DESIGN OF A TRIBOMETER RETROFITTED ONTO A COMPUTER NUMERICAL CONTROLLED MACHINING CENTER FOR ROCK DRILLING STUDIES

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Design of a Tribometer Retrofitted onto a Computer Numerical Controlled Machining Center for Rock Drilling Studies. (May 2015)

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The objective of this research project is to design the components of a tribometer, instrument the assembly for force data acquisition, and to retrofit it onto an existing computer numerical controlled (CNC) machining center; this design will be used for fundamental tribometric testing of tooling materials suited for rock drilling. When reproducing machining conditions in a traditional tribometer, the machine dynamics of the cutting process which determines the tribological response of the tool material is not well captured. Retrofitting an existing CNC machine for rock tribometric testing replicates the machine dynamics more accurately than traditional tribometer tests. Further, simultaneous rotary-percussive drilling capabilities would be enabled. For achieving this objective, the tribological parameters relevant to rock machining will first be identified, then individual components for applying and measuring forces will be designed, and finally the assembly will be instrumented for real-time data acquisition. This work is expected to provide a low-cost adaptation, as well as a template for in-situ tribological testing designs on equipment used for similar field-level operations.

ACKNOWLEDGEMENTS

I would like to thank my undergraduate research professor, Dr. Mathew Kuttolamadom, for allowing me to conduct this research experiment. His guidance and expertise in the field of tribology helped me to learn new concepts quickly and accomplish great work in a short time. This was a great experience and I am thankful to have had this opportunity.

I would also like to thank Texas A&M University and its faculty members who were always willing to lend help or resources whenever possible. It is extremely fortunate to have performed this research at an institution that is abundant in this aspect. This experience and information gained from this experiment will be useful in my remaining time as a student, as well as my future career after graduation.

NOMENCLATURE

AC: Alternating Current

A/D: Analog to Ditigal

CNC: Computer Numerical Controlled

d1: Diameter 1

d2: Diameter 2

DAQ: Data Acquisition

DC: Direct Current

F: Force Resultant

F1: Force 1

F2: Force 2

Ft: Force Tangential

Fr: Force Radial

Lb.: Pounds

N: Newtons

NI: National Instruments

q1: Fluid flow to the face of piston

q2: Fluid flow to the rod side of piston

r: Radius

rpm: Revolutions per minute

Tc: Frictional force

V: Linear Speed

v1: Velocity 1

v2: Velocity 2

ω: Angular Speed

Wc: Normal Force

CHAPTER I

INTRODUCTION

Tribology, the science of interacting surfaces in relative motion, has been limited in the type and scale of materials studied in relation to rock drilling. The need for better understanding rock cutting technology and data supporting these findings is becoming increasingly important with its growing applications in the oil and gas industry.

As an interdisciplinary area of research, tribology requires a thorough understanding of the specific properties of the material in question in relation to the surfaces of moving components. This in turn can provide important information for industrial applications by enabling the prediction of wear rates in practical industrial problems [1]. By conducting fundamental tribological research on applied problems, such investigations can lead to resolving industrial, scientific or biomedical friction and wear issues. By conducting experiments on simplified specimens that decouple the effects of geometry on the tribological response, the fundamental material behavior can be captured. Individual wear mechanisms and processes such as edge chipping may be separately and easily identified using such material-level test procedures. Directed investigation in such areas has the potential to lead to beneficial discoveries otherwise overlooked in the study of prolonged and multi-mechanistic wear testing [2]. Further, by varying speeds, lubricants, pressures and durations, a material response map as a function of process conditions can be obtained.

Motivation

The majority of documented tribological information has been primarily focused on specific types of metal/ceramic/polymer contacts. This research is focused on improving rock-cutting technology, which has numerous applications especially in the oil and gas industry. Rock cutting technology has primarily been studied on full-scale tests, leaving fundamental tribological research under-investigated. Furthermore, using a CNC machine to accomplish this task has numerous advantages over traditional tribology studies. Wear is significantly affected due to vibrations and other machine dynamics that occur during tribometric testing. The damping characteristics built into CNC machining centers counteract this to a certain extent and allow for more accurate results. Such mechanisms are in place for real-world rock machining applications. Another advantage that should be addressed is the capability of programming CNC machines to provide a variety of different movements and patterns. A related prime advantage would be the enabling of simultaneous rotary-percussive drilling capabilities. This important functionality is critical when considering the many possibilities of relative motion causing wear of tooling used in rock machining. Thus, incorporating tribometric testing capabilities onto an already existing CNC machine has significant advantages over traditional tribometers for fundamental rock machining studies.

Objectives

The specific objectives of this project are listed below:

1. To identify the parameters of interest that must be applied and measured for rock tribology studies.

    - Rock tribology poses additional and unique variables of interest that differ from metal/ceramic/polymer contacts. These will be systematically identified through literature review.

2. To design the components for controlling applied loads and measuring frictional forces.
    - Mechanical components will be designed, fabricated and calibrated for precise application and measurement of the relevant forces.
3. To instrument this assembly for real-time data acquisition and control.
    - Force data will be acquired using NI LabVIEW and associated hardware.

Expected Contributions

The major expected contributions from this work are:

- Design and assembly of individual tribometric testing components
- Retrofitted assembly of this pin-on-disc tribometer onto an existing CNC machining center
- Implementation of hardware and software for real-time force data acquisition
- A standardized template usable by other investigators for retrofitting existing CNC machining centers with tribometric testing capabilities
- Preliminary results from rock tribology experiments to identify the material’s tribological response as a function of time and process conditions

CHAPTER II

BACKGROUND & LITERATURE REVIEW

The understanding of Tribology involves an extensive working knowledge of its uses and applications as well as the multiple possibilities of acquiring the specific information needed to analyze this information appropriately. For the purposes of this research, an overview of the most important aspects of this field will be covered to give a general knowledge of what is being evaluated. The following sections include general information on tribometers, their working principles, the forces being measured and how those forces are converted to useful information.

Tribology of Rock Cutting/Machining

The science of analyzing rock cutting is a difficult matter due to the constant irregularities of both the surface and contact. To accomplish this with much detail, the interference between the cutting tool and rock must be located after each tool movement. There is a bounding area that includes the tool's previous and current locations. A search is then performed on the rock surface vertices to locate any that are within the region defined by the motion of the normal and frictional force mechanics of rock drilling [5]. However, for the purposes of this experiment, just an overall view of the wear rate and volume will be evaluated along with the accurate detection of the coefficient of friction. The mechanics of forces experienced at any contacting points during cutting applications can be seen in **Figure 1** [12], which shows the forces experienced by a typical tri-cone cutting bit. The normal and frictional forces (shown by the indentation and cutting forces respectively) represent the force geometry found on a drill bit or pin/ball of a tribometer. After measuring these two forces and inputting them into LabVIEW, a coefficient of friction will be calculated and compared with that of an actual tribometer.

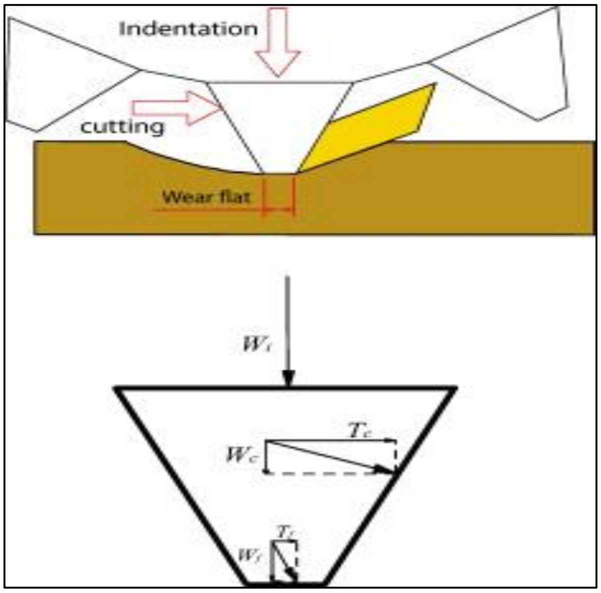


Figure 1: Tri-Cone Bit Tooth Forces

Principle of Tribometers

Tribometers can use both linear and rotary modes of motion in a large range of rpm's. After the sample is mounted, a known normal force is applied on a pin or ball. This is commonly done with the use of a dead-weight force. The contact of the pin or ball with the surface to be studied generates wear. Whether the motion is linear or rotary, the deflection of the elastic arm is detected by a high resolution force sensor as seen in **Figure 2** [6]. This information is then converted by software equipped with the tribometer to the appropriate coefficient of friction [7]. In addition, the volume lost allows for calculating the wear rate of the material.

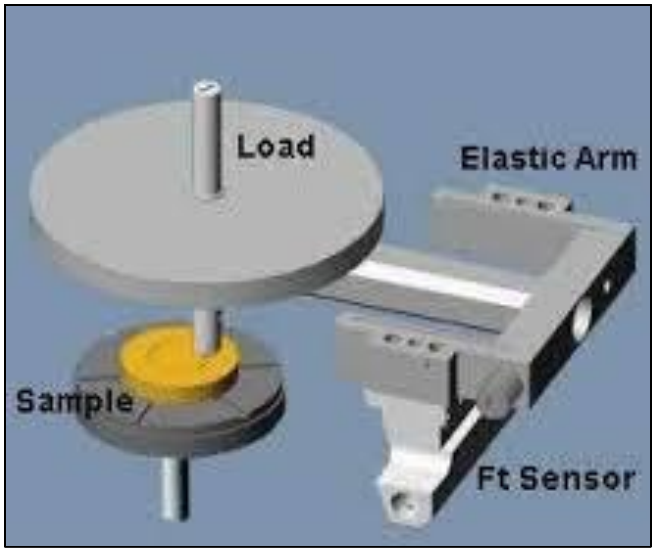


Figure 2: Working Principle of a Tribometer

Force Measurement Using Different Strain Gauge Types

The strain gauge is the primary component of a load cell/sensor which allows the measurement of a voltage output caused by a change in the resistance of the circuit. This is used to represent useful information including presser, force, torque, position, etc. They rely on a pattern of resistive foil mounted on the backing of the material. As the foil is subjected to stress, its resistance changes. This change in resistance is measured using a Wheatstone bridge circuit. A quarter Wheatstone bridge circuit is displayed in **Figure 3** [9]. The circuit is excited using a DC supply and various signal conditioning. Then as a load is applied to the sensor, the resistance change causes the Wheatstone bridge to become unbalanced and results in a signal output. Typically, this output is in millivolts and is amplified by the conditioning electronics to around 5 to 10 volts [8].

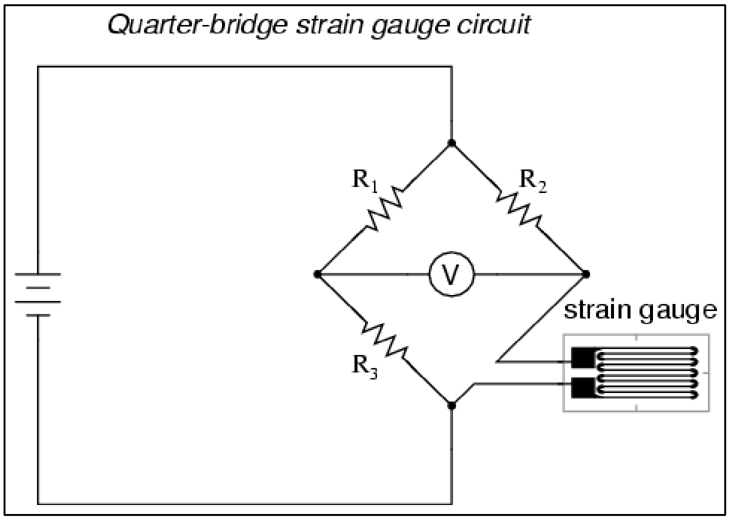


Figure 3: Wheatstone bridge Circuit

The sensors used in this experiment are capable of measuring applied loads in more than one direction. If absolutely symmetrical, the measured force in each direction should be the same magnitude but negatives of each other. **Figure 4** [10] shows the compression and tension forces for this concept within a half Wheatstone bridge circuit.

