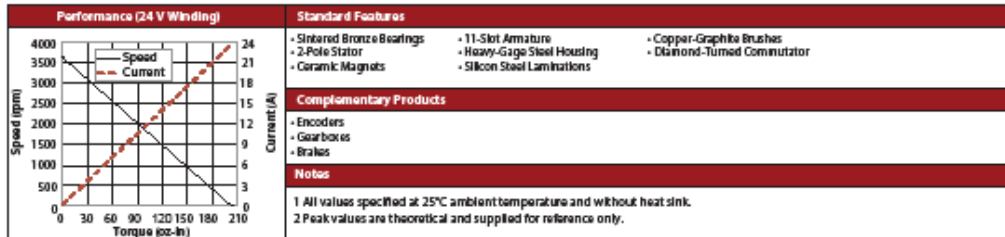
Function	Description	LabVIEW Palette Location
Analog Input	Acquires a specific number of samples at a specified sample rate from an input channel.	Functions>>DAQ>> Analog Input>>AI Acquire Waveform
AC & DC Estimator	Computes an estimate of the AC and DC levels of the input signal.	Functions>>Analysis>> Measurement
Loops	Executes the program inside it a number of times based upon the conditions set.	Functions>>Structures
Arithmetic	Performs arithmetic operations on signals.	Functions>>Numeric

Brush Commutated DC Servo Motors
14204 Series

PITTMAN
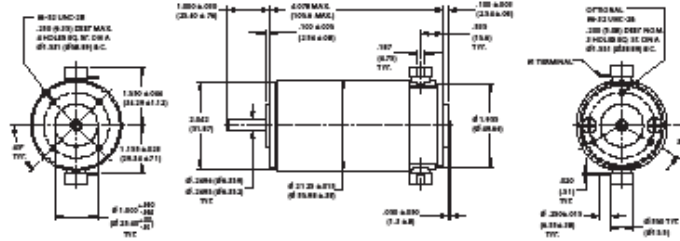
Specification	Units	Part/Model Number							
		14204 12.0 V	14204 15.2 V	14204 19.1 V	14204 24.0 V	14204 30.3 V	14204 38.2 V	14204 48.0 V	14204 60.0 V
Supply Voltage	VDC	12.0	15.2	19.1	24.0	30.3	38.2	48.0	60.6
Continuous Torque	oz-in	26	26	26	26	26	26	26	26
	Nm	0.1836	0.1836	0.1836	0.1836	0.1836	0.1836	0.1836	0.1836
Speed @ Cont. Torque	RPM	3130	3190	3190	3200	3240	3230	3220	3200
Current @ Cont. Torque	Amps (A)	7.34	5.87	4.64	3.67	2.94	2.32	1.83	1.44
Continuous Output Power	Watts (W)	60	61	61	62	62	62	62	62
Motor Constant	oz-in/sqrt W	8.3	8.4	8.5	8.6	8.7	8.7	8.7	8.8
	Nm/sqrt W	0.059	0.059	0.06	0.061	0.061	0.061	0.061	0.062
Torque Constant	oz-in/A	4.33	5.42	6.86	8.67	10.844	13.7	17.3	22.039
	Nm/A	0.031	0.038	0.048	0.061	0.077	0.097	0.122	0.156
Voltage Constant	V/krpm	3.20	4.01	5.07	6.41	8.02	10.2	12.8	16.3
	V/rad/s	0.031	0.038	0.048	0.061	0.077	0.097	0.122	0.156
Terminal Resistance	Ohms	0.27	0.42	0.65	1.01	1.57	2.50	3.96	6.33
Inductance	mH	0.40	0.62	1.00	1.60	2.50	4.01	6.40	10.3
No-Load Current	Amps (A)	0.52	0.42	0.33	0.26	0.21	0.17	0.13	0.10
No-Load Speed	RPM	3630	3670	3650	3630	3660	3650	3630	3610
Peak Current	Amps (A)	44.4	36.2	29.4	23.8	19.3	15.3	12.1	9.57
Peak Torque	oz-in	190	194	199	204	207	207	208	209
	Nm	1.3414	1.3696	1.4049	1.4402	1.4614	1.4614	1.4685	1.4755
Coulomb Friction Torque	oz-in	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
	Nm	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113	0.0113
Viscous Damping Factor	oz-in/krpm	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	Nm s/rad	1.21E-5	1.21E-5	1.21E-5	1.21E-5	1.21E-5	1.21E-5	1.21E-5	1.21E-5
Electrical Time Constant	ms	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.6
Mechanical Time Constant	ms	7.5	7.5	7.2	7.0	7.0	6.9	6.9	6.8
Thermal Time Constant	min	29	29	29	29	29	29	29	29
Thermal Resistance	Celsius/W	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Max. Winding Temperature	Celsius	155	155	155	155	155	155	155	155
Rotor Inertia	oz-in-sec2	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037
	kg-m2	2.61E-5	2.61E-5	2.61E-5	2.61E-5	2.61E-5	2.61E-5	2.61E-5	2.61E-5
Weight (Mass)	oz	35.2	35.2	35.2	35.2	35.2	35.2	35.2	35.2
	g	997.9	997.9	997.9	997.9	997.9	997.9	997.9	997.9

