The Design and Construction of a Torque Measuring Arm for an Air Motor

Logan Dearinger
Central Washington University, dearingerl@cwu.edu

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Table of Contents

Introduction ........................................................................................................................................... 4
Motivation ............................................................................................................................................... 4
Function Statement ............................................................................................................................... 4
Requirements .......................................................................................................................................... 5
Engineering Merit .................................................................................................................................. 5
Scope of Effort ......................................................................................................................................... 6
Success Criteria ....................................................................................................................................... 6
Design and Analysis ............................................................................................................................. 7
Approach ................................................................................................................................................ 7
Description ............................................................................................................................................. 7
Benchmarks ........................................................................................................................................... 9
Performance Predictions ...................................................................................................................... 10
Analysis .................................................................................................................................................. 10
Scope of Testing and Evaluation .......................................................................................................... 11
Construction ......................................................................................................................................... 12
Description ........................................................................................................................................... 12
Drawing Tree, Drawing ID’s ................................................................................................................ 12
Parts list and labels ............................................................................................................................... 15
Manufacturing issues ............................................................................................................................ 15
Discussion of assembly ......................................................................................................................... 17
Testing Method ...................................................................................................................................... 19
Introduction ........................................................................................................................................... 19
Method/Approach ................................................................................................................................ 19
Test Procedure ....................................................................................................................................... 20
Proposed Budget and Schedule ........................................................................................................... 22
Labor ..................................................................................................................................................... 22
Estimate total project cost ................................................................................................................... 22
Funding Sources ................................................................................................................................... 23
Proposed Schedule .................................................................................................................. 23
Project Management .................................................................................................................. 24
Human Resources ....................................................................................................................... 24
Physical Resources .................................................................................................................... 24
Soft Resources ............................................................................................................................ 24
Financial Resources .................................................................................................................... 24
Discussion .................................................................................................................................. 24
Design Evolution ........................................................................................................................ 24
Project Risk Analysis .................................................................................................................. 25
Conclusion .................................................................................................................................. 26
Acknowledgements ..................................................................................................................... 27
References: .................................................................................................................................. 28
Appendix A – Analyses .................................................................................................................. 29
A-1: Analysis for cross section of beam ...................................................................................... 29
A-2: Analysis for length of beam ................................................................................................. 30
A-3: Analysis for deflection of beam ......................................................................................... 32
A-4: Analysis for Load Cell choice ............................................................................................ 33
A-5: Analysis for Critical Load of Column ................................................................................ 34
A-6: Analysis for moment on Brass Fitting ............................................................................... 36
A-7: Analysis for Mount Bearing ............................................................................................... 37
A-8: Analysis of Moment of Column fastener .......................................................................... 39
A-9: Analysis for Forces on mount fasteners ............................................................................ 40
A-10: Analysis for Bending in Air motor shaft ......................................................................... 41
A-11: Analysis for Torque on air motor shaft ........................................................................... 42
A-12: Analysis for Necessary Torque on Fasteners ................................................................. 43
Appendix B – Drawings ............................................................................................................... 44
B-1: General Design Ideas ........................................................................................................ 44
B-2: Hand Sketches ..................................................................................................................... 45
B-3: Final Part and Assembly Drawings .................................................................................... 48
B-4: Drawing Tree ........................................................................................................................................... 52
Appendix C – Parts List ....................................................................................................................................... 53
Appendix D – Budget ........................................................................................................................................... 54
Appendix E – Schedule ...................................................................................................................................... 55
Appendix F - Expertise and Resources ............................................................................................................. 56
Appendix G – Testing Data ............................................................................................................................... 60
G-1: Calibration Test Deliverable ..................................................................................................................... 60
G-2: Interference Test Deliverable ................................................................................................................... 60
G-3: Weight Test Deliverable ........................................................................................................................... 61
G-4: Construction Test Deliverable .................................................................................................................. 61
G-5: Torque Test Deliverable ............................................................................................................................ 62
Appendix H – Evaluation Sheets ....................................................................................................................... 63
H-1: Calibration Test Table of Values ............................................................................................................. 63
H-2: Interference Test Table of Values ............................................................................................................ 63
H-3: Weight Test Table of Values ................................................................................................................... 63
H-4: Construction Test Table of Values ........................................................................................................ 64
H-5: Torque Test Table of Values .................................................................................................................. 64
Appendix I – Resume ......................................................................................................................................... 65
Introduction

Motivation

Central Washington University (CWU) has a Thermodynamics Lab (Thermo Lab) within their Mechanical Engineering Technologies (MET) department; this Lab is home to an air motor that is one part of a system efficiency lab. System efficiency is the comparison of the energy in to the energy out. A low system efficiency means that a large amount of energy is lost or wasted somewhere in the system. Using system efficiency, an engineer can determine what needs to be replaced or optimized to help the system use more of the input energy. The system efficiency lab can be expanded when the torsional output of an air motor is known. This proposed project offers a solution to the lack of a torque measuring device. Contained in Appendix F is a copy of the system efficiency lab write-up with all the blanks that would be filled in during the lab. Table 1.1, also in Appendix F, shows the technical specifications of the air motor in question. It is a Dayton Speedaire model no. 4Z231 motor.

The system efficiency lab is a demonstration of system efficiency through the use of an air motor powered water pump. The lab ends with a general system efficiency calculation based on the power ratio of the power from the water (Power_{in}) to power from the air (Power_{out}). The general efficiency can be broken down into the sub categories of efficiency: isentropic efficiency, mechanical efficiency, and pump efficiency. Before a torque measuring device was added, it was only possible to separate the isentropic efficiency from the general efficiency. However, the mechanical efficiency and pump efficiency cannot be separated into individual values. If the torsional output of the motor can be measured, the mechanical efficiency can be separated from the pump efficiency. With the three efficiencies separated, the system can be optimized to be more efficient. By breaking up the efficiencies of the system into its parts, the effect that each part has on the total system can be more clearly seen.

The best way for a total understanding of system efficiency is to break it down into the smallest parts possible and study them. These parts are the three system efficiencies previously mentioned. To understand these different efficiencies and how they affect the overall system efficiency, they must be separated. The isentropic efficiency is separated in the current lab setup, but the pump efficiency and mechanical efficiency can only be separated by knowing the torsional output of the air motor. A torque measuring arm is the optimal choice to fill this need. The breakdown of system efficiency shows which part of the system is causing the most strain or loss of energy in the system. Being able to break it down into its parts would show the students which part of the system is the one that must be changed, optimized, or replaced. This concept is an example of real world efficiency problems that might occur in an engineer’s line of work.