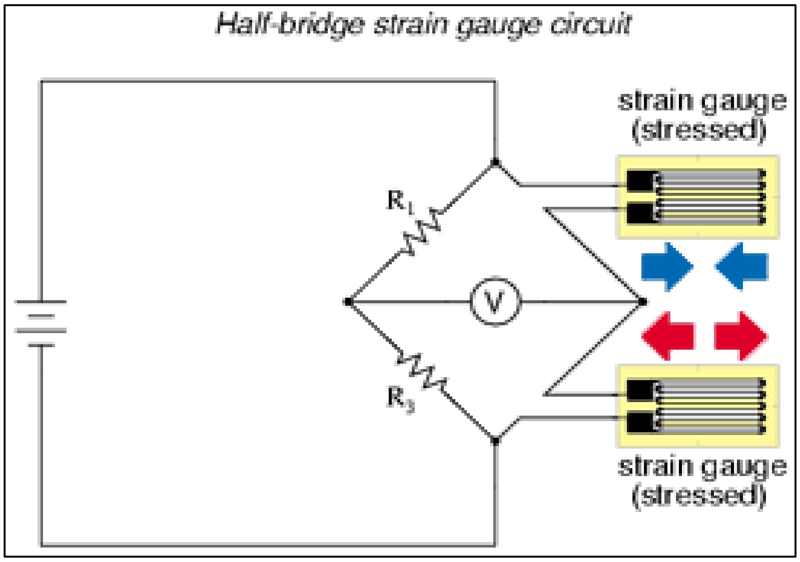


Figure 4: Compression and Tension Forces

Force Data Acquisition (DAQ) Systems

Data acquisition systems are available in a variety of forms. The main principle behind DAQ systems involves acquiring signals from measurement sources and storing these signals in a digitalized form for analysis and presentation on a PC. There are five main components of a typical DAQ system commonly needed for almost any application:

Transducers and Sensors

Transducers and sensors are devices used to transform the physical characteristics to electrical. These are most commonly in the form of force, pressure, temperature, flow, etc.

Signals

There electrical signal produced by the transducers will typically be in the form of dc voltage, ac voltage, resistance, frequency, and current. For strain gauges, voltage is the electrical characteristic that is evaluated.

Signal Conditioning

Each signal a transducer or sensor produces will need to be conditioned or amplified to a form that is more easily measured by the system. Strain gauges typically produce electrical signals in the millivolt range that will need to be amplified to volts to make measuring feasible.

DAQ Hardware

Data Acquisition hardware commonly uses an A/D converter, which converts dc voltages acquired from the transducers into digital data. Advanced systems may include this conversion in the same control module used to condition the signal.

Driver Software

A supporting driver software is required in order to view the output data acquired by the transducers. Many hardware systems will come with their own software capable of viewing this data for real-time analysis.

CHAPTER III

COMPONENT DESIGN & SETUP FOR FORCE DATA ACQUISITION

This chapter deals with the design of the various components needed for applying and measuring forces that will replicate the functionality of a tribometer. It will explain the details of the forces that need to be applied and measured, and review the options available that were considered. Lastly, the selection and design process is explained so that proper reasoning may be shown supporting the final decision for the experimental design setup.

Force-Related Requirements of the Tribometer for Rock Drilling Studies

Specimens of a tribometer experiment will experience two basic forces that are shown in **Figure 5** [4]. These are the normal and frictional forces imparted on the pin or ball from the disc.

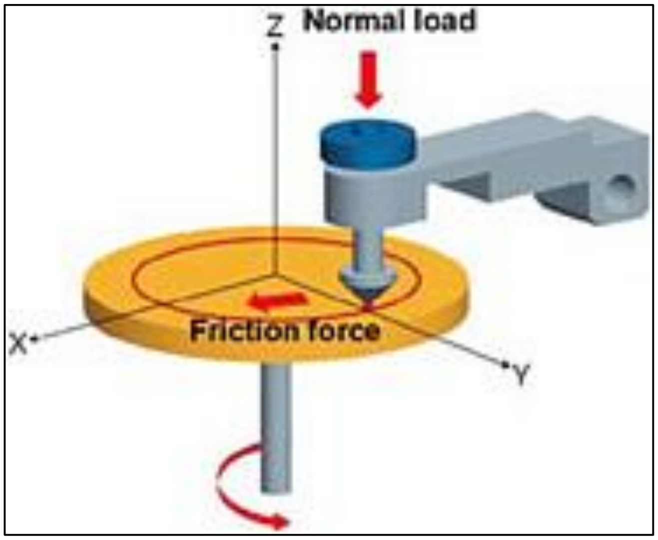


Figure 5: Tribometer Forces

There are similar turning forces experienced when machining using a lathe, as shown in **Figure 6** [11]. These forces will be felt typically when performing facing or turning operations.

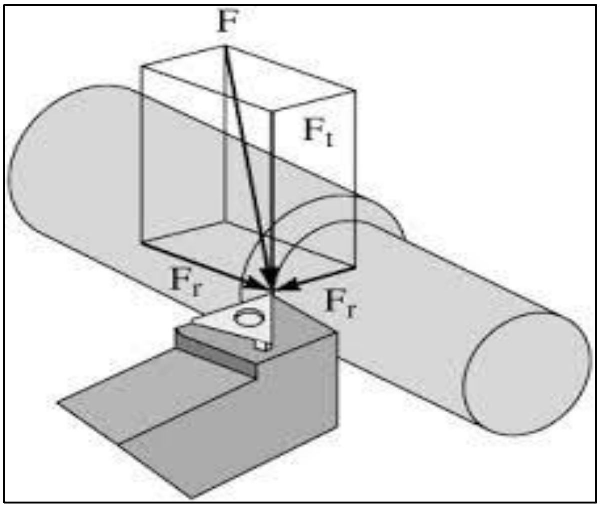


Figure 6: Lathe Turning Forces

Furthermore, the original intent for investigating these phenomena can easily be seen in the tri-cone bit forces experienced during actual rock drilling applications as in **Figure 7** [12].

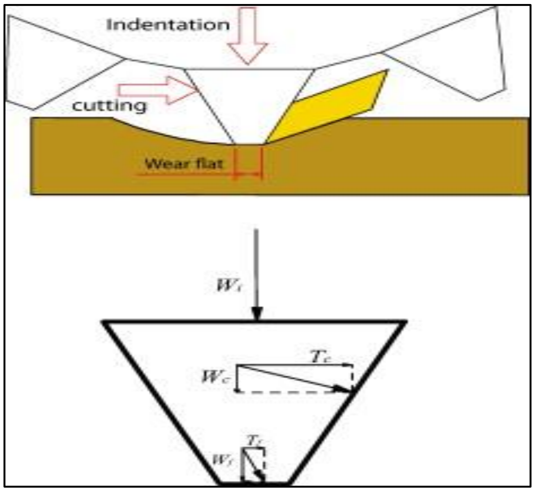


Figure 7: Tri-Cone Bit Forces

An additional requirement aside from gathering the appropriate forces that affect the drilling bit is the sliding velocity felt at the point of contact. Since a CNC lathe will be used, noting the real-time rpm of the spindle and the radial distance of the pin/ball from the center of the specimen will allow for the calculation of the correct sliding speed. This formula is as follows:

$$\boldsymbol{V = \omega * r} \tag{1}$$

Where "$\boldsymbol{V}$" equals linear speed, "$\boldsymbol{\omega}$" equals angular speed, and "$\boldsymbol{r}$" equals radius (distance of point of contact from the center of the disc. The angular speed for this experiment was kept at 180 rpm's (18.85 radians/second), and the radius was 1.4 inches. Therefore, the velocity of the disc at the point of contact was 26.39 inches/second.

Options for Attaining these Requirements

Normal Force Application

The application of the normal force can be achieved by a variety of methods. The options that were considered for the purpose of this research experiment include the following:

1. Dead Weight Force: This has proven from past researchers to be a crude but simple force application technique [3]. Due to unwanted variables in the machine from movement and vibration, this method may not produce results that are in the desired range of accuracy. However, with further experimentation this concept may be a possibility if a sound and robust fixture system is designed and implemented onto the CNC. **Figure 8** [13] shows a dead-weight force application.

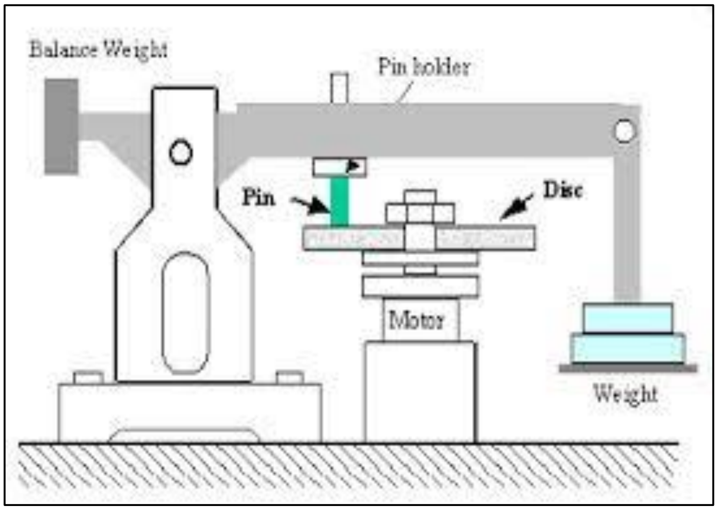


Figure 8: Dead-Weight Force Application

2. Pneumatic Air Piston: Using controlled air to provide a constant normal force application, pneumatics is a reliable and cost effective technique to exert a normal force. It relies upon the concept of differential pressure inside a cylinder, thus causing a constant force in either direction. This would include an air cylinder fixed to either the tool post or carriage table while controlled by means of a regulator. **Figure 9** [14] shows a pneumatic cylinder force application.

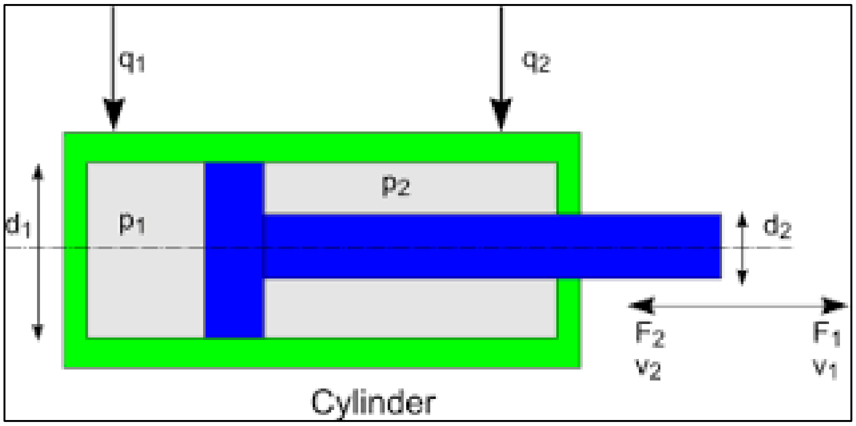


Figure 9: Pneumatic Cylinder Force Application

3. Force Transducer: A force transducer is a common device used to accurately measure an applied force onto a surface. These are commercially available in many different forms, most including options for DAQ. This device may either be incorporated with the existing tool post or on the carriage table. It may also be used with other force application devices such as pneumatic air pistons. Another requirement to keep in mind for this type of application would be the resolution of the device. These features are dependent of the quality of the force sensor. **Figure 10** [15] shows an S-beam force measurement.

Figure 10: S-Beam Force Measurement

Frictional Force Measurement

The application of the frictional force can also be demonstrated by several methods. This will be a more difficult characteristic to measure in this experiment. The ability of an actual tribometer to measure the frictional force between two objects is what primarily sets it apart from typical applications that measure contact forces. The options that were considered for the purpose of this research experiment include the following:

1. Torque Sensor: There are torque sensors available commercially that if incorporated correctly could effectively measure the frictional force caused by the contact made during the

experiment. This would be accomplished by measuring the real time torque output of the lathe spindle and noting the different torque value displayed while making contact with the specimen. This information along with the known rpm value will allow for the frictional force calculation. **Figure 11** [16] shows a torque sensor measurement.

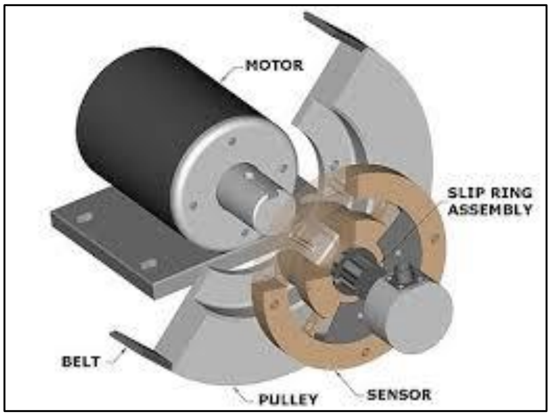


Figure 11: Torque Sensor Measurement

2. Bending beam load cell: This is a much simpler means of acquiring the frictional force. Because the measured load output of this device is transverse to the sensor rather than a compressional or tensional load, it can be used to gather frictional force data. **Figure 12** [17] shows a bending beam force measurement.