Performance (24 V Winding)

Speed
Current

Speed (rpm): 4000, 3500, 3000, 2500, 2000, 1500, 1000, 500, 0
Current (A): 24, 21, 18, 15, 12, 9, 6, 3, 0
Torque (oz-in): 0, 30, 60, 90, 120, 150, 180, 210

Standard Features

- Sintered Bronze Bearings
- 2-Pole Stator
- Ceramic Magnets
- 11-Slot Armature
- Heavy-Gage Steel Housing
- Silicon Steel Laminations
- Copper-Graphite Brushes
- Diamond-Turned Commutator

Complementary Products

- Encoders
- Gearboxes
- Brakes

Notes

1 All values specified at 25°C ambient temperature and without heat sink.
2 Peak values are theoretical and supplied for reference only.

G 22

AMETEK
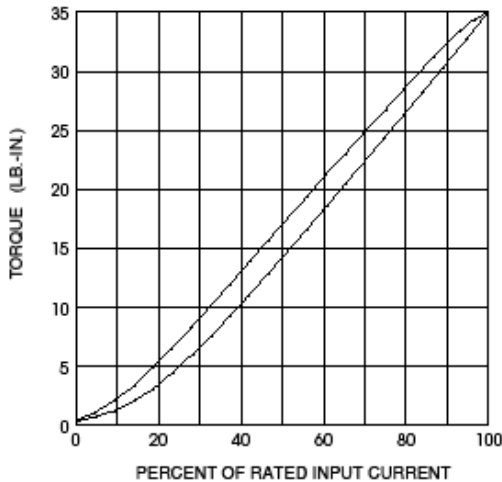TECHNICAL & INDUSTRIAL PRODUCTS

Figure A.1. Electric motor datasheet

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magnetic particle BRAKE B35 — 0.6 to 35 lb.-in.

DATA SHEET

CHARACTERISTICS - With no electrical excitation, the shaft freely rotates. With electrical excitation, the shaft becomes coupled to the housing. Torque is proportional to input current (see torque graph), and independent of RPM. While the load torque is less than the output torque, the shaft won't rotate. When the load torque is increased, the brake will slip smoothly at the torque level set by the coil input current.

Torque range . . . . 0.6 to 35 lb.-in.
Maximum RPM . . . . 1800 RPM
Maximum heat dissipation . . . . 30 watts
Maximum case temperature . . . . . 160 degrees F
Maximum overhung load . . . . 50 lbs.
Shaft inertia . . . . 12 x 10^{-5} lb.-in.-sec^2
Response (unforced) . . . . 35 mSec.
Response (forced) . . . . 20 mSec.
Weight . . . . 4 lbs.

← Use the lower curve when approaching a current value from 0 amps. Use the upper curve when approaching a current value from 100% rated current.