Function Statement

A device is needed that would measure the torsional output created by an air motor.
Requirements

The requirements for this device to function are as follows:

- Measure torque up to 60 in-lbs
- Total weight of product does not exceed 10 lbs
- Reliable torque measurement within 2% of measured
- Fits within 1 cubic foot
- Cost of the project must be less than $250
- Device must have a digital readout system

Engineering Merit

The optimization of this design is based on the forces that act on the torque arm. The torque arm is a form of beam, so beam analysis was used to design it. For the torque measuring device to read up to 60 in-lbs, the beam must be designed to handle the force applied to it. Using the below equation, the force at the end of the beam can be calculated by plugging in the design torque and length of the torque arm.

\[
\text{Torque} = \text{Force} \times \text{Distance}. \quad (1 - 1)
\]

With the given force and the calculated torque value, the bending stress in the beam was calculated. Using the calculated bending stress, the beam was designed to resist deformation under this critical load. The bending stress calculation is done with the following equation:

\[
\sigma_{\text{Bending}} = \frac{Mc}{I}. \quad (1 - 2)
\]

The cross sectional area of the beam is used to obtain the bending stress in the beam. The mass moment of inertia measures the resistance to bending in the beam about a particular axis. The following equation is used to determine the moment of inertia for a beam with a rectangular cross section:

\[
I = \frac{bh^3}{12}. \quad (1 - 3)
\]

All the previously mentioned equations are related to a force on a horizontal beam that causes deformation. If the beam were to be treated like a column, then the force on the beam can cause buckling. The following equation is used to calculate the buckling on a column with an axial force.

\[
P_{cr} = \frac{\pi^2 EA}{SR^2}. \quad (1 - 4)
\]

The beam was fastened around the National Pipe Thread (NPT) brass fittings that serve as the inlet and exhaust of the air motor. To check if the brass NPT fittings can handle the bending stress on them, equation 1-1 above was used.

Bearing calculations were done to decide an acceptable bearing for the given conditions. This was started with given values for revolutions per minute and design life. The following equation was used in conjunction with tables from the Machine Elements Text Book to decide upon a bearing:
\[ C = P_d \left( \frac{L_d}{10^6} \right)^{1/k}. \]  

(1 - 5)

A single fastener was used to connect the column to the beam. The fastener must not fail when subjected to the force on it. The front and back pieces of the mount were both attached to the plate using two fasteners each. Along with the motor mount, the load cell mount was also attached to the plate using two fasteners. The load cell fasteners are meant to restrain the movement of the load cell, so the load they hold is negligible. The mount fasteners must hold the air motor and not allow it to separate from the plate. These fasteners must hold a specific load so that they do not fail and the assembly falls apart.

The shaft of the air motor was subjected to bending and a torsional load. Equations 1-1, 1-2, and 1-3 from above were used to analyze these values.

**Scope of Effort**

The device created for this project served to measure the torsional output of an air motor. For this device to function properly, a mounting system was created to hold the air motor. The current mount is too rigid and keeps the air motor from moving. Due to this inconvenience, a new mount was created to hold the air motor so that the body of the air motor will rotate freely about its center of rotation. With the air motor freely rotating, a torque measuring device can be connected to the body of the motor. The beam is then connected to a column that transmits the torsional force from the air motor to the load cell. Using this process, the torsional output of the motor will be measured and not the torsional output of the shaft.

**Success Criteria**

The success of this device was dependent on the consistency of its measurements and its ability to meet requirements. In the testing section, the various tests used to claim success will be outlined and explained. The most important test to prove success is the torque measuring test. This test will see if the values outputted are correct or near correct.

Another criterion for success is the amount of bouncing the numbers do on the readout. This is to say that if the numbers are jumping from low values to high with a constant force on them, then the project will not be usable, thus unsuccessful. This was tested by the interference test. For the project to be deemed a success in this field, the numbers should not jump more than 2% of the total reading.
Design and Analysis

Approach
The design process began with general sketches (Appendix B) of multiple possible designs and a short description of how they functioned. These general designs were brought to the customer as a starting point to check their validity against their opinion. The initial designs were used as stepping stones to create more design ideas. Along with the creation of new designs, all the old designs were broken down to base elements and simplified. After a lengthy discussion of possible designs, a final design was decided upon. The final design serves as a lightweight, simple, and optimal solution to the need for a torque arm.

Description

![3D model of Air Motor](image)

The design consisted of five major components: mount, horizontal beam, column, load cell, and a digital readout. The horizontal beam and column were made from ANSI 6061 T635 aluminum.

The mount holds the front and back faces of the air motor. This will allow the air motor’s body to freely rotate about its centroid. The mount was designed so that the concentricity of the air motor was not affected by the change in mounts. This means that the entire air motor will revolve around a central axis of rotation. The mount was attached to the plate of the original system efficiency lab set up.
The next component was the horizontal beam that connects the air motor to the vertical column. The beam was attached at the top face of the air motor. The column was then connected at the far end of the beam. The length of the beam will serve as the distance measurement in the torque equation. Bending stress in the beam was used to designate length and cross sectional area.

A column between the horizontal beam and the load cell served to transfer the force on the air motor to the load cell. Column analysis was used to insure the beam will not permanently deform or buckle. The cross sectional area of the column was the same as the beam for the sake of cost efficiency. That way only one bar of aluminum would need to be purchased and then cut into appropriate lengths for different parts.
The load cell was provided by Greg Layman. It was necessary to house it in a load cell mount. This mount made it possible to remove or replace the load cell with ease. The load cell was not fastened to the column, but did have constant contact with the column on its top face.

The digital readout has been provided by Greg Layman as well. It serves to display the numerical value of the force on the load cell in pounds. The digital readout was fastened to the plate so that it does not take up too much space. This will also help the presentation capabilities of the finished project. It would be ideal for the lab if digital readout had the ability to turn or move so that the entire class can see it.

**Benchmarks**

There are many benchmarks that could be listed for this torque measuring device. The major benchmarks taken into consideration for this project were: torque wrenches, strain gages, and electric motor dynamometers.

A torque wrench is a tool that is used to precisely apply a specific torque on a fastener. They can come with a digital readout or a dial readout. The way in which a torque wrench works was used as an initial benchmark for early designs. It was a simple torque measuring system that this project could have been based on. As the requirements became more specific, the torque wrench idea began to fade from relevance.

Strain gages are used to measure the strain on one surface of an object. This is usually done by attaching strain gage to a single side of the object. The load cell to be used in the final design is a strain gage based load cell. A strain gage load cell is a system of four strain gages in a Wheatstone bridge configuration. Strain gages are an important benchmark because they are the building block of the load cell that was used.

A dynamometer is a device for measuring torque, force, or power. It is a comparable system to the one that is being proposed. Though it is on a larger scale then the proposed project, a dynamometer is a comparable system that can be used as a baseline.
**Performance Predictions**

Using the mass properties option in Solidworks, the mass of all the parts is 2.18 lbs. The parts that were measured in this mass measurement are the mount, torque arm, column and load cell mount. The air motors weight and load cells weight have been left out because they are provided for the project.

The cost was estimated to be under $250. This cost requirement was met due to the provided load cell and digital readout. Without those parts being provided, the price would exceed the estimated cost.

The system as a whole is rigid and rugged in a way that should minimize the interference. Given this information, the interference requirement of reliable torque measurement within 2% of the total measurement should be a success.

Torque measurement values will be usable and adequately relay the torque on the air motor to the students.