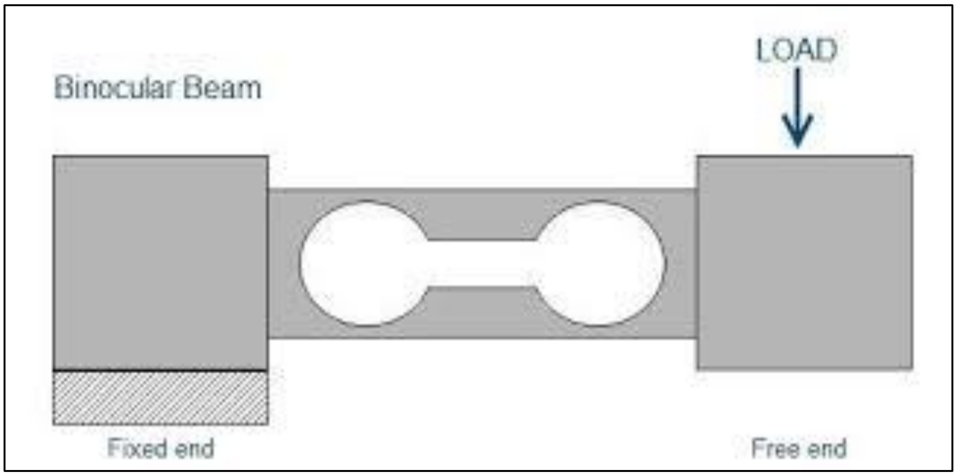


Figure 12: Bending Beam Force Measurement

Component Selection & Design for Tribometer

The desired force range for measurement and acquisition has initially been estimated to be 1 - 100 N (0.225 - 22.48 lb.). The S-beam type transducer was selected to fulfill the normal force application **(Figure 13).**

Figure 13: S-Beam Transducer

A bending beam type transducer **(Figure 14)** was chosen to apply and measure the normal and frictional forces to the specimen. These options were chosen because they are accurate, use full-bridge strain gauge circuits, are DAQ compatible and are adaptable for use of a fixture with the CNC machine.

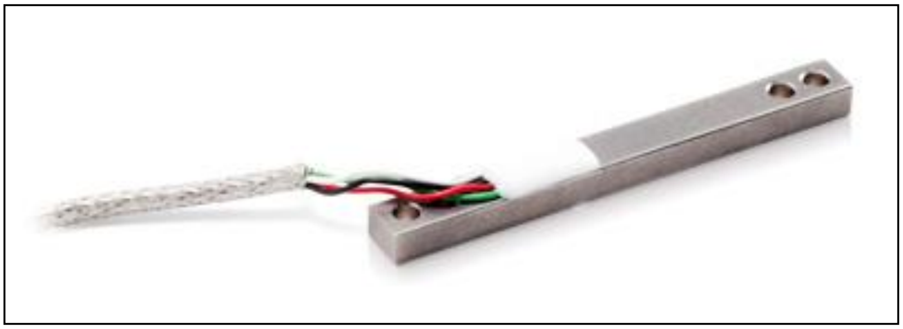


Figure 14: Bending-Beam Transducer

The following shows the first design iteration for this component setup. **Figure 15** shows a solid model of design 1 assembly.

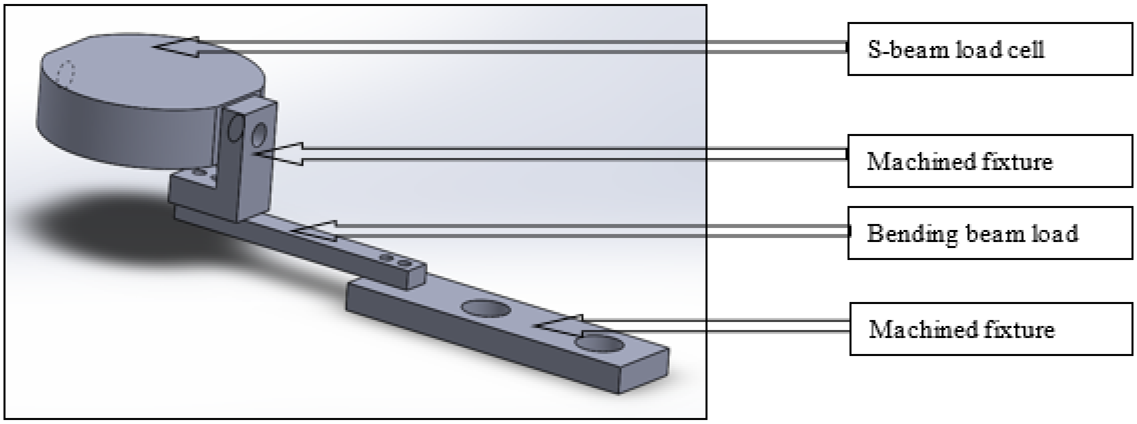


Figure 15: Design 1 Assembly

This first design was not found to be optimal due to the misalignment of the S-beam axis of measurement with the center of the system. Design analysis suggested this would have caused the normal force to produce an unwanted upward bending moment about the bending beam load cell, which would be counter-productive in the frictional force measurement and yield incorrect data. **Figure 16** shows the expected force misalignment in design 1.

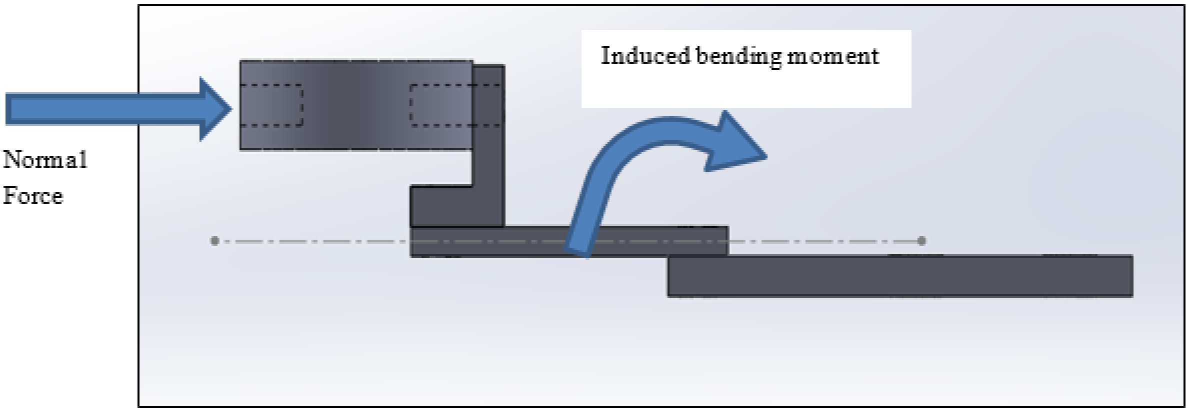


Figure 16: Design 1 Force Misalignment

A design iteration (design 2) was created to eliminate the previous misalignment problem. The machined fixture pieces were altered in the 3D modeling software, allowing the entire system to become aligned properly. **Figure 17** shows the design 2 to minimize/eliminate the unwanted moment.

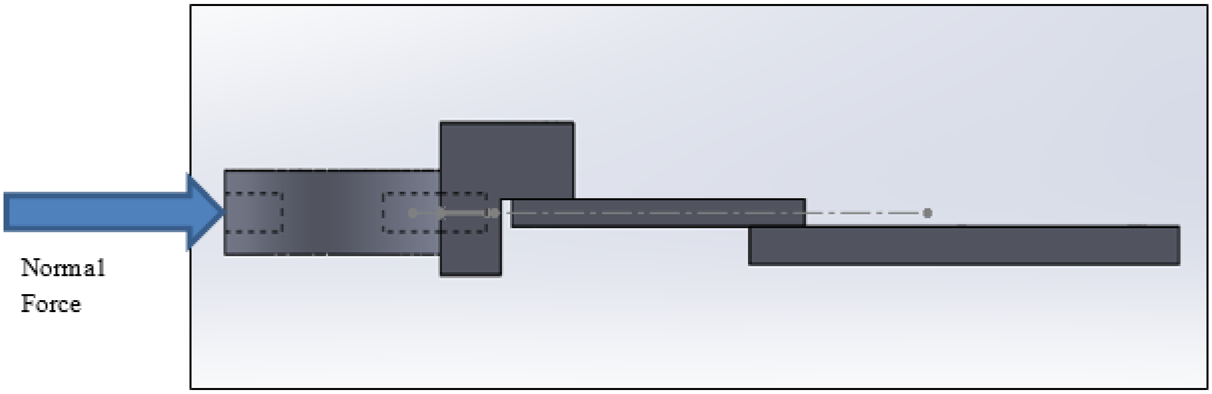


Figure 17: Design 2 Minimizing the Misaligned Forces

The final solid model of design 2 can be seen in **Figure 18**.

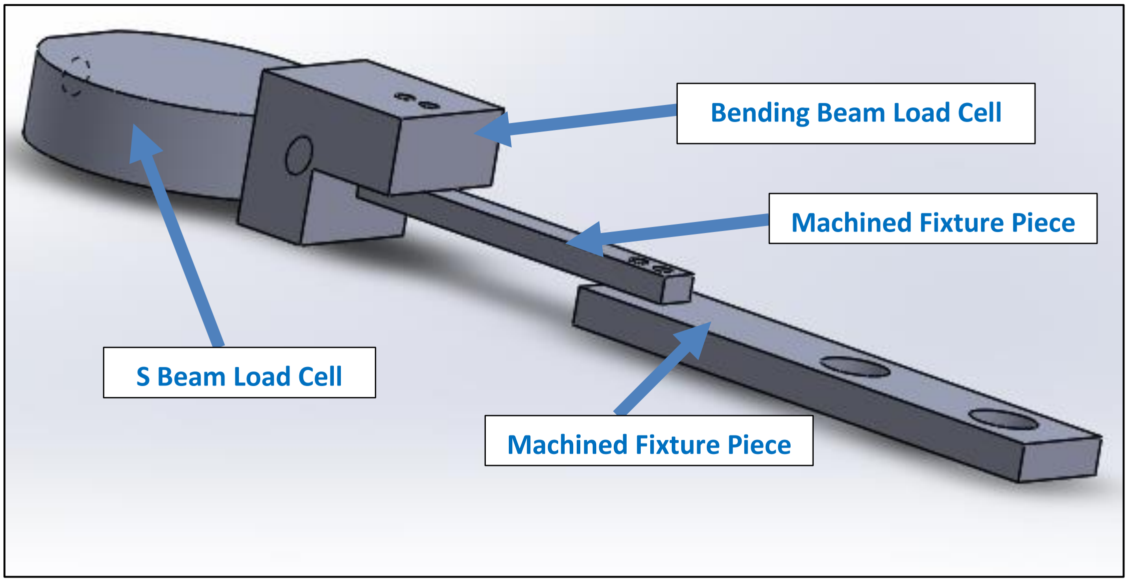


Figure 18: Solid Model of Design 2 Assembly

Fabrication of the Fixtures

For instrumenting this transducer assembly, the CNC machine was examined in depth and strategies for incorporating force application and measurement capabilities were explored and evaluated. The applied normal force will need to have low variability, and be perpendicular to the sliding velocity. The design geometry and dimensions for the two fixture pieces can be seen in **Figure 19**. All dimensions are inches.

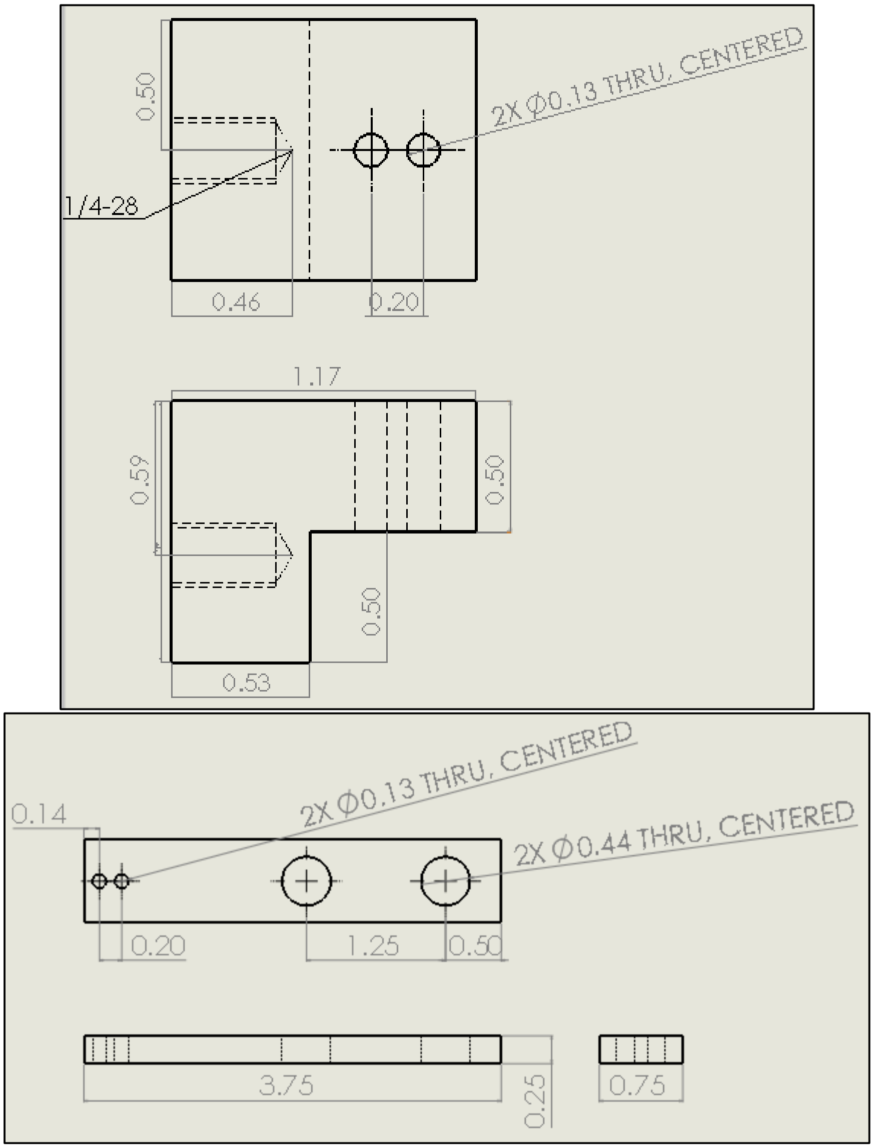


Figure 19: Geometry and Dimensions of Fixtures

The material chosen for this experiment was aluminum for its light weight characteristics. Adequate thicknesses were chosen to ensure that the minimal material deflection caused by the normal and frictional forces would be much less than that of the force sensors and therefore have little effect on the data results. A manual milling machine using appropriate tooling and feeds/speeds was used to create the fixtures that included flat faces, square geometry and adequate surface finish. This ensured that the entire fixture system would assemble correctly with the transducers and the CNC machine bed. **Figure 20** shows photos of the completed fixture pieces.