	6 V	12 V	24 V	90 V
COIL RESISTANCE (ohms)	4.4	17	65	830
100% INPUT CURRENT (amps)	1.3	0.67	0.35	0.10

← Rated D.C. coil voltages available: 6 VDC (yellow leads), 12 VDC (green leads), 24 VDC (red leads), 90 VDC (blue leads).

BRAKE PERFORMANCE

TORQUE: At the rated voltage, the brake will draw 100% of the rated input current. Output torque will be 35 lb.-in.

POWER SUPPLY: A "constant-current" D.C. power supply is recommended for the best accuracy in open-loop control systems. This type of power supply will maintain a fixed (but adjustable) output current, regardless of the temperature of the brake, so output torque is constant (but adjustable).

HEAT DISSIPATION: The brake can dissipate 30 slip (thermal) watts continuously. For continuous slip, calculate the heat input by the formula :

HEAT (watts) = RPM x TORQUE (lb.-in.) x 0.012

Using the above formula: At rated torque, the maximum continuous slip RPM is 71. The brake can dissipate higher amounts of heat for short periods of time, but the average must not exceed 30 watts. The case temperature must never exceed 160 degrees F.

INSTALLATION INFORMATION

Do not drop, or strike with a hammer. Keep away from fine metal filings and fine metal chips. Shield from liquids.

Do not attempt to remove the brake shaft or retaining rings.

All pulleys, sprockets, couplings, thru-shafts (hollow shaft models), etc. must mount as slide fits. Use a puller to remove stuck components. Never pry or hammer to install or remove components.

Solid Shaft Models: Center your set-screw on the flat of the brake shaft.

Hollow Shaft Models: Never tighten the #10 set screws of the clamp ring without the thru-shaft installed. Tighten set screws to 36 in.-lbs.

Always use a flexible coupling when connecting the shaft of a rigidly mounted brake to the shaft of another rigidly mounted device. Precisely align both shafts.

Always electrically ground the brake.

Placid Industries, Inc.
139 Mill Pond Drive, Lake Placid, NY 12946 USA

www.placidindustries.com
Phone 518 523-2422   Fax 518 523-2746   1/95

Figure A.2. Particle brake datasheet

Transducer Techniques®
Load Cell Systems

smart sensors
PLUG&PLAY

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MINI LOW PROFILE LOAD CELL UNIVERSAL / TENSION OR COMPRESSION

MLP SERIES

MADE IN USA

CAPACITY RANGES:
10, 25, 50, 75, 100, 150, 200,
300, 500, 750, 1,000 LBS.

The model MLP Series load cells were designed with economy as first priority. They are a scaled down version of our successful LPO Series Load Cells. MLP-10 through MLP-300 are anodized aluminum and the MLP-500 through MLP-1K are made from 17-4ph heat treated stainless steel. The unique low profile design of the MLP Series provides excellent stability for in line applications for tension and/or compression, while saving space at the same time.

OPTIONS
CO   Mini Gold Pin Connector System, male and female with 10' 4 cond. color coded shielded cable
DB   Dual Bridge

SPECIFICATIONS

Rated Output (R.O.): 2 mV/V nominal
Nonlinearity: 0.1% of R.O.
Hysteresis: 0.1% of R.O
Nonrepeatability: 0.05% of R.O.
Zero Balance: 1.0% of R.O.
Compensated Temp. Range: 60° to 160°F
Safe Temp. Range: -65° to 200°F
Temp. Effect on Output: 0.005% of Load/°F
Temp. Effect on Zero: 0.005% of R.O./°F
Terminal Resistance: 350 ohms nominal
Excitation Voltage: 10 VDC
Safe Overload: 150% of R.O.
Calibration Included: Compression
Optional Calibration: Tension
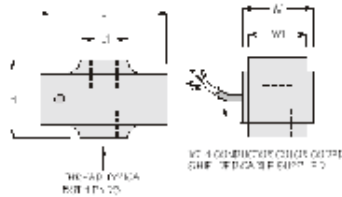
DIMENSIONS (INCHES)