**Analysis**

The analysis of the torque-measuring device began with the aluminum stock. Haskins Steel in Yakima, Washington is the provider of the aluminum stock for CWU. A quick trip to the Haskins Steel website to see what dimensions aluminum stock was available in served as a starting point to analysis. All the possible stock dimensions were put into an excel spreadsheet (Appendix A-1) that calculated the moment of inertia for those dimensions. The spreadsheet was used to choose a favorable moment of inertia based on the dimensions given.
With the spreadsheet made, the moment on the torque arm was used to calculate the stress in the various beam lengths (Appendix A-2). Three beam lengths were acceptable based on the size requirements. These three lengths are used in the beam deflection analysis (Appendix A-3) to test which length deflects an acceptable amount. None of the three lengths are thrown out due to beam deflection analysis. The stress in the beam is then compared to the ultimate yield stress of aluminum 6061-T6.

When deciding on a load cell, there are a plethora of options. In Appendix A-4 is a comparison of three applicable load cells based on cost, load range, dimensions, and max loading. Two of the three load cells were found to be acceptable for the projects need. The third load cell had a load range of 25 lbs to 200 lbs. This range is far out of the necessary range for this project.

The load cell decision had to be made first to know the necessary length of the column. With two acceptable load cell choices, there are two lengths used in the column calculations to find a favorable one (Appendix A-5). To optimize the purchasing process, the column was designed for the same aluminum stock dimensions as the horizontal beam. Both column lengths were found to have acceptable critical loads. With the load cell provided late in the project, the length of the column had to be changed to fit the new height.

The beam design was found to be satisfactory. To optimize the purchasing process, the column was designed for the same aluminum stock dimensions. The column is then taken through the design process by means of column analysis. The slenderness ratio is compared to the column constant to classify the column as either long or short. Once it is classified as a long column or a short column, the equation for critical load is used to check if the column can hold the load made by the air motor.

Secondary analysis was done to pick a bearing if necessary, makes sure the NPT piping can handle the force put on it, and check that all the fasteners can handle their respective loads.

**Scope of Testing and Evaluation**

The scope of the testing encapsulated the requirements provided. This was done through a series of tests that would check the precision of readings, the accuracy or readings, and the overall interference of the system. Along with the running tests, the requirements of size, weight, and cost were also checked for passing outcomes.
Construction

Description

Aluminum stock was purchased and used for the torque arm and column components of the assembly. The stock was cut to the proper length of the necessary components. Once the lengths of all components are cut to satisfactory lengths, the features were machined to each specific part. The column was drilled and tapped so that a bolt can be used to fasten it to the torque arm. The torque arm with need a hole at the end that the bolt can go through to fasten the column to it.

The mount was made from 7 inches of 6x4x0.5 aluminum angle that was ordered from Haskin Steel along with the aluminum stock. This aluminum angle was cut in half to become the two sides of the air motor mount. The two halves of the air motor mount needed a hole drilled into the face. Holes were also drilled into the bottom of both pieces so it can be bolted to the rig plate.

A small mount for the load cell was machined and attached to the rig plate. Made from extra aluminum that was cut off of the aluminum angle, this part has a hole in the middle of it for the load cell. A pathway was made for the load cell wires to feed through. A lock bolt was originally thought about to constrict the movements of the load cell further. This was unnecessary due to the precise hole bored into the load cell mount.

Drawing Tree, Drawing ID’s

The drawing tree is in Appendix B-4

The air motor is the most significant part to the assembly, so it is designated as FA-1. The air motor is part of the lab and is a given for this project.

A mount needs to be created because the current mount does not satisfy the mount needs. The created mount is designated as FA-2. The mount was machined from aluminum. It was fastened to the plate of the assembly with four fasteners.
The Torque arm is designated as FA-3. It was made from ½ in x ½ in aluminum stock. It was fastened to the air motor with another shorter piece of the same aluminum stock. They were placed around the NPT intake and exhaust pipes to the air motor. This was done with two fasteners.

The Column is designated as FA-4. It was cut from the aluminum stock used for the torque arm. The end of the column was centered over the load cell to focus the load on the center of the load cell. It has a tapped hole on the other end and was fastened to the torque arm by a single fastener.
The load cell was provided by the electrical department for this project. Only one load cell is necessary for the assembly. The load cell was placed within a manufactured load cell mount. The load cell mount was permanently attached to the rig plate. This was done so that the load cell can be removed and used for other purposes if necessary while the mount keeps its position centered on the rig plate. The load cell was designated as FA-5 and the load cell mount was designated FA-7.
A Digital Readout is needed to convert the load cell signals into a number value. The digital readout was provided along with the load cell for this project and designated FA-6. It was not fastened to the plate so that the rest of the assembly has space and is not crammed into a small area. This may change after seeing the completed assembly and noting the amount of space left.

**Parts list and labels**

The parts mentioned in the previous section are labeled and explained in the table below.

<table>
<thead>
<tr>
<th>Part</th>
<th>Part ID</th>
<th>Material</th>
<th>Provider</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Motor</td>
<td>FA1 Actual: 4AM-NRV-92</td>
<td>Cast Iron</td>
<td>Granger</td>
<td>1</td>
</tr>
<tr>
<td>Load Cell</td>
<td>FA5</td>
<td></td>
<td>Greg Layman</td>
<td>1</td>
</tr>
<tr>
<td>Load Cell Mount</td>
<td>FA7</td>
<td>Aluminum</td>
<td>Haskin Steel</td>
<td>1</td>
</tr>
<tr>
<td>Digital Readout</td>
<td>FA6 Actual: 060-F508-03</td>
<td>Multiple</td>
<td>Greg Layman</td>
<td>1</td>
</tr>
<tr>
<td>Torque Arm</td>
<td>FA-3</td>
<td>½ in square Aluminum stock</td>
<td>Haskens Steel</td>
<td>12in</td>
</tr>
<tr>
<td>Column</td>
<td>FA-4</td>
<td>½ in square Aluminum stock</td>
<td>Haskens Steel</td>
<td>12in</td>
</tr>
<tr>
<td>Mount</td>
<td>FA-2</td>
<td>7x4x0.5 Aluminum Angle</td>
<td>Haskens Steel</td>
<td>7 in</td>
</tr>
</tbody>
</table>

**Manufacturing issues**

During the construction of the torque measuring device, a myriad of manufacturing issues arose. These issues ranged from simple problems that were quickly fixed to large problems that took extra time to deal with.

The torque arm and 4 in connection piece created an interesting issue. A slight round was necessary in both parts so that they snugly fit around the NPT piping on the top face of the air motor. The process of creating this round was an issue. It was necessary to use an end mill and slightly touch the edge of the parts till the proper depth round was created. A round that was not too deep as to cause structural issues later down the line, but large enough to create a close fit. This round can be seen in figure 9 below.

Figure 9: Round in Attachment beam
Working on the mount was an issue all on its own. The mount was made from a 7x4x0.5 aluminum angle. Due to the shape and size of this specific angle, fixing it to be machined was difficult every time. Starting with cutting it into two pieces, which was done by the ban saw, creating a non-straight line cut and having to mill it with half the part hanging free and not securely clamped. This caused minor issues to the speed of making the part. Due to the mounting issue, the holes in the mount were made with a boring head on the mill instead of the initial plan of using the lathe to drill the holes. This made the holes take 3 times as long as estimated.