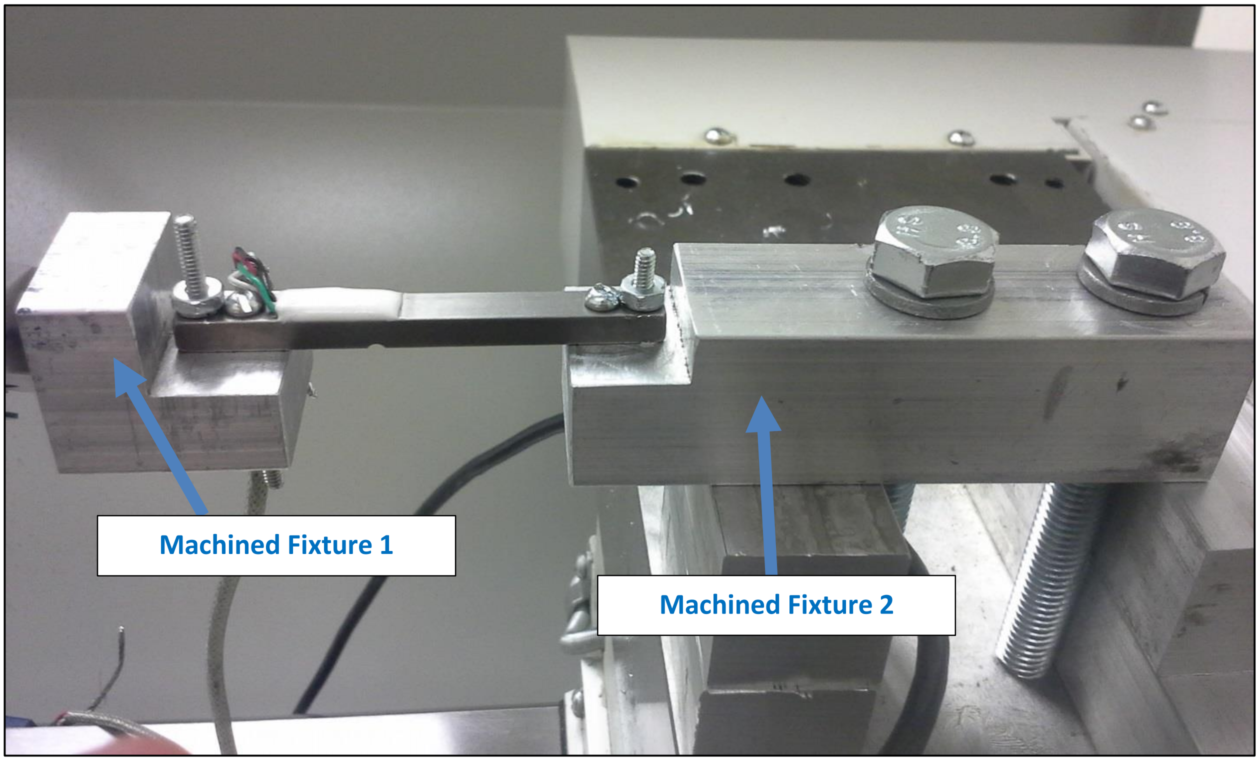


Figure 20: Actual Fixture Pieces

CHAPTER IV

DATA ACQUISITION & SENSOR CALIBRATION

The data acquisition system is the brain of the experiment and has the ability to convert the voltage output of the transducers into a usable unit such as force in pounds or newtons. This chapter will explain the selection of DAQ equipment used, as well as a brief guide to the initial installation, connecting, calibrating and general user interface for taking real-time measurements.

Selection of DAQ Equipment

The data acquisition hardware/software provider chosen for this experiment was National Instruments. They were able to supply all of the components needed in order to extract information from a transducer and convert to a usable format for display and analysis. The items listed below are the products purchased that were used to produce the data found in this experiment:

1. DAQ Module with Chassis and DAQmx (NI 9237): Displayed in **Figure 21**, the DAQ module and chassis was chosen based on specific criteria. In order to provide results comparable to that of an actual tribometer, the sampling rate and bandwidth of the module needed to be adequate enough to view multiple frequencies of data. The ability to perform signal conditioning internally, offset/null calibration and shunt calibration were all attributes of the DAQ module that simplified the data measurement. The installation and specific set-up is completed using NI-DAQmx that can be purchased

together or separately with the module. The module is USB bus-powered and contained 4 RJ50 I/O connection ports.

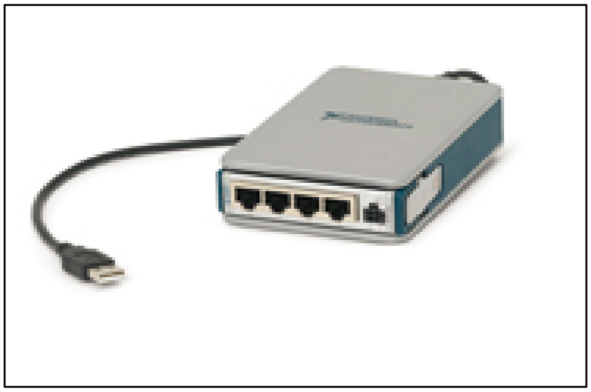


Figure 21: DAQ Module

2. Screw Terminal Block (NI 9949): This is an adapter used for connecting the module to the transducers. Although it is not the only means for connectivity to the module, it is among the simplest available. The block connects to the module with the RJ50 cable and contains 10 pin screws that will accept connectivity wires from transducers. It is shown in **Figure 22**.

Figure 22: Terminal Block Connectors

3. RJ50 cable (199022-02): This cable is used to connect the screw terminal block to the DAQ module. It should not be confused with a RJ45 cable (standard Ethernet cable), which looks very similar. It is shown in **Figure 23**.

Figure 23: RJ50 Cable

4. LabVIEW Software: LabVIEW was chosen as the driver software because of its compatibility with the previously selected hardware and its simple user interface. This software allows the user to create programs to display, monitor and analyze data in real time. It is easily purchased and downloaded and ready to use following a quick initial set-up procedure.

Initial Installation and Setup

The DAQ module requires its own installation software (NI-DAQmx) which is used to set-up the module and define the specific parameters of the user's experiment. It will need to be installed on the computer used for data analysis along with the driver software previously mentioned. This set-up procedure is unique to the experiment design and selection of DAQ hardware/software. Instructions will need to be followed correctly in order to successfully and accurately collect data.

Connecting DAQ System and Wiring Transducers

Connecting the entire DAQ system correctly is absolutely imperative in allowing data to be extracted from the transducers. The following procedure will display the connection and wiring required for the DAQ system selected for this experiment:

1. Connect the DAQ module to the computer via the USB port.
2. Connect the DAQ module to the terminal blocks via the RJ50 cable.
3. Wire the transducer wires to the terminal block as specified in the user's manual for the DAQ module. Most strain gauge transducers will have 4 wires connected to it. These are Excitation (+), Excitation (-), Output (+), and Output (-). Depending upon the transducer chosen, the specifications page will include the color coded wiring information for an analog to digital data conversion. This is displayed in **Figure 24**.

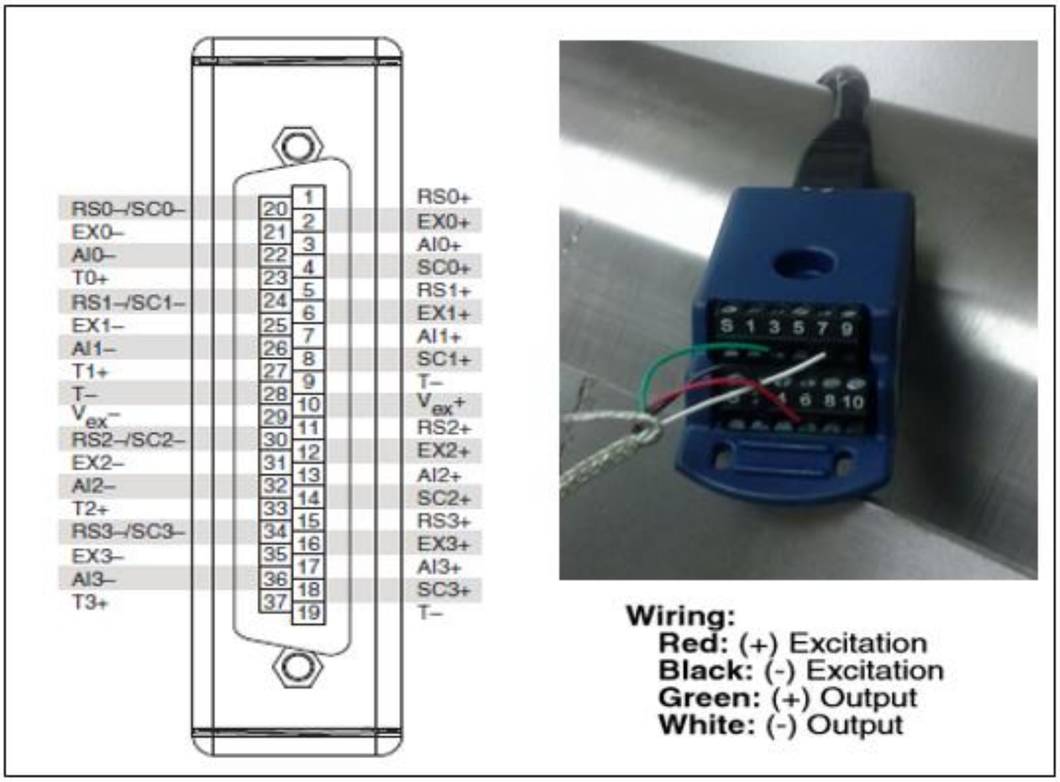


Figure 24: Wiring Transducer to the Terminal Block

Calibration of Transducers

All transducers must first be calibrated before any accurate measurements can be taken. This may be done using a known weight or another transducer that has previously been calibrated. The DAQ system for this experiment has the ability of performing both offset/null and shunt calibration without the use of supplementary weights or transducers. Therefore, calibration may be performed using the DAQmx software or LabVIEW after all set-up and connections are complete. LabVIEW uses an intuitive drag and drop method of creating usable programs to analyze data. A brief calibration procedure is shown below using the DAQ system previously mentioned:

1. Create a VI program in LabVIEW like the one shown in **Figure 25**.

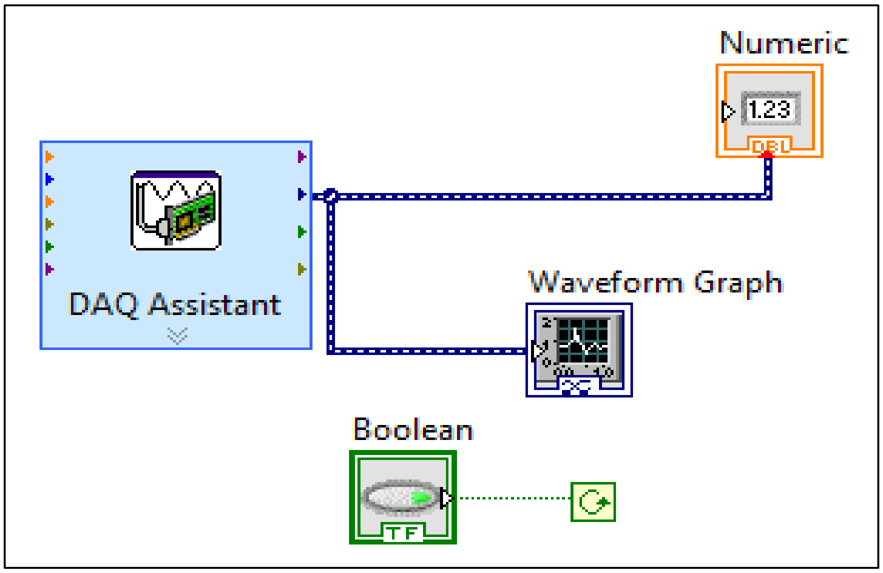
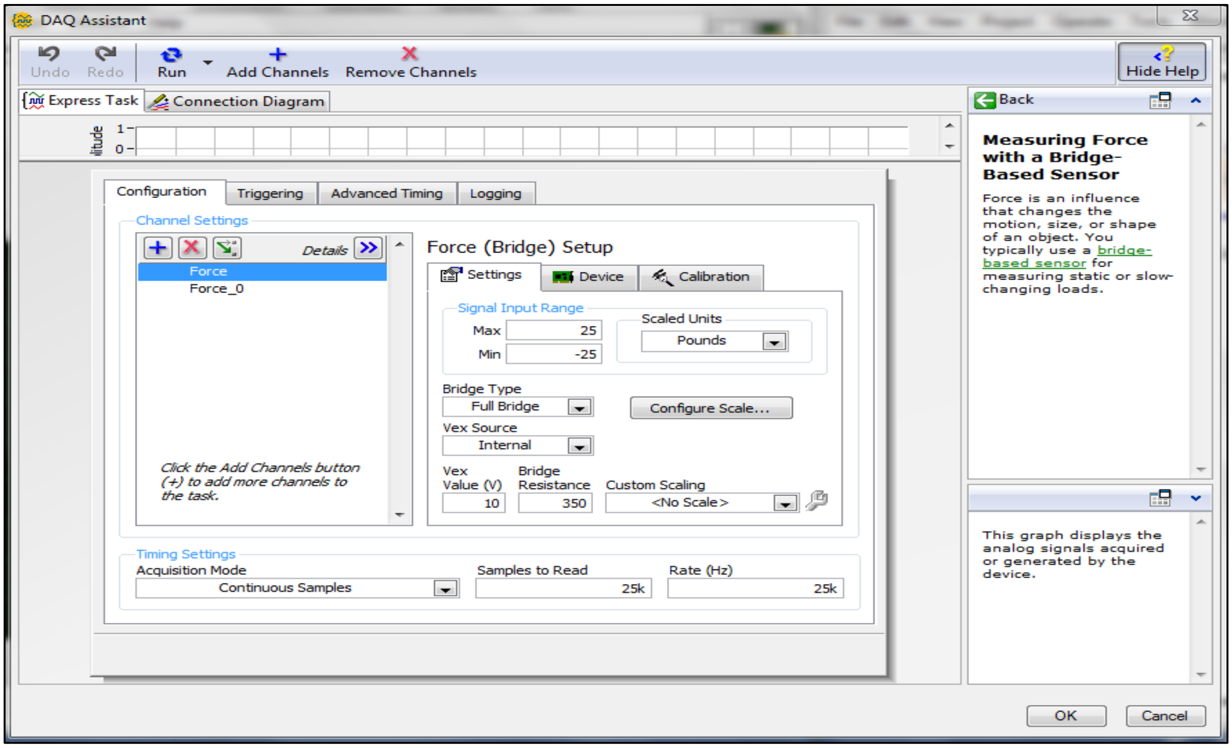


Figure 25: Virtual Instrument (VI) Circuit Diagram

2. Double-click on the DAQ Assistant icon and wait for the window to appear as in **Figure 26**.



Measuring Force with a Bridge-Based Sensor

Force is an influence that changes the motion, size, or shape of an object. You typically use a bridge-based sensor for measuring static or slow-changing loads.

This graph displays the analog signals acquired or generated by the device.

Click the Add Channels button (+) to add more channels to the task.

Max 25

Min -25

Scaled Units: Pounds

Bridge Type: Full Bridge

Vex Source: Internal

Vex Value (V): 10

Bridge Resistance: 350

Custom Scaling: <No Scale>

Acquisition Mode: Continuous Samples

Samples to Read: 25k

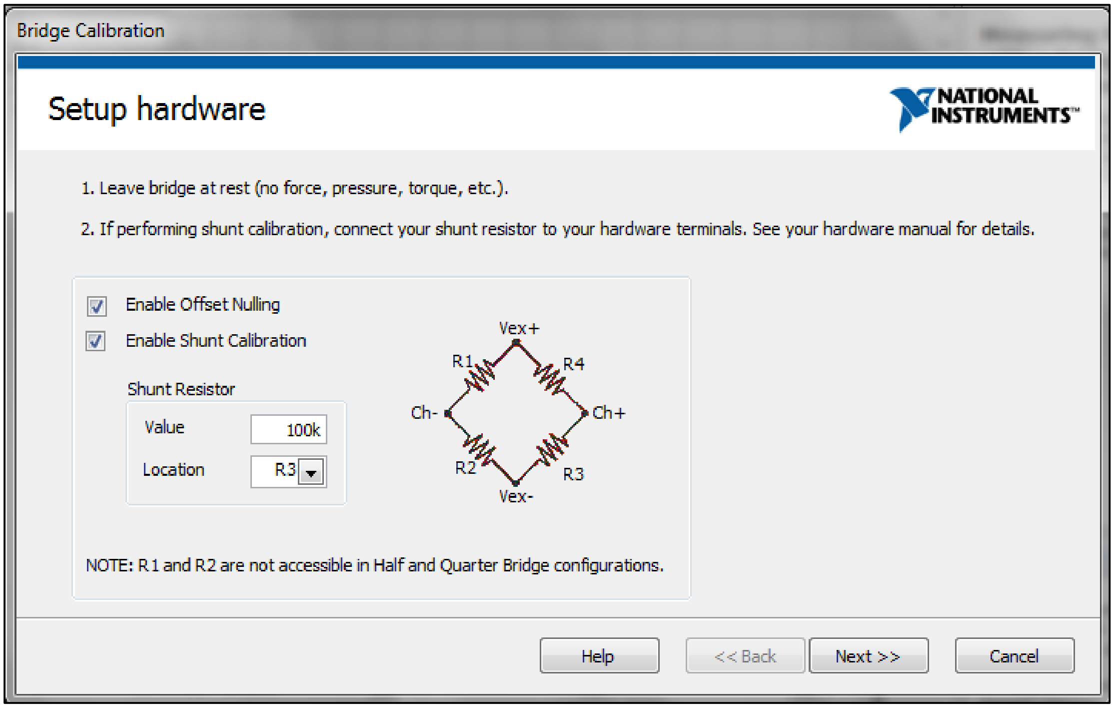
Rate (Hz): 25k

Figure 26: DAQ Assistant Window

3. Fill in all available fields shown in **Figure 26** that correspond to the transducer being used. Add channels as needed.

4. The “Device” tab is used for bridge calibration of the transducer, utilizing the built-in offset/null or shunt calibration ability of the DAQ system. See **Figure 27**.

5. The “Calibration” tab is used to calibrate with multiple known loads on the transducer to use for reference calibration points in the experiment. See **Figure 28.**



Bridge Calibration

Setup hardware

1. Leave bridge at rest (no force, pressure, torque, etc.).

2. If performing shunt calibration, connect your shunt resistor to your hardware terminals. See your hardware manual for details.

☑ Enable Offset Nulling

☑ Enable Shunt Calibration

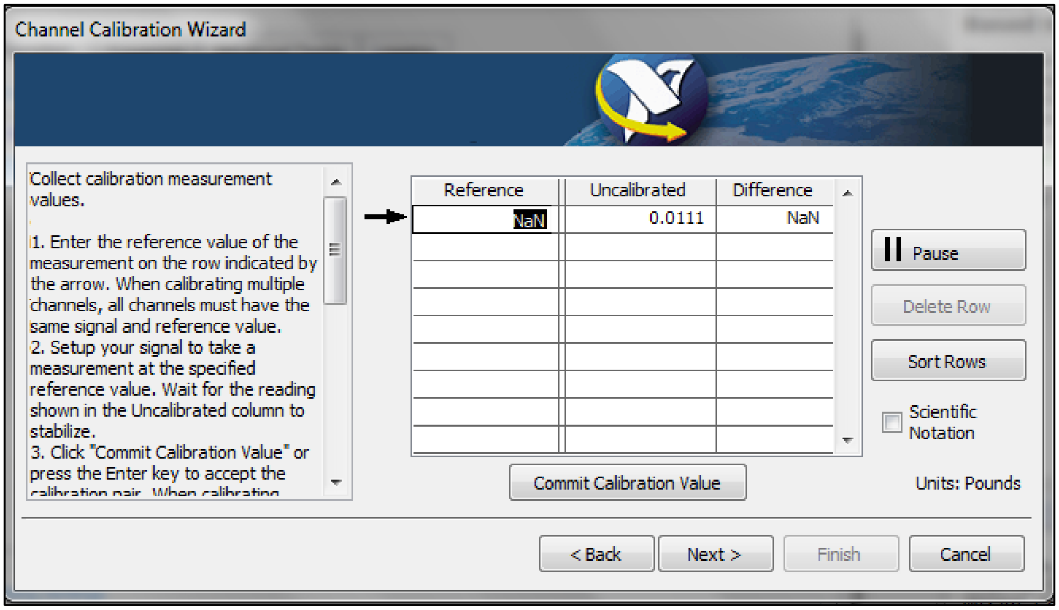
Shunt Resistor

Value: 100k

Location: R3

NOTE: R1 and R2 are not accessible in Half and Quarter Bridge configurations.

Figure 27: Bridge Calibration



Channel Calibration Wizard

Collect calibration measurement values.

1. Enter the reference value of the measurement on the row indicated by the arrow. When calibrating multiple channels, all channels must have the same signal and reference value.
2. Setup your signal to take a measurement at the specified reference value. Wait for the reading shown in the Uncalibrated column to stabilize.
3. Click "Commit Calibration Value" or press the Enter key to accept the

Reference	Uncalibrated	Difference
NaN	0.0111	NaN

☐ Scientific Notation

Units: Pounds

Figure 28: Channel Calibration

Taking Real-Time Measurements

Once the DAQ system is connected correctly and calibration is complete, data may then be collected and evaluated. First click "Run Continuously" in the upper left corner of the front panel window of LabVIEW. See **Figure 29**.