| MODEL	CAPACITY LBS.	L	L1	W	W1	H	THREAD	THREAD DEPTH	NATURAL RINGING FREQUENCY HZ	DEFLECTION INCHES	WT. OZS.
MLP-10	10	1.504	.600	.54	.375	.750	10-32	.200	2,175	.003	.5
MLP-25	25	1.521	.600	.66	.500	.750	1/4-28	.230	2,200	.003	.7
MLP-50	50	1.584	.625	.66	.500	.750	1/4-28	.230	2,500	.003	.7
MLP-75	75	1.640	.650	.66	.500	.750	1/4-28	.230	2,800	.003	.8
MLP-100	100	1.664	.660	.66	.500	.750	1/4-28	.230	4,500	.003	.8
MLP-150	150	1.642	.575	.93	.750	1.00	3/8-24	.375	4,500	.003	1.3
MLP-200	200	1.688	.580	.93	.750	1.00	3/8-24	.375	5,200	.003	1.4
MLP-300	300	1.748	.600	.93	.750	1.00	3/8-24	.375	5,200	.003	3.0
MLP-500	500	1.658	.580	.93	.750	1.00	3/8-24	.375	5,200	.003	3.0
MLP-750	750	1.734	.585	.93	.750	1.00	3/8-24	.375	5,200	.003	3.0
MLP-1K	1,000	1.784	.615	.93	.750	1.00	3/8-24	.375	5,200	.003	3.0

Figure A.3. Load cell datasheet
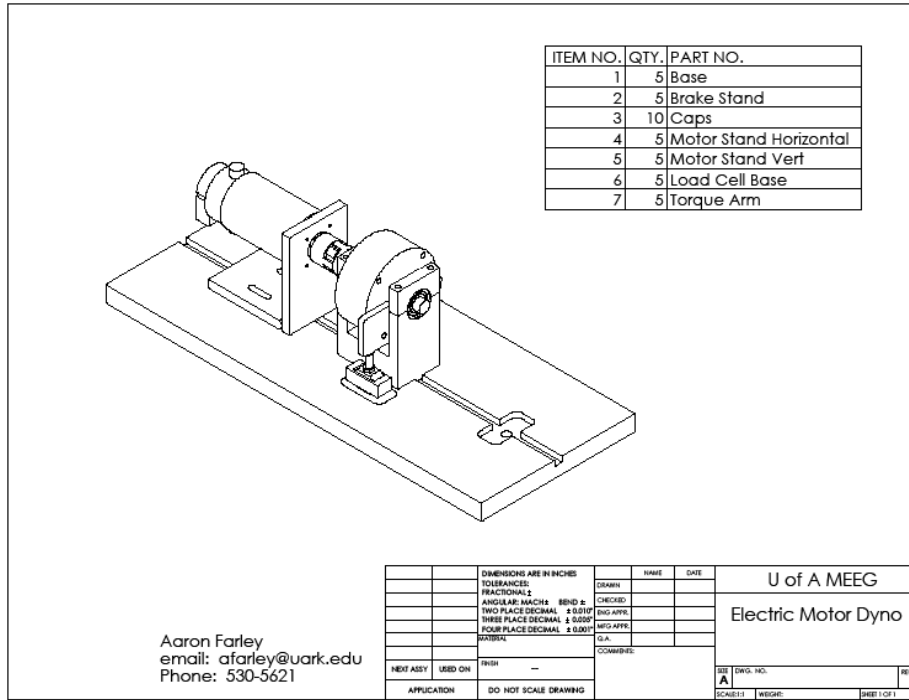
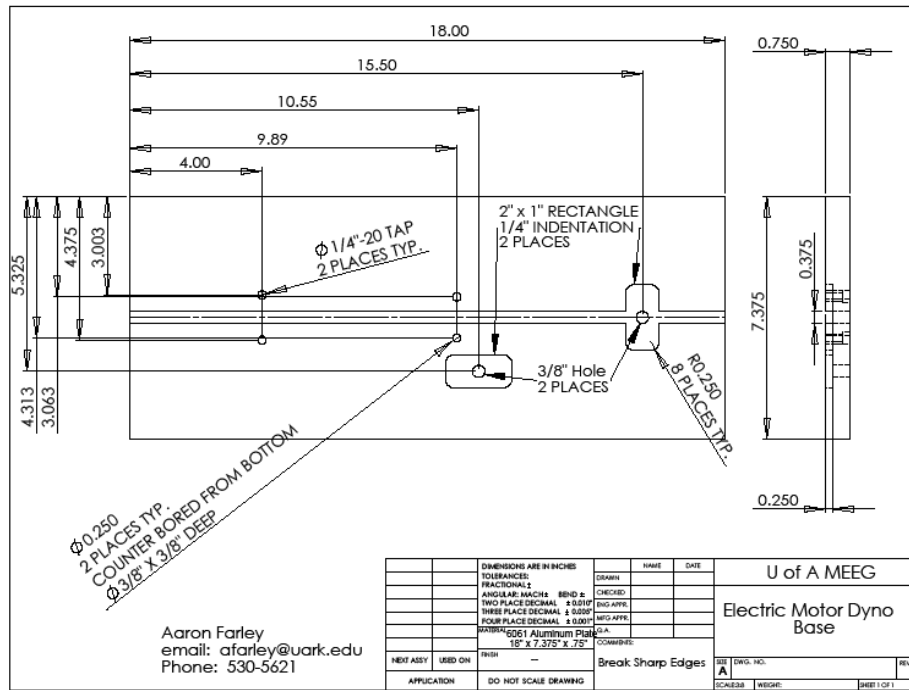Figure A.4. Assembly drawing and BOM