When manufacturing the mount to hold the air motor, a design flaw was found. The back half of the mount was not concentric to the front. The original mount design was made for a concentric line through both the front and back mount. This had to be changed before the mount holes could be bored. Quick measurements were taken to find the centerline of the back face of the air motor. These measurements were taken while the air motor was in the stock motor mount. Due to this, the measurements were off when put into the new mount. This problem was quickly fixed by adding a spacer under the back mount made of spare aluminum. With this fix, the front and back mounts fit around the air motor as originally intended. The additional piece can be seen under the bottom mount in figure 10 below.

Figure 10: Air Motor in Mount
There is a chance of interference occurring once the assembly is fully put together. This means that the parts move or vibrate in a way that was previously thought to be negligible or not even considered until fully assembled. This can lead to minor or major manufacturing issues depending upon the amount of interference present.

A need for a load cell mount was a manufacturing issue. The original design was meant to have the load cell attached to the rig permanently. This design was altered when Greg Layman offered a load cell and digital readout that was already in the possession of the MET department. Taking into account the new parts, a mount was needed for the load cell. The mount is needed so that the MET department can take the load cell for another project if necessary. A mount will serve as the positioning for the load cell. The load cell mount was permanently fixed to the rig plate in the proper positioning so that the load cell can be added or removed from the rig when needed. The load cell mount with the load cell seated in it can be seen in figure 11 below.

![Figure 11: Load Cell Mount with Load cell in it](image)

**Discussion of assembly**

The entire assembly begins with the connection of the torque arm to the air motor. This was done with a 4 in piece of ½ in x ½ in aluminum stock along with the torque arm. These two pieces of stock were fixed around the 5/8 in input and exhaust hoses. A fixed beam connection was created from this mounting process.

At the end of the torque arm, a single hole was drilled to put a bolt through to the column. The column was tapped to have a threaded hole in its body so that the bolt holds the two parts together firmly. This connection was considered a fixed connection.

The mount was securely mounted to the plate that the entire air motor rig is attached to. The mount was not bolted or attached to the air motor in any way. The mount is being designed to hold the motor and allow it to freely rotate. To accomplish this task, there was no fasteners for the mount to air motor.
Under the column sat the load cell. The load cell and column were touching and have constant contact, but were not fastened to each other. The load cell was placed in a mount that fixes its location. This made it possible to remove and replace the load cell quickly and efficiently. All of these connections can be seen in figure 12 above.

The load cell was then wired to the digital readout. A digital readout served to give a numerical value to the force on the load cell. The readout was not attached to the plate. This will help if the digital readout needs to be moved or turned for presentation purposes.
Testing Method

Introduction

The testing process is used to verify the legitimacy of the torque-measuring device. The tests and deliverables were related to one or more of the previously mentioned design requirements. The different tests show the success of the project’s parts and any other minor interactions. The general success of the assembly as a whole was based on the results of these tests. In figure 13 below, the travel testing rig can be seen.

![Portable Lab Rig](image)

Method/Approach

The testing process was split up into five tests. Each test is described below.

1. The first test was used to calibrate the load cell. Different calibration weight values were placed on the load cell to check the precision and accuracy of its measurement. This test is necessary before the final test is attempted to assure the values reported are correct.
2. The second test would check the overall weight of the project. The parts will all be weighed and compared to the estimated weight given by Solidworks. This test will check if the weight requirement was met.
3. The third test judged the movement of the device once it is assembled. It served to test the amount of interference in the device. This was done by running the motor at three known PSIs, at varying revolutions per minute, to see how much the load cell readings vary.
4. The fourth test was the construction and deconstruction of the device. A stopwatch is used to time how long it takes to assemble the parts into the device. The amount of time it takes to assemble and disassemble the device is important information to have when it comes to fixing the assembly or replacing parts.
5. The final Test was an overall test of the measuring values achieved with this device. The air motor was turned on and the digital readout was checked for values. These values were fed into a spreadsheet that was used to calculate the torque on the air motor.

Test Procedure

Calibration Test Procedures
   Time: Variable
   Place: Thermodynamics Lab
   1. Obtain calibration weights of 100, 200, 500, 1000, and 2000 grams
   2. Place load cell into load cell mount
   3. Place 100 g weight onto load cell
   4. Record readout value
   5. Compare to converted weight
   6. Repeat steps 3-6 with all weight values

Weight Test Procedures
   Time: 10-15 minutes
   Place: Foundry
   1. Disassemble project to base parts
   2. Take parts to foundry scale
   3. Weigh part
   4. Record actual weight
   5. Repeat for all parts
   6. Compare values to estimated weight values from solid works

Interference Test Procedures
   Time: 1-2 Minutes per run
   Place: Thermodynamics Lab
   1. Make sure assembly is properly put together
   2. Hook up Digital readout and load cell
   3. Hook up water hoses
   4. Run air motor at RPM values of: 800, 900, 1000, 1100, and 1200
   5. Run motor at 800 RPM’s for about 1 minute or until numbers are steady
   6. Record the high, low, and range of measurement from load cell
   7. Repeat steps 5-6 for all RPM values

Construction/Deconstruction Test Procedures
   Time: Variable
   Place: Senior Project Room
   1. Gather stopwatch, assembly parts, and mounting plate
   2. Begin stopwatch
3. Assemble the device in its entirety
4. Stop stopwatch and record assembly time
5. Reset stopwatch
6. Start stopwatch disassemble device
7. Record disassembly time.
8. Repeat steps 2-7 3 times for consistent data

Torque Test Procedures
   Time: 1-2 Hours
   Place: Fluke Lab
1. Make sure tests are completed before running Final Test
2. Make sure assembly is properly assembled
3. Hook up water tank hoses to gear pump and compressed air source to air motor
4. Run air motor at varying PSI’s (20, 30, and 40)
5. Run air motor for 3 minutes at 200 RPM’s
6. Record areas of interference in blank deliverable
7. Repeat steps 5 and 6 with RPM values of: 200, 400, 600, 800, 1000, 1200, 1400, and 1600
Proposed Budget and Schedule

Labor

A majority of the labor for this project was the machining and assembling of the assembly. The following table shows the cost of labor for this project. These numbers are meant to be a reference to how much it could possibly cost to manufacture this product. All tasks of labor fell on the lead engineer for the project.