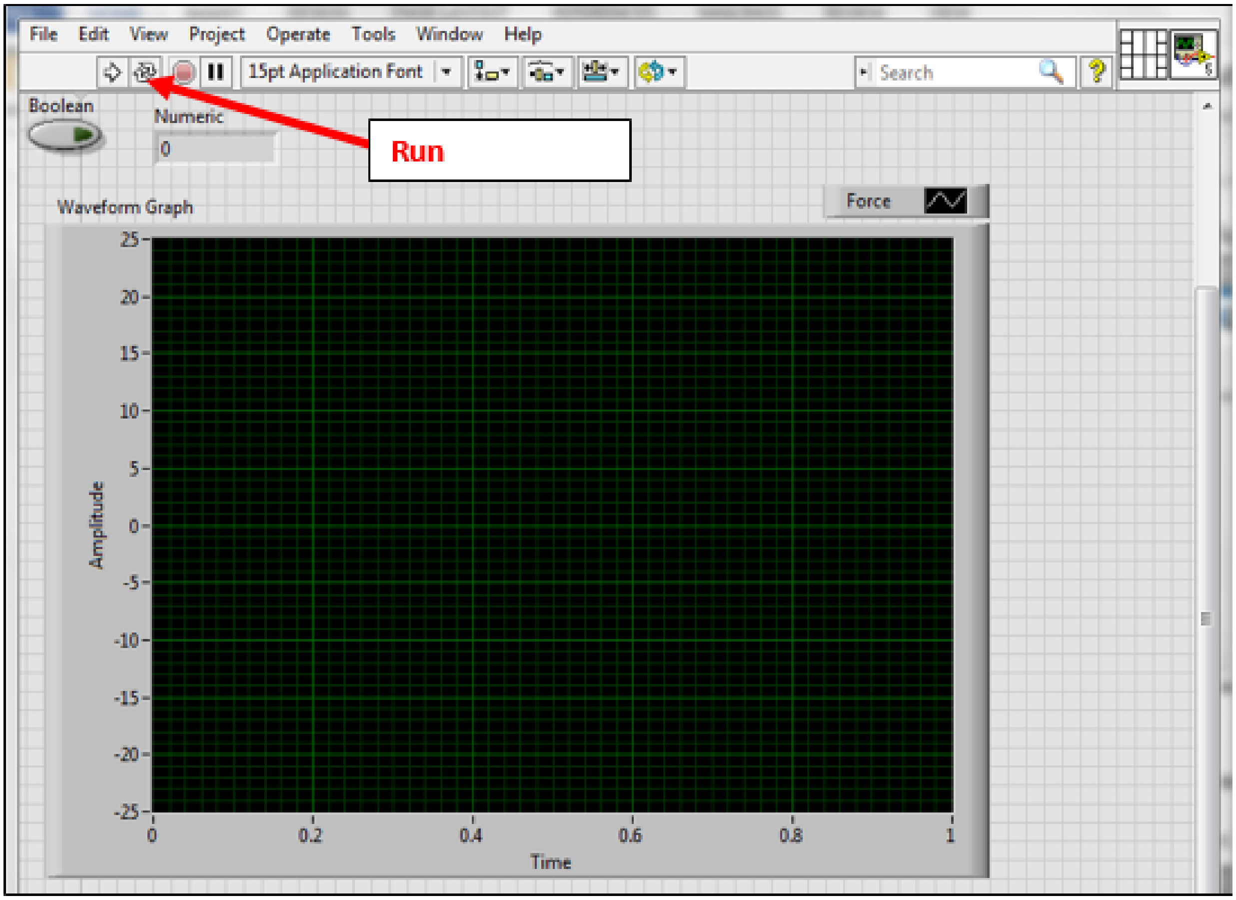


Figure 29: Run Continuously Button

At this point, LabVIEW is able to display in real time the data output from the transducer. The DAQ system used for this experiment is able to acquire up to 25,000 readings per second. Therefore, data can be measured consisting of high-frequency irregular impacts such as those seen in actual rock drilling. Unlike a standard tribometer, CNC machines are capable of being programmed to represent nearly any wear or impact patterns that mimic those seen in real applications. This advantage is both safe and repeatable on these machines, guaranteeing accurate and reliable results. An example of applying a constant force can be seen in **Figure 30**. Both of the transducers used in this experiment have two degrees of freedom that can be accurately measured with a DAQ system. For the s-beam transducer, this is compression or tension caused by a force directly in line with the mounting holes. For the bending-beam transducer, it is also a compression or tension force experience from one end of the beam directly up or down in a direction perpendicular to the top face. The absolute value of the compression and tension forces for both transducers should be identical, but opposite in their sign convention. Because of this, values displayed in the waveform graphs may be either negative or positive depending upon which direction the applied force is acting on the transducers.

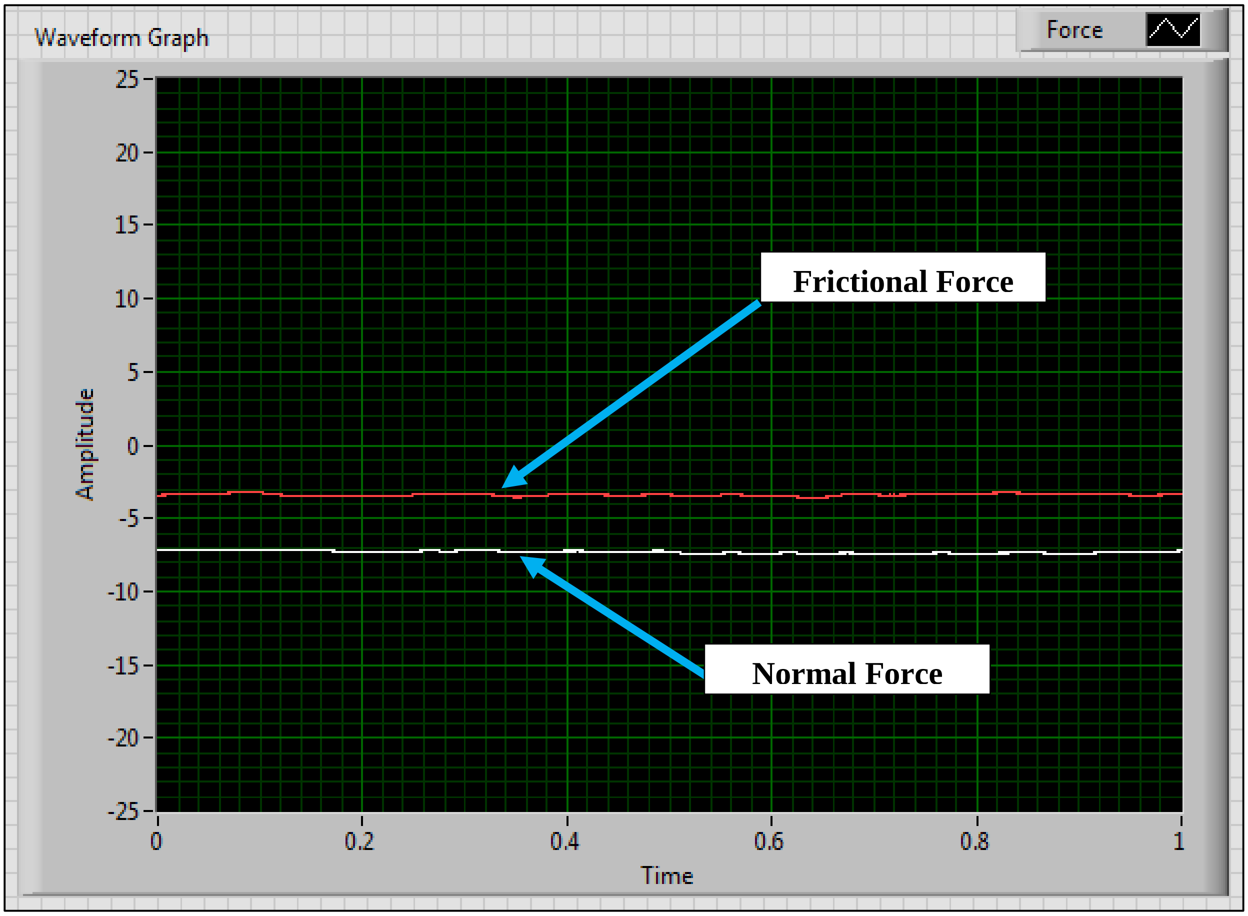


Figure 30: DAQ of Constant Force

Because of the high sample rate capabilities of this DAQ software, a relatively constant data waveform is generated. This allows for the user to easily pause the data acquisition and export the data for analysis. This set-up is also capable of simulating and displaying a low frequency force **(Figure 31)**. Even with constant changes in the applied force, the software is still able to display a smooth data waveform line that can be exported for review.

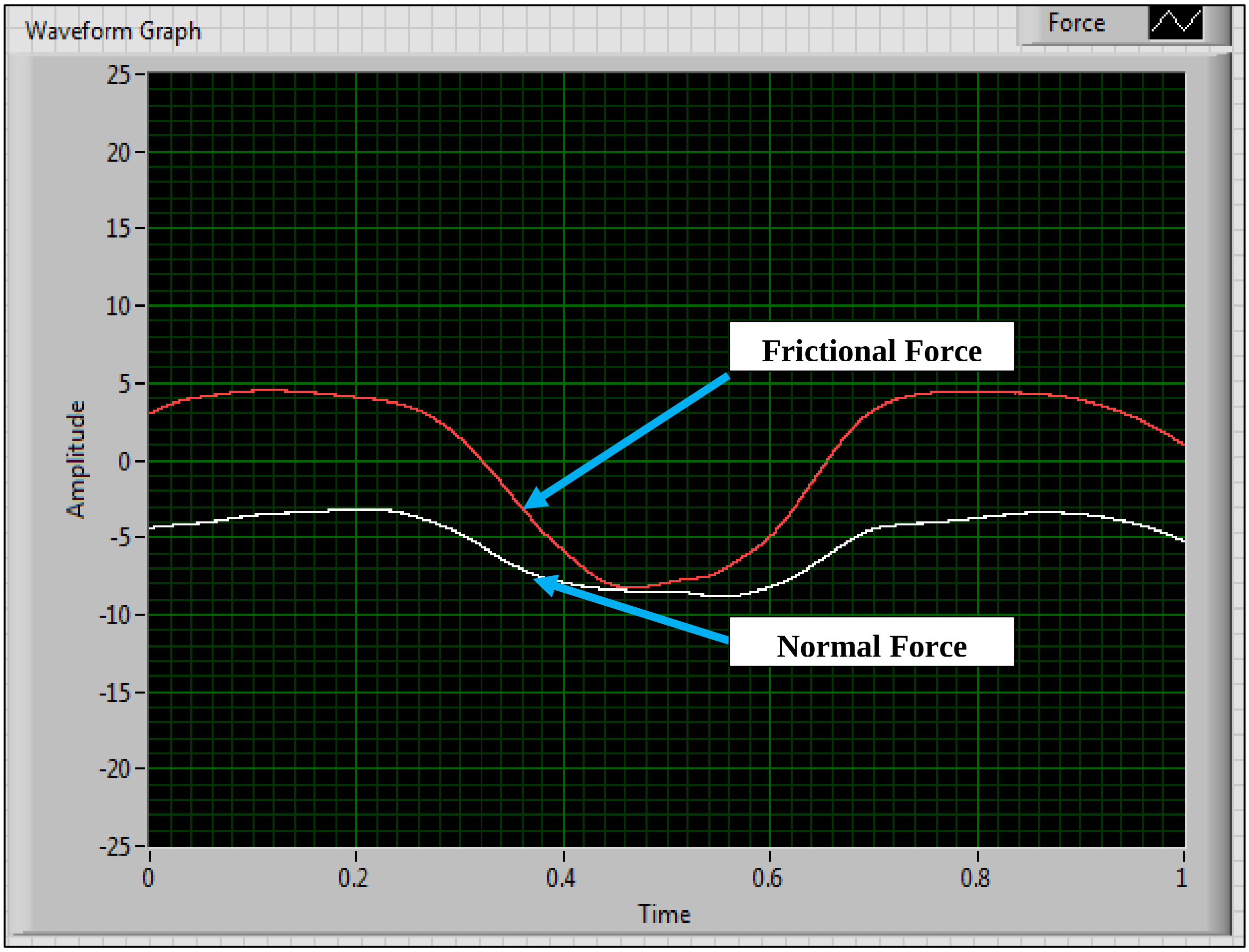


Figure 31: DAQ of Low Frequency Force

Another example of the software's capabilities is displayed in **Figure 32** which imparts a high frequency force application to the specimen.

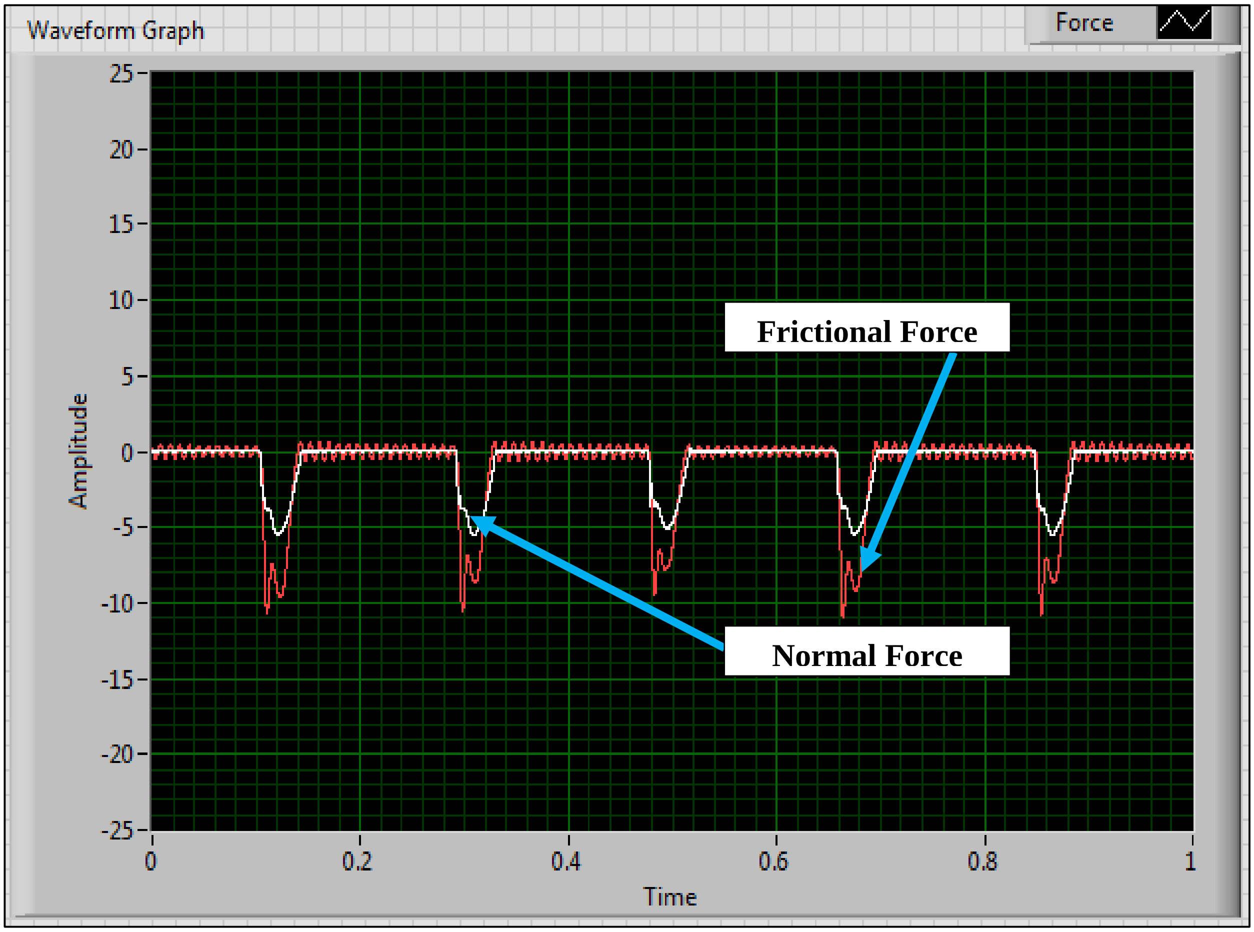


Figure 32: DAQ of High Frequency Force

The data may then be evaluated within LabVIEW or exported to an excel file to calculate the coefficient of friction. This can be done at any instant or with respect to time for any duration, which mimics the intentions of an actual tribometer.