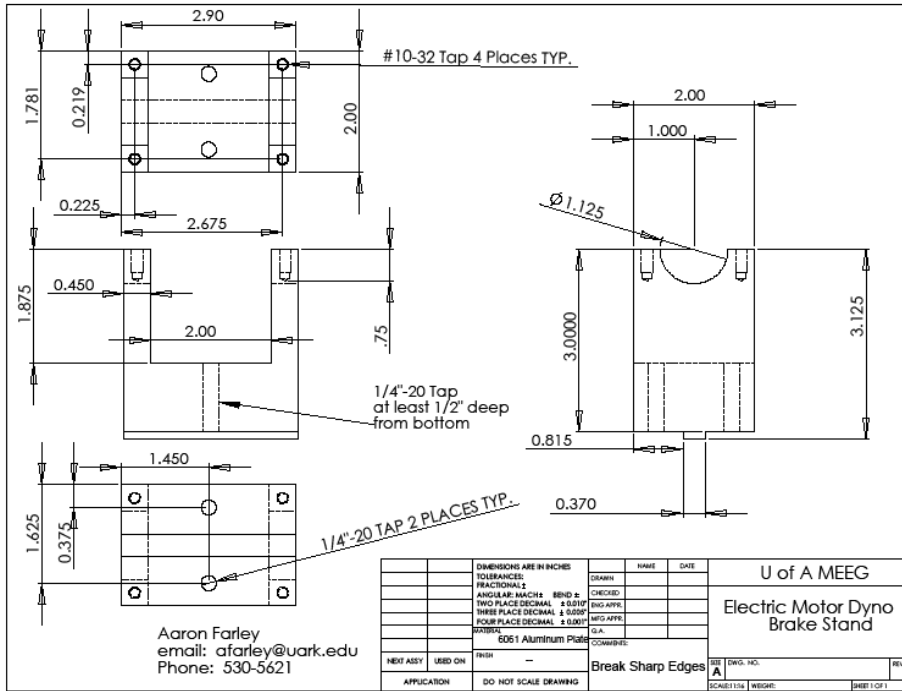

Figure A.5. Dyno base drawing
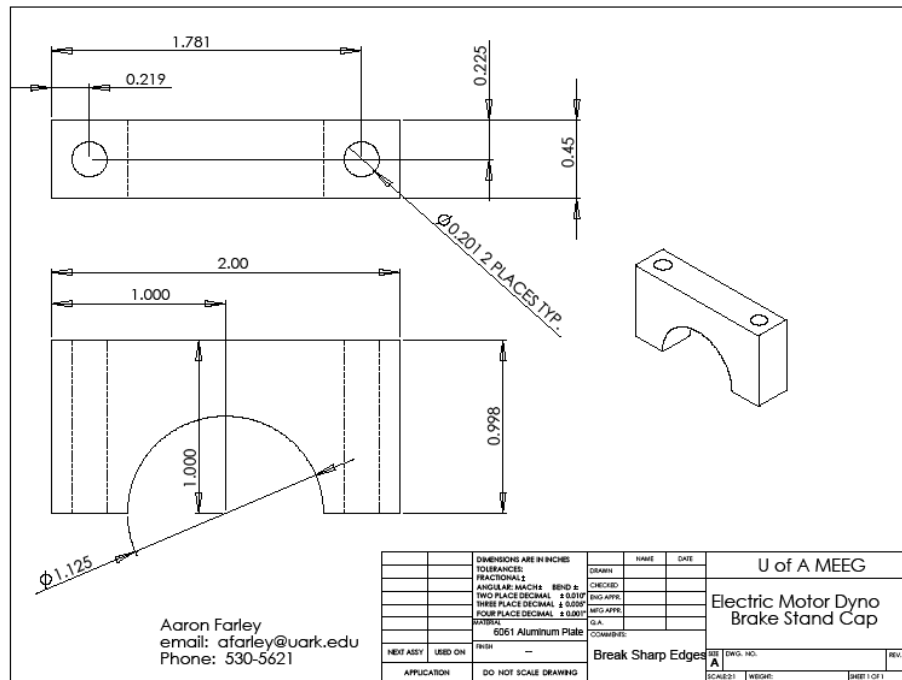