<table>
<thead>
<tr>
<th>Part</th>
<th>Hours of Labor</th>
<th>Cost Per Hour</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque Arm</td>
<td>3</td>
<td>$15</td>
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<td>$15</td>
<td>$30</td>
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<tr>
<td>Mount</td>
<td>5</td>
<td>$15</td>
<td>$75</td>
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<tr>
<td>Total Assembly</td>
<td>2</td>
<td>$10</td>
<td>$20</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
<td></td>
<td>$170</td>
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</tbody>
</table>

Estimate total project cost

The estimated total cost of the proposed project is as follows:

<table>
<thead>
<tr>
<th>Part/Product</th>
<th>Quantity</th>
<th>Source</th>
<th>Cost</th>
<th>Total Spent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque arm 0.5 in square Aluminum</td>
<td>12in</td>
<td>Haskin Steel</td>
<td>$3/ft</td>
<td>$3.00</td>
</tr>
<tr>
<td>stock</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column 0.5 in square Aluminum stock</td>
<td>12in</td>
<td>Haskin Steel</td>
<td>$3/ft</td>
<td>$3.00</td>
</tr>
<tr>
<td>6x4x0.5 Aluminum angle</td>
<td>7 in</td>
<td>Haskin Steel</td>
<td>$38</td>
<td>$38</td>
</tr>
<tr>
<td>Load Cell</td>
<td>1</td>
<td>EET Department</td>
<td>$600</td>
<td>$0</td>
</tr>
<tr>
<td>Digital Readout</td>
<td>1</td>
<td>EET Department</td>
<td>$1,850</td>
<td>$0</td>
</tr>
<tr>
<td>Assorted fasteners</td>
<td>6</td>
<td>Machine Shop</td>
<td>$10</td>
<td>$0</td>
</tr>
<tr>
<td>Total Cost of Bought Parts Project</td>
<td></td>
<td></td>
<td>$44</td>
<td></td>
</tr>
<tr>
<td>Total Cost of All Parts</td>
<td></td>
<td></td>
<td>$2,504</td>
<td></td>
</tr>
</tbody>
</table>
Funding Sources
The funding sources for the proposed project came from CWU or more specifically, the MET department’s budget. The professor that brought this project to me will be keeping it for use in the Thermo lab. due to the lab need for the torque-measuring device, the financial portion of this project was taken care of by the department budget. Professor Roger Beardsley is the customer that the final proposal was presented to. Once a complete budget was created, it was taken to Professor Beardsley for approval before he sends it to CWU’s Financial and Budget department, where the proposal was approved.

Proposed Schedule
The proposed schedule spanned from October 2015 to May 2016. The first three months was spent on the proposal portion of the project. The next set of three months handled the manufacturing of the product. The final three months was spent testing the assembly in various ways. Also in the last three months, all the information was organized into a report that was turned in at the end of the final three-month period. A more detailed schedule can be found in Appendix E. The project was estimated to take 119.5 hours to complete from start to finish. The actual time it took to complete the project was 123.25 hours.
Project Management

Human Resources
Logan Dearinger is the Lead Engineer in charge of this project. He is in charge of the proposal, manufacture, and testing of the proposed project.

Customer and MET Professor Roger Beardsley has been the most prominent human resource used. On multiple occasions, a simple question turned into a lengthy discussion that forwarded the entire project as a whole. The requirements and desired outcomes have been decided based upon these discussions.

Nathan Willhelm has also been a good human resource. Little moments of confusion were brought to him in an attempt to understand a concept. This led to a better understanding of the project as a whole and a better understanding of the engineering process and its steps.

Matt Burvee greatly assisted the manufacturing process. As a lab tech and the person in charge of material accusation, Matt was a major reference during the construction of the torque measuring device.

Greg Layman assisted in the electrical aspects of this project. He has knowledge in Load cells and digital readouts and was a necessary resource for the manufacturing process.

Physical Resources
The Machine Lab in the engineering building at CWU was where a majority of the manufacturing was done. In this lab an end mill, drill press, and thread taps were used during the manufacturing process.

Soft Resources
The soft resources for this project include the programs and web support that were used. Solidworks was the 3D modeling software used for the rendering of this project. Excel spreadsheets were used, along with calculation double checks, to show large amounts of comparative values.

Financial Resources
The budget for this project came from the MET department at CWU. A final budget was given to Professor Beardsley for approval before being sent to the CWU Financial and Budget department for final approval.

Discussion

Design Evolution
The design began as a series of sketches with possible ways to measure the torque. These initial ideas were taken to Professor Beardsley for evaluation and discussion.

The initial design sketches can be found in Appendix B. The initial designs had numerous minor things that overcomplicated them which led to most of them being disregarded. The designs had problems
with mounting, contact with motor, and a proper distance for accurate torque measurement. In a few of the initial designs, springs were used to measure the force on the torque arm. Springs do not last as long as other possible design options. Springs also can affect the precision of the reading if they become worn out or stretched.

The initial designs did not use a load cell. To simplify the system a little bit, a load cell was decided upon. Load cells are known to be more precise and can be reported on a digital readout. The requirement for a digital readout was then fulfilled.

Discussions of how the torque arm could interact with the load cell were the next step. These discussions led to the final design idea. The final design uses the distance of the torque arm as the distance in the torque equation. This optimizes the design by minimizing the number of moving parts. The rotation of the motor causes a force at the end of the torque arm. An equal and opposite force is then created on the load cell by the column that is connected to the torque arm.

**Project Risk Analysis**

There is not a large amount of risks associated with this project. The device does not support a large load or have many small parts. The need for a chain or apparatus to limit the movement of the torque arm may be necessary so that if the motor is put into reverse no one is injured and the rig isn’t damaged. Fasteners used can also be a possible risk. If the proper strength fastener is not used, then the entire assembly could fall apart or scatter into pieces when turned on.
Conclusion

The torque measuring device was a success. The weight requirement of 10 lbs is achieved with a total weight of 2.2 lbs for the assembly (Air Motor excluded). This design minimizes the need for a plethora of parts. With the minimal amount of moving parts, replacing broken or old parts becomes easy, quick, and inexpensive. With a cost of $44 in parts, the cost requirement of under $250 is achieved. The device was successful in reading the torsional output of the motor up to the stall torque. The stall torque of the air motor is 56 in-lb. It is reasonable to say that the torque measuring device was successful in its requirement to read up to 60 in-lb. The device is a simple and efficient way to measure the torsional output of the air motor. This is the most inexpensive, lightweight, and reusable torque measuring device that could be designed.
Acknowledgements

Acknowledgements of appreciation go out to the following people and resources that were available for this project:

- **Central Washington University**
  - For funding this project
  - Access to Machining labs, computers, and a library full of information
- **Professor Roger Beardsley**
  - Bringing this project to my attention
  - Answering questions throughout the design process.
- **Dr. Craig Johnson**
  - Always trying to get “more” out of the proposal
- **Professor Charles Pringle**
  - Time taken to discuss problem situations with me.
- **Matt Burvee**
- **Greg Layman**
- **Jose Bejar**
- **Jared Dearinger and Tonya Berry**
  - Proof reading and moral support
References:

Appendix A – Analyses

A-1: Analysis for cross section of beam

<table>
<thead>
<tr>
<th>Base</th>
<th>Height</th>
<th>Moment of inertia (I)</th>
<th>sBending (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.25</td>
<td>0.00032552083</td>
<td>23040.00</td>
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<tr>
<td>0.38</td>
<td>0.38</td>
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<tr>
<td>0.50</td>
<td>0.50</td>
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<td>0.63</td>
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<tr>
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<td>1.00</td>
<td>0.06250000000</td>
<td>480.00</td>
</tr>
</tbody>
</table>
A-2: Analysis for length of beam

Given: Cross Section of Beam: 1.5 in x 1.5 in

\[ I = 0.005208 \text{ in}^4 \]

\[ A = 60 \text{ in} \times \text{lb} \]

Find: Acceptable length of Beam

Solution:

\[ \sigma_{	ext{allow}} = \frac{M_i}{I} \cdot \frac{a}{(d - a)}(25\text{ in}) = 2850,184 \text{ psi} \]