CHAPTER V

REAL-TIME MONITORING AND RESULTS

This chapter displays the results that were obtained from the DAQ set-up in comparison to that of an actual tribometer. An aluminum round rod material was used as the work piece in the chuck, and a steel cylindrical pin material connected to the transducer fixture was used as the tooling to be evaluated. This is shown in **Figure 33.**

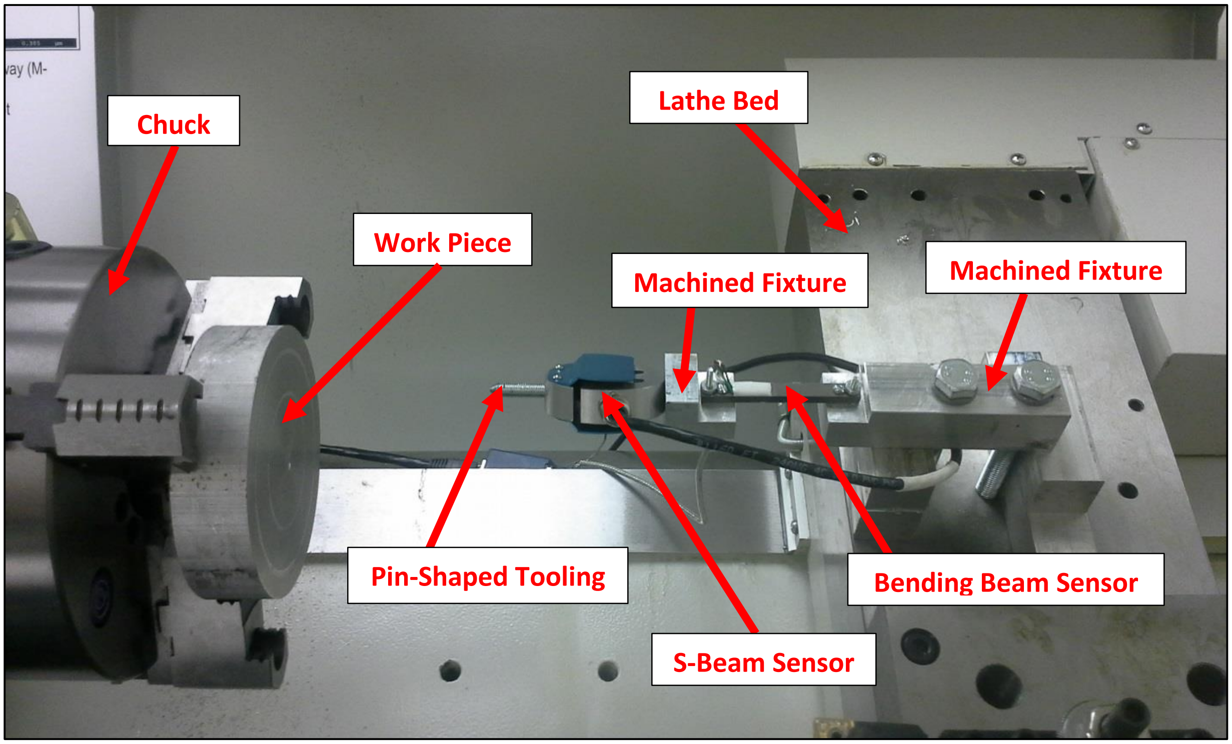


Figure 33: Photo of the Tribometer Setup

Taking Real-Time Measurements

Data was collected for this specific set-up and compared to those of an actual tribometer. The primary characteristic that is evaluated when making this comparison is the resolution of the force felt by the specimen being tested. The resolution of a measurement is the smallest distinguishable difference in value when taking a measurement. The smaller the resolution, the better the machine is able to detect any changes in that phenomenon. The resolution of an actual tribometer used to measure forces in the same range as this experiment is typically about .0011 lbs. [18]. The resolution of the CNC machine retrofitted with tribological capabilities was measured to be around 0.3 lbs. as can be seen from the plots in **Figure 34** and **Figure 35** which display the force calibration curves from 0-5 lb and 0-35 lb respectively. The progressive force readings with respect to table feed is shown in **Table 1**.

Table 1: Resolution of Force per inch of table feed

LINEAR JOG (INCHES)	FORCE READING (LBS)
0.0001	0.0218
0.0002	0.0300
0.0003	0.1133
0.0004	0.1612
0.0005	0.1720
0.0006	0.2123
0.0007	0.2389
0.0008	0.2464
0.0009	0.2463
0.0010	0.2322
0.0011	0.2338
0.0012	0.2531
0.0013	0.2531
0.0014	0.2629
0.0015	0.2739
0.0016	0.3218
0.0017	0.3729
0.0018	0.3844
0.0019	0.4088
0.0020	0.5572
0.0021	0.6556
0.0022	0.9317
0.0023	1.2596
0.0024	1.3635
0.0025	1.7210
0.0026	2.1121
0.0027	2.4920
0.0028	2.6133
0.0029	2.9610
0.0030	3.3562
0.0031	3.4957
0.0032	3.8541
0.0033	4.2325
0.0034	4.3796
0.0035	4.7786
0.0036	5.1187

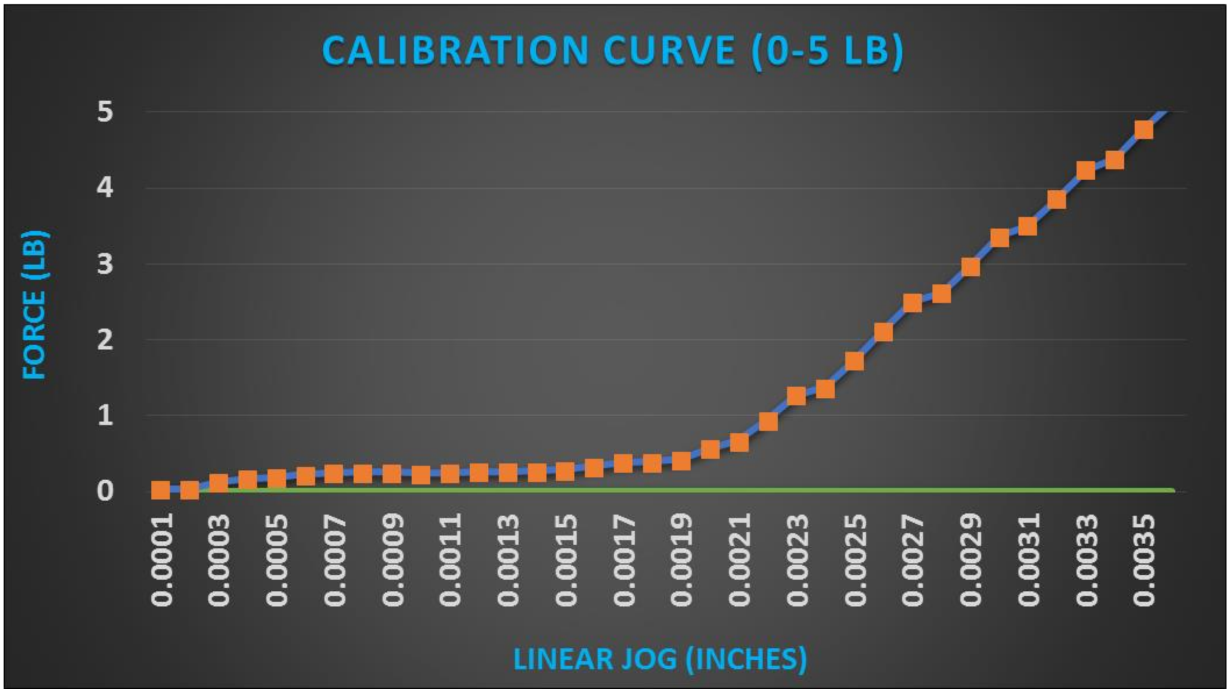


Figure 34: Calibration Curve for normal forces applied (0-5 lbs.)

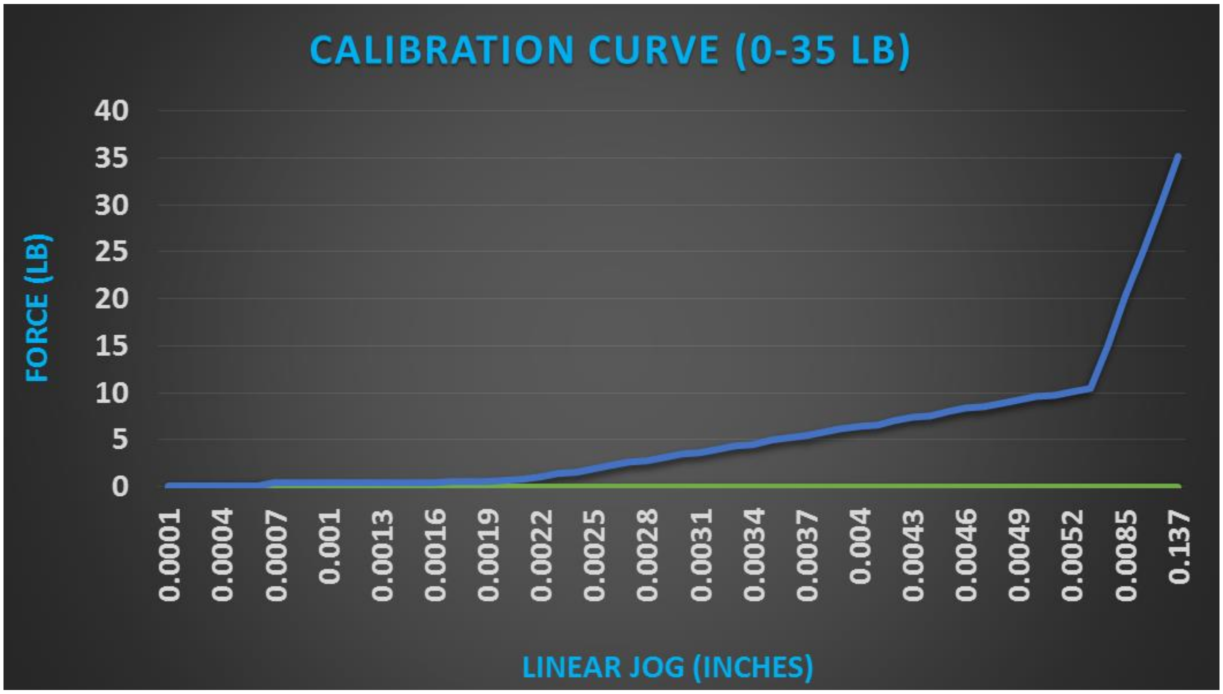


Figure 35: Master Calibration Curve for the applied normal forces (0-35 lbs.)

Validating Tribometric Capability through Pin-on-Disc Runs

Shown in the following two figures are two different instances of a grade 5 steel pin with approximately a 2 mm inch tip diameter producing an oscillatory force pattern on a 6061 Aluminum disc. The first plot (**Figure 36**) shows a varying force pattern for a maximum normal load of about 0.5 lb, while the next plot (**Figure 37**) shows a similar force pattern measurement for a maximum normal force of about 2 lb.