Figure A.6. Brake stand drawing
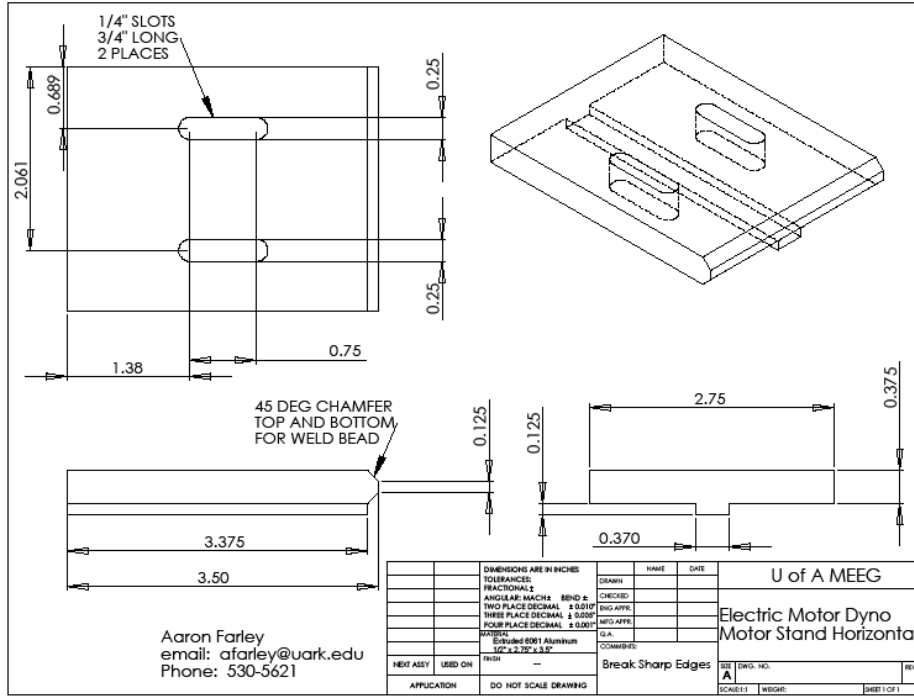