A-1 Excel spreadsheet value of 2880,00 psi is correct

2850,184 psi < 40,000 psi (Ultimate yield of A-1)

A longer arm creates more accurate measurements

But must be under 12 in long
to follow space envelope requirements

\[ (12 \text{ in}) \cdot \left( \frac{254 \text{ mm}}{1 \text{ in}} \right) = 304.8 \text{ cm} \]

\[ x_1 = (2.5)(8.5) = 0.635 \text{ m} \]

Use 8.5 cm as \( x_1 \)

\[ x_2 = \frac{(3.518 \text{ in})(8.94 \text{ in})}{2} = 6.47 \text{ cm} \]

\[ x = x_1 + x_2 = 0.635 \text{ cm} + 25 \text{ cm} + 6.47 \text{ cm} = 30.105 \text{ cm} = 11.85 \text{ in} \]

30.105 < 30.48 cm

Fits length requirements
Checks for other possible lengths

if

\( x' = 20 \text{ cm} \)
\[
x = 0.635 \text{ cm} + 20 \text{ cm} + 4.47 \text{ cm} = \frac{25.105 \text{ cm}}{2.54 \text{ cm}} = 9.91 \text{ in}
\]

if

\( x' = 15 \text{ cm} \)
\[
x = 0.635 \text{ cm} + 15 \text{ cm} + 4.47 \text{ cm} = \frac{20.105 \text{ cm}}{2.54 \text{ cm}} = 7.92 \text{ in}
\]

if

\( x' = 6 \text{ in} = 15.24 \text{ cm} \)
\[
x = 0.635 \text{ cm} + 15.24 \text{ cm} + 4.47 \text{ cm} = \frac{20.346 \text{ cm}}{2.54 \text{ cm}} = 8.01 \text{ in}
\]

Use \( x' = 6 \text{ in} \)
A-3: Analysis for deflection of beam

Given: Beam lengths from A-2
Cross sectional area and moment of inertia from A-1

Find: Deflection in beams of 3 lengths

Solve:

\[ y_{\text{max}} = \frac{-PL^3}{3EI} \]

\[ L_1 = 11.85\text{ in} = 30.105\text{ cm} \]
\[ L_2 = 9.88\text{ in} = 25.105\text{ cm} \]
\[ L_3 = 7.32\text{ in} = 18.626\text{ cm} \]

\[ I = 0.005208\text{ in}^4 \]
\[ E = 68.9\text{ Gpa} = 100000\text{ ksi} \]

For a load of 60 in-lb at the three lengths,

\[ F = MA \]

\[ F_1 = \frac{42\text{ in-lb}}{11.85\text{ in}} = 3.563\text{ lb} \]
\[ F_2 = \frac{42\text{ in-lb}}{9.88\text{ in}} = 4.253\text{ lb} \]
\[ F_3 = \frac{42\text{ in-lb}}{7.32\text{ in}} = 5.757\text{ lb} \]
\[ F_1 = \frac{60\text{ in-lb}}{11.85\text{ in}} = 5.053\text{ in-lb} \]

\[ y_1 = \frac{(5.053\text{ in-lb})(11.85\text{ in})^3}{3(100000\text{ ksi})(0.005208\text{ in}^4)} = -0.0539\text{ in} \]

\[ y_2 = \frac{(6.013\text{ lb})(9.88\text{ in})^3}{3(1\times10^9\text{ psi})(0.005208\text{ in}^4)} = -0.0375\text{ in} \]

\[ y_3 = \frac{(7.576\text{ lb})(7.92\text{ in})^3}{3(1\times10^9\text{ psi})(0.005208\text{ in}^4)} = -0.0241\text{ in} \]

\[ y_4 = \frac{(8.01\text{ lb})(8.01\text{ in})^3}{3(1\times10^9\text{ psi})(0.005208\text{ in}^4)} = -0.0240\text{ in} \]
A-4: Analysis for Load Cell choice

Given: 3 different load cells
Find: Dimensions, Cost, Weight, Max load, Part #
Solution:

1) From Karlsson Robotics, rectangular bar
   Cost = $11.95 + Shipping  - 2nd Cheapest
   Dimensions = 130mm x 30mm x 22mm  - Usable Max load
   Max load = 10 kg = 22.0462lb
   Weight =
   Part # = SEN-13330

2) From Ebay
   Cost = $9.49
   Dimensions = 75.60mm x 13mm x 13mm  - Cheapest
   Max load = 5 Kg = 11.0231lb
   Weight =
   Part # = SKU: 00200-689

3) From Cole Parmer
   Cost = $54.00 + tax
   Dimensions =
   Max load = 25lb to 200 lb  - Load Range too High
   Weight =
   Part # = LBC-014

Load Cell Provided By
Greg Laymon
A-5a: Logan Darvisner  MET 495

Given: Column  Fixed-Free Connection

Find: Critical load On Column

Solve:

\[ f = \frac{0.25kL}{L_e} \]

\[ L_e = KL \]

\[ SR = \frac{40000}{E} \]

\[ C_i = \frac{2(2E)}{8} \]

Use to find if Column is Short or Long

Distance from Bottom of Torque arm to plate is 5.89 in

\[ f = 0.25(1.5) = 0.375 \]

L changes depending on load cell height

\[ L_1 = 5.89 \text{ in} - 22 \text{ mm (50.8)} = 5.89 \text{ in} - 0.086 \text{ in} = 5.804 \text{ in} \]

\[ L_2 = 5.89 \text{ in} - 13 \text{ mm (33.0)} = 5.89 \text{ in} - 0.512 \text{ in} = 5.38 \text{ in} \]

\[ L_3 = \text{Height of 3rd load cell is unknown} \]

Using \( L_1 \),

\[ L_e = KL = (2.10)(9.99) = 20.97 \text{ in} \]

\[ SR = \frac{40000}{E} = \frac{2(2E)}{8} \]

\[ C_i = \frac{2(2E)}{8} \]

\[ SR > C_i \]

\[ 75.52 > 70.25 \quad \checkmark \]

Long Column

\[ P_a = \frac{\pi^2 AE}{SR} = \frac{\pi^2 (10 \times 10^6 \text{psi})(0.25 \text{ in})^3}{(75.52)^3} = 43260 \text{ lb} \]
Using $L_e = 5.38\text{ in}$
$\frac{h}{D} = 0.11495\text{ in}$

$L_e = KL = 2.10(5.38\text{ in}) = 11.208$
$SR = \frac{h}{D} = 78.19$

$CC = \sqrt{\frac{3.25}{8}} = 70.25$

$SR > CC$

78.19 > 70.25 \checkmark$

Long Column

$P_{cr} = \frac{\pi^2EA}{(SR)^2} = \frac{\pi^2(10,000\text{ psi})(0.25\text{ in}^3)}{(78.19)^2}$

$P_{cr} = 4035.87\text{ lb}$

Both critical loads are acceptable.