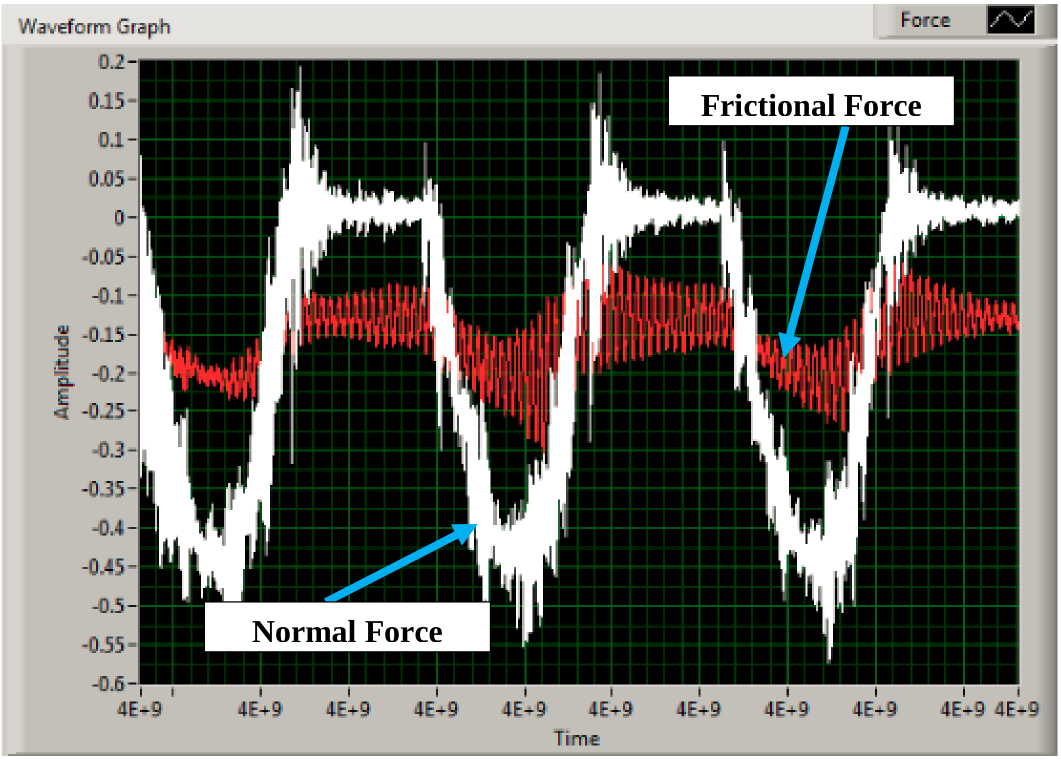


Figure 36: Force plots of a Steel Pin sliding against an Aluminum 6061 Disc (max normal force ~ 0.5 lb)

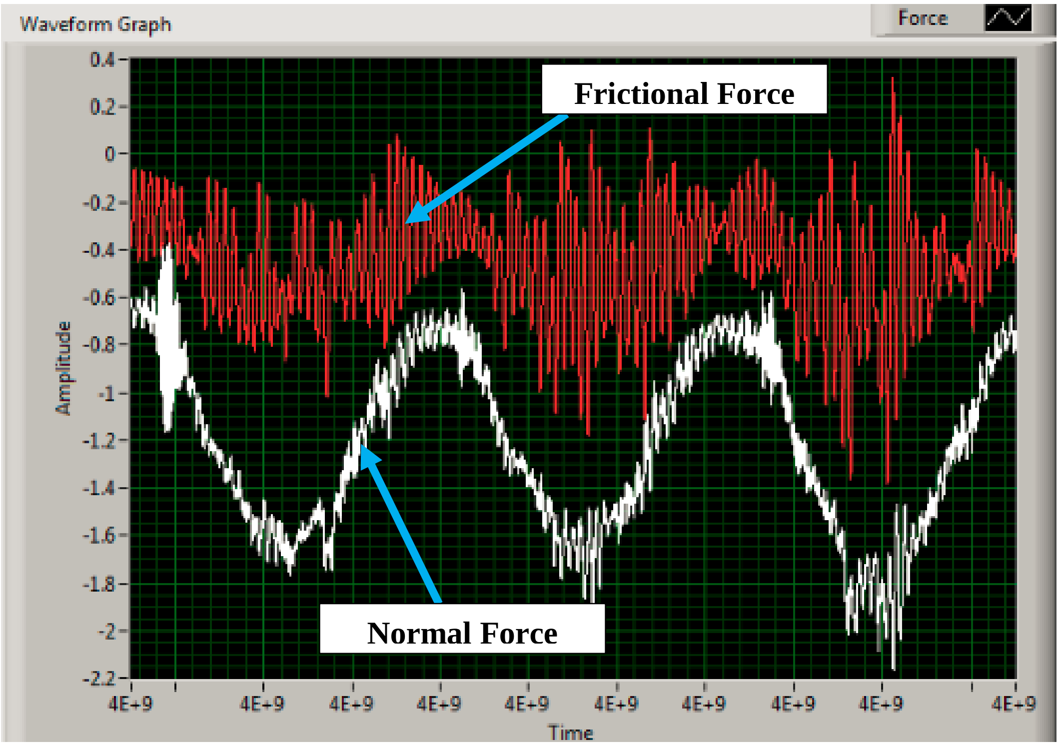


Figure 37: Force plots of a Steel Pin sliding against an Aluminum 6061 Disc (max normal force ~ 2 lb)

From the above plots and discussions, it can be seen that the designed tribometer components work in unison to measure and deliver normal and frictional force data in a reliable fashion with high accuracy and resolution. The capability to acquire such real-time data enables the tracking of the evolution of the coefficient of friction which is one of the primary functions of traditional tribometers. After combining the normal and frictional forces, the coefficient of friction was then graphed and evaluated. **Figures 38** and **39** show different views of real-time plots displaying the coefficient of friction over a 2 minute time interval. A moving average graph was created in excel of the coefficient of friction over a 40 second time interval for the same data. The reason for a shorter time period is due to the high volume of data points that were generated during this test run. This can be seen in **Figure 40.**

Figure 38: Zoomed-out view of coefficient of friction over a 2 minute time interval

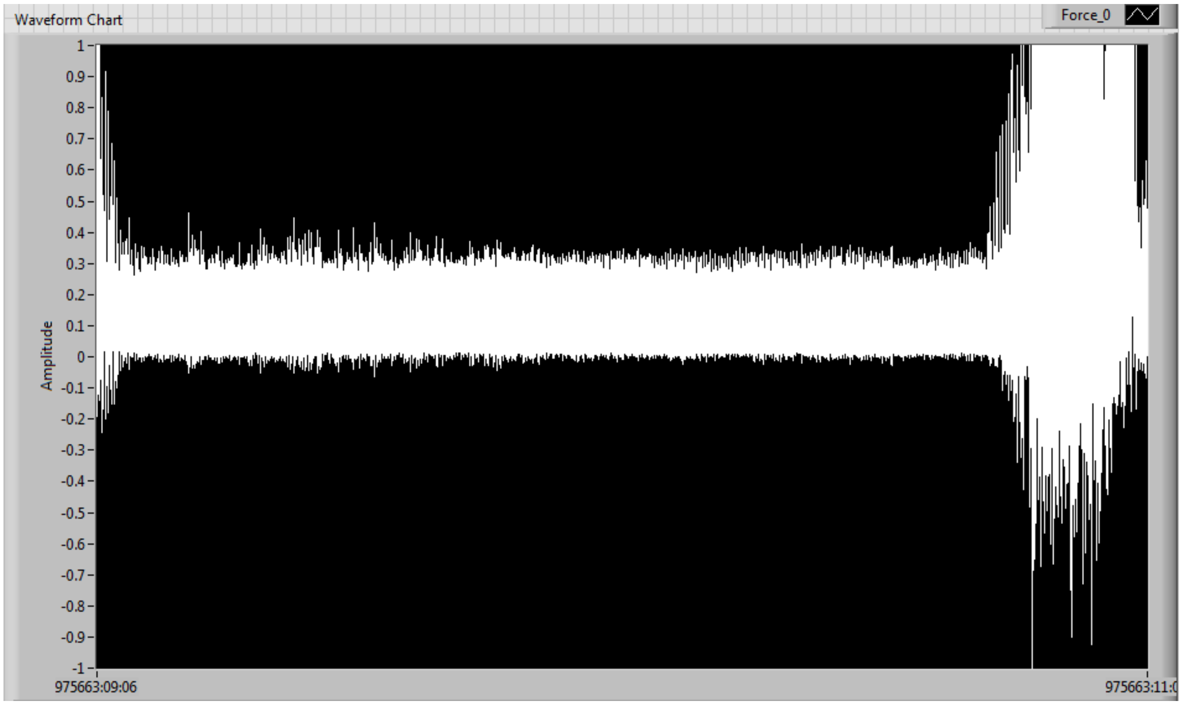


Figure 39: Zoomed-in view of coefficient of friction over a 2 minute time interval

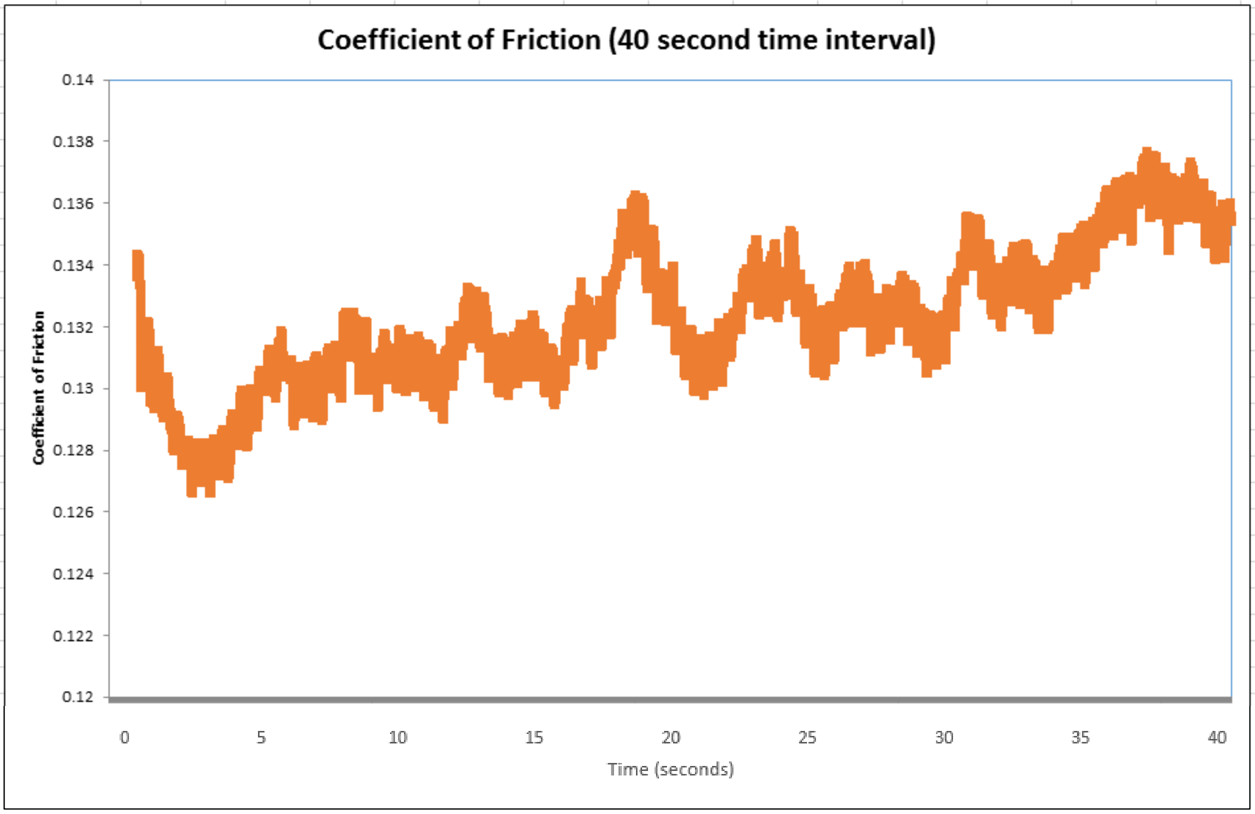


Figure 40: Average coefficient of friction over 40 seconds

CHAPTER VI

CONCLUSIONS

In this research project, an adaptation of a functional tribometer retrofitted onto a computer numerical controlled (CNC) machining center was successfully completed. Besides enabling a relatively low-cost (~ $2,000) model, this design provided a standardized template usable by other investigators for retrofitting CNC machining centers with tribometric testing capabilities. The following project objectives were met upon the completion of this project:

1. Parameters of interest were identified for the purposes of measuring forces related to rock-bit interaction and associated tribology studies.
2. The core mechanical components that constitute a functional pin-on-disc tribometer were designed, fabricated, assembled and calibrated for precise high-resolution application and measurement of normal and frictional forces.
3. The assembly was integrated on an existing CNC machining center and instrumented for real-time data acquisition with potential for controlling the process.
4. Using the high-resolution calibration curves that were generated, the tribometer assembly was validated for representative pin-on-disc measurements between a steel pin and aluminum 6061 discs.

The high-resolution of applicable normal loads as well as the capabilities of force data acquisition at high resolution and bit-rate with minimal noise of this this setup was found to be comparable to that of industry standard tribometers. This capability of serving as a reliable and functional tribometer will be expanded for the testing and validation of rock samples (discs) for a better fundamental understanding of bit-rock interactions.

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