Figure A.7. Brake stand cap drawing

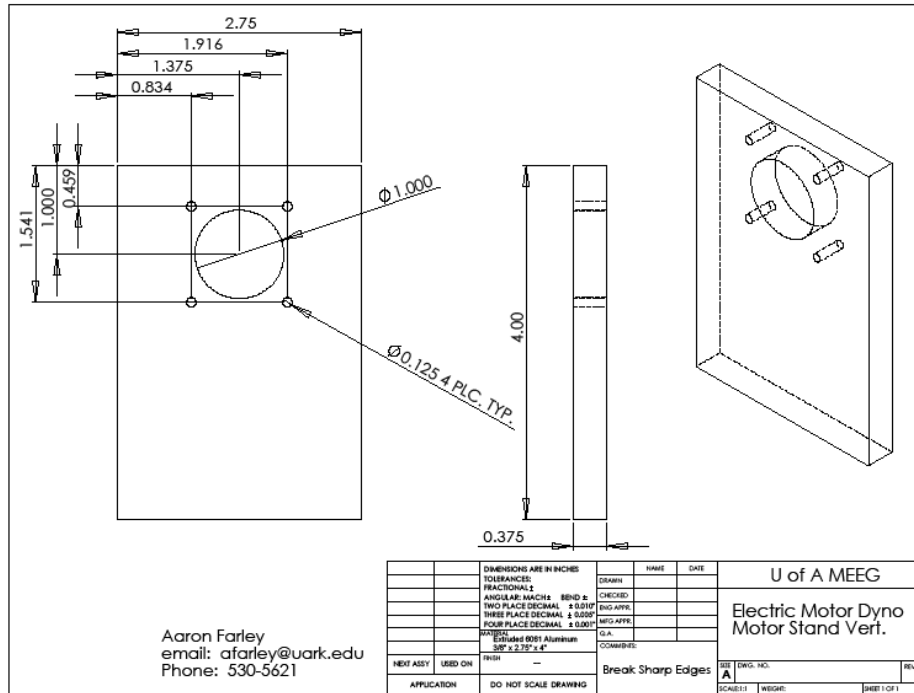Figure A.8. Motor stand horizontal drawing
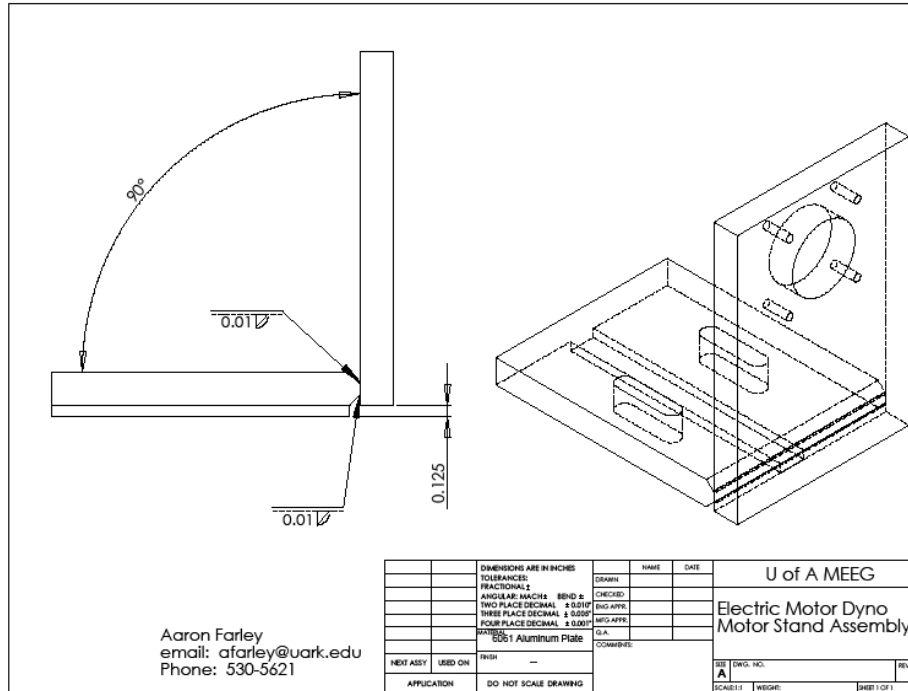