New load cell provided

$L_{new} = 5.89\text{ in} = 0.385\times 5.505$

$L_e = KL = 2.10(5.505) = 11.5605$
$SR = \frac{h}{D} = 80.003$

$CC = \sqrt{\frac{3.25}{8}} = 70.25$

$SR > CC \checkmark$

20000 > 70.25

Long Column

$P_{cr} = \frac{\pi^2EA}{(SR)^2} = \frac{\pi^2(10,000\text{ psi})(0.25\text{ in}^3)}{(80.003)^2}$

$P_{cr} = 3854.96\text{ lb}$ Acceptable
A-6: Analysis for moment on Brass Fitting

Given: FBD of Forces on Brass Connector

Find: Loads and Bending Stress

Solution:

Round 5/8" Hole Mode of Brass

\[ \frac{5/8"}{\frac{5/8"}{2}} = 0.0044 \text{ in}^2 \]

\[ \text{Bending} = \frac{MC}{I} = \frac{602 \text{ lbs-in}(9.81)}{0.0044 \text{ in}^2} = 4239.99 \frac{1}{4} \text{ psi} \]

Yield strength of Brass = 72.1 ksi = 79000 \text{ psi}

4239.99 psi < 79000 psi; √

Brass can handle Bending stress.

For max scenario, Assume air meter is not supporting load, All moment is on NPT Fitting.

\[ M = F \times \text{distance} \]

\[ F = \frac{M}{\text{distance}} \]

\[ F = \frac{602 \text{ in-lbs}}{3.744 \text{ in}} = 32.05 \text{ lbs} \]

NPT Fitting must handle 32.05 lbs of shear.
A-70 Logan Dearinger MET 495

Given: Bearing ID

Find: Design Bearing
Boyle: Dynamic load rating

D = 2 in

Radial load is the weight of the Air Motor on the bearing

W = 10 lbs

Radial load of 10 lbs

300 RPM at Max Pressure

Design life of 7000 hrs

Eq (14.7 pg 57) \( L_d = \frac{(20001.18)(300\text{rpm})\text{ (min^-1)}}{36 \times 10^9} \text{ rev} \)

Eq (14.48 pg 58) \( C = \frac{P_d (D/10)^{1/3}}{1.0} \)

= 10 lbs \((36 \times 10^9)^{1/3}\)

= 10 lbs \((36)^{1/3}\)

= 10 lbs \((3.302)\)

= 33.02 lbs

Minimal Acceptable diameter = 2 in

V = 1.0

From given info, bearing is decided (Summary on following page)
Summary of Bearing Choice

From Table 14-3.

Bearing Number = 6011 single row Deep Groove Ball Bearing
Bore = 55 mm (2.165 in)
Outside Diameter = 90 mm (3.543 in)
Width = 16 mm (0.626 in)
Maximum Fillet Radius = 1.0 mm (0.039 in)
Basic Dynamic Load Capacity = 28.1 kN (6317 lb)
A-8: Analysis of Moment of Column fastener

Given: Moment on Torque Arm Column Measurements
Find: Moment on Column fastener
Solve:

\[ x = \frac{3.74 \text{ in}}{2} = 1.87 \text{ in} \]

\[ F_x = \frac{W \cdot \text{distance}}{1.87} = \frac{60 \text{ in} \cdot \text{lb}}{1.87} = 32.05 \text{ lb} \]

Column \( L_1 = 4.99 \text{ in} \)

Column \( L_2 = 5.73 \text{ in} \)

\[ V_0 = 0 \]

\[ M_0 = 10 \]

\[ 30 \text{ in} \]

\[ 177 \text{ lb} \]

Column fastener must be able to withstand 32.05 lb of shear and 177 lb of bending force.
A-9: Analysis for Forces on mount fasteners

Given: Mount Connections to Plate
Find: Forces on Mount Fasteners

Solution:

- \( R_2 \) in lb
- \( 600 \text{ in}-\text{lb} \)
- \( 20 \text{ in} \)
- \( 60 \text{ in}-\text{lb} \)

FBD:

- \( R_2 \)\( \rightarrow \)
- \( \rightarrow \)
- \( \rightarrow \)
- \( \rightarrow \)
- \( \rightarrow \)

\[ \text{FBD:} \]

- \( R_2 = 24 \text{ lb} \)
- \( \Sigma F_Y = -R_1 + R_2 \)
- \( R_1 = 24 \text{ lb} \)

Bolt must take a load of 24 lb.

Load Cell:

- FBD

Any fasteners will do

2 fasteners equal weight
A-10 Analysis for Bending in Air motor shaft

Given: Shaft Dimensions
Find: Bending in Shaft
Solve:

Shaft Diameter = 5/8"
Shaft Length = 1.12"
RPM @ Max Pressure = 300
Torque = 561 in-lbs
HP = 1.8
K_c = 1.6 for Sied Runner Key seat
Assume Axial 1020 CR Steel
S_u = 61,000 psi
S_y = 51,000 psi
S_f = 22,000 psi

\[
\begin{align*}
S_{in} &= S_n C_s C_r \left( \frac{2.000}{0.122} \right) \left( 0.81 \right) = 16430.04 \text{ psi} \\
C_s &= (D/0.3)^{10.1} = \left( \frac{0.25}{0.3} \right)^{10.1} = 0.922 \\
V &= \text{Vertical shear force}
\end{align*}
\]

\[
T_{max} = K_c \frac{4V}{3A} \quad A = \text{Cross sectional area}
\]

\[
T_{max} = 1.6 \left( \frac{16430.04 \times 10.1}{2\pi (2.1271)} \right) = 1511 \text{ psi}
\]
A-11: Analysis for Torque on Air Motor Shaft

Given: Shaft Dimensions
Find: Torque on Shaft
Solve:
  Shaft Diameter = 3/8"  
  Shaft Length = 14.72"  
  RPM & Max Airflow = 300  
  Torque = 50 in-lb

Free on outer diameter of shaft

\[ F = \frac{T}{R} = \frac{50 \text{ in-lb}}{3/8"} = 179.2 \text{ lb on outer diameter} \]

Assume Material is AISI 1020 CR Steel

\[ S_u = 61,000 \text{ psi} \]
\[ S_y = 51,000 \text{ psi} \]
\[ S_t = 22,000 \text{ psi} \]

\[ T = \frac{63000 \text{ (P)}}{22000} \]
\[ T = \frac{63000 \times 1.8}{300} = 378 \text{ in-lbs} \]

The torque on the shaft is 378 in-lbs
A-12: Analysis for Necessary Torque on Fasteners

Given: Fasteners Dimensions

Find: Torque needed on Fasteners

Solution:

\[
\begin{align*}
&\frac{1}{4} - 20 \\
&\frac{5}{16} - 18 \\
&\frac{3}{8} - 16 \\
&\frac{1}{2} - 18
\end{align*}
\]

Common Bolt Sizes

\[T = KDF\]

\[T = \text{Torque (ft-lb)}\]

\[K = \text{Nut factor}\]

\[D = \text{Nominal Diameter}\]

\[F = \text{Force}\]

\[K = 0.3 \text{ for Un-lubricated Stainless Steel Bolt}\]

For \(\frac{1}{4} - 20\):

\[T = (0.3)\left(\frac{1}{4}\right)^{2}(440)\]

\[= 10.8 \text{ in-lb needed}\]

For \(\frac{5}{16} - 18\):

\[T = (0.3)\left(\frac{5}{16}\right)^{2}(240)\]

\[= 2.25 \text{ in-lb needed}\]