Figure A.9. Motor stand vertical drawing
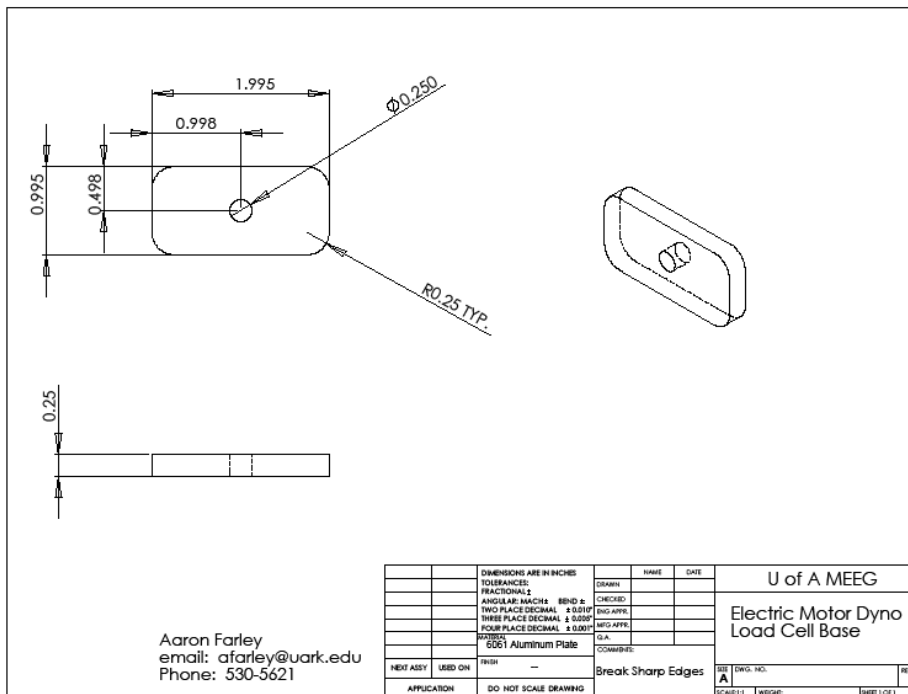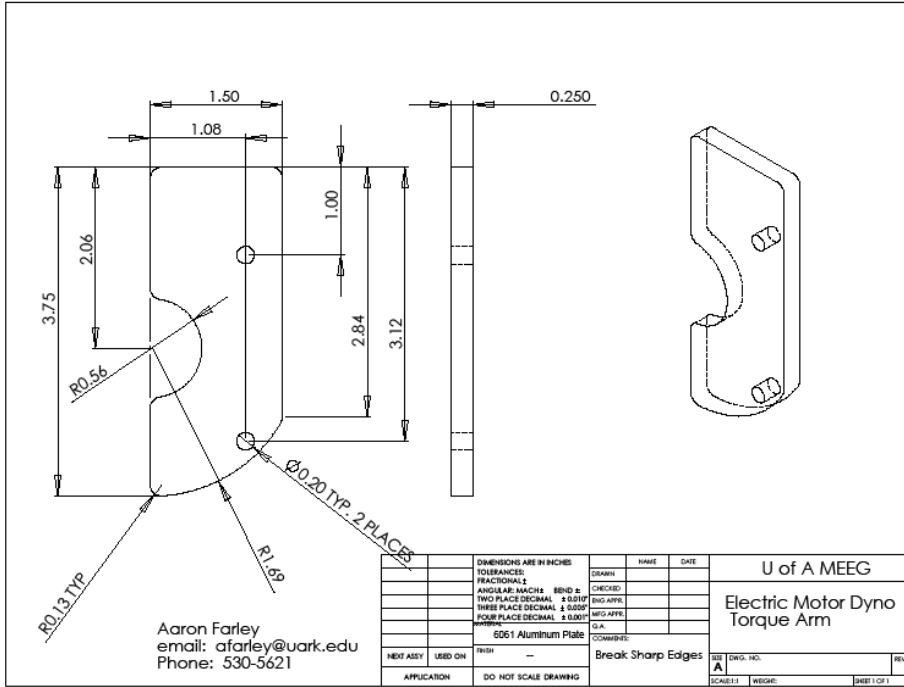
Figure A.10. Motor stand assembly drawing

Figure A.11. Load cell base drawing

Figure A.12. Torque arm drawing