For \(\frac{3}{8} - 16\):

\[T = (0.3)\left(\frac{3}{8}\right)^{2}(240)\]

\[= 2.7 \text{ in-lb needed}\]

For \(\frac{1}{2} - 18\):

\[T = (0.3)\left(\frac{1}{2}\right)^{2}(240)\]

\[= 3.6 \text{ in-lb needed}\]

Smaller diameter makes for less

Torque necessary on the bolt

Less torque on bolt means easier Assembly and disassembly
Appendix B – Drawings

B-1: General Design Ideas

1. Arm fixed to motor
   - Air motor turns and displaces spring
   - Spring displacement = force x distance = torque

2. Arm fixed away from motor
   - Deflection caused by air motor
   - Chain gauge used (top-bottom bar)
   - Gauge value used to find torque

3. Arm fixed to bolt
   - Motor turns on pull on bar
   - Force x radius (Distance ball to arm center) = torque

4. Arm fits into key hole
   - Deflection value calculated
   - Chain gauge for value

5. Motor pulls on arm attached to bolt
   - Arm pulls on spring
   - Spring displacement tells arm
   - Secondary arm displaced scale
   - Scale gives displacement measurement
   - Displacement (length of arm) used to find torque
**B-2: Hand Sketches**

**Mount**

- Front
- Side

- Axis of Rotation
Torque Arm

Side

Top
Total Assembly
**B-4: Drawing Tree**

```
Torque Measuring System
  ├── Air Motor
  │     └── FA1
  ├── Mount
  │     └── FA2
  ├── Torque Arm
  │     └── FA3
  └── Column
      ├── Load Cell
      │     └── FA5
      │         └── Digital readout
      │                 └── FA6
      └── Load Cell Mount
          └── FA7
```
## Appendix C – Parts List

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# Appendix D – Budget

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**Total Cost of Bought Parts Project** $44

**Total Cost of All Parts** $2,504
### Appendix E – Schedule

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<tr>
<td>4e</td>
<td>Narrative Video</td>
<td>6</td>
<td>6</td>
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<td></td>
</tr>
<tr>
<td>4f</td>
<td>Update Web Page</td>
<td>2</td>
<td>1</td>
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<td></td>
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<td></td>
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</tbody>
</table>

**Total Hours** | 119.5 | 123.25 |
Appendix F- Expertise and Resources
Blank Report Guide for System Efficiency Lab

MET 314LAB Applied Thermodynamics Lab
Lab 6: System Efficiency for Air Motor powered Water Pump

Objective: The objective of this experiment is to determine the overall steady state efficiency of an air motor-gear pump system.

Equipment:
- Vane type Air Motor: WW Grainger pn 4Z231, Gast Model 4AM-NRV-130
- Gear Pump for water: WW Grainger pn 1P777, TEEL brand
- Pressure Meters: 1 FLUKE Process calibrator with pressure module (0-30 psia)
  2 FLUKE DMM plus PV350 pressure modules (water pressure)
- Temperature meter: 2 FLUKE 52 two channel K-type thermocouple meter
- Water & Air Variable Area Flow Meters
- Shaft RPM tachometer (SHIMPO reflective tachometer, or magnetic pick up type)

Description: In this experiment, our system is a vane type air motor running on compressed air powering a gear pump to pump water. A valve on the outlet of the pump will produce a restriction and create a pumping load. Compressed air delivers energy to the air motor, turning the pump.

Each group will be assigned a shaft RPM to perform the lab with, ranging from approx 400 RPM to 1400 RPM. At the assigned RPM, each group will take data for pump pressures of 0, 20, 40, 60, and 80 psig. Each individual group will do a lab report for their own data set (with given RPM) only. The water pressure created by the pump x water volume flow rate is the power output. The change in enthalpy of the air determines the energy input to the system, Pwr in = (dm/dt)(h<sub>out</sub> – h<sub>in</sub>). A change in enthalpy for an ideal gas is dh = C<sub>p</sub> dT. Your power units should eventually convert to Watts, even though the data is taken in english units.

For water pump, 
\[ \text{Power}_{\text{out}} = \frac{dW}{dt} = \Delta P \left( \frac{dV_{\text{ol}}}{dt} \right) \] 
= (Pressure change of water) x water flow rate

For the air motor, 
\[ \text{Power}_{\text{in}} = \frac{dQ}{dt} = \frac{dm}{dt} \left( \left( \frac{h_{\text{out}} - h_{\text{in}}}{\Delta h} \right) = \frac{dm}{dt} \Delta h \right) \] 
= (Vol<sub>air</sub> P<sub>abs,air</sub> / R<sub>air</sub> T<sub>abs,air</sub>) C<sub>p,air</sub> (ΔT air motor)

System efficiency 
\[ \eta_{\text{system}} = \frac{\text{Power}_{\text{out}}}{\text{Power}_{\text{in}}} = \frac{\text{Power}_{\text{water}}}{\text{Power}_{\text{air}}} \]

Use values of C<sub>p,air</sub> and R<sub>air</sub> from table A-2E, or other equivalent data source. The main issue for finding the energy flow is determining the mass flow rate of the air. The air volume flow rate is given by the exhaust flow meter, but the specific volume v is dependent on pressure and temperature.
Lab Procedure: This lab requires a group of three (or more) to operate equipment, watch and read data, and record readings. ATTENTION!: Do not exceed a maximum of 1600 RPM for this experiment.
ATTENTION!: Do not allow pump output pressure to exceed 100 psi

1. Hook up water tank hoses to gear pump and compressed air source to air motor. Connect air motor Thermocouples (type K) to temp meter and pump pressure taps to pressure sensors. There will be three temp measurements (Air motor in & out, air temp at air flow meter) and three pressure measurements (Pump in & out, absolute pressure at the air flow meter).

2. With pump outlet valve wide open, turn on air supply slowly to start pumping water through system with water outlet. Check for leaks and proper data equipment set up.

3. Follow instructions given for data to be taken by each lab group (each group will take readings for one or more RPM set points). Wait for temperature readings to stabilize before taking data for each data point (ie, let the system reach steady state (ie, data readings stable), approx 30-45 seconds or more). Take readings for RPM, water pump pressure in/out, water flow rate, air motor temp in & out, air volume flow rate, & air flow meter temp & pressure.

Lab Report: Due in one week. Write a lab report (include cover sheet, introduction, procedure, data, results (with summary table & graph), discussion, and conclusion sections, raw data and calcs in appendix.

1. Calculate the power in and power out (in Watts), and net system efficiency for each data point.
2. Summarize these results in a table in the results section.
3. Graph Power\(_{out}\) vs Power\(_{in}\) (y axis vs x axis) in Excel and insert graph image in results section.
4. Graph System Efficiency vs Power\(_{in}\) (y axis vs x axis) in Excel and insert graph results

In the discussion or results section, address the following questions:

a. Does the efficiency of the total system vary at the different data points?
b. Do you see trends in the data or calculations? Does the graph show efficiency?
c. What are some of the sources of error in this experiment?
d. Add any general observations about the experiment procedure or the results

Lab grading:  
20 Format  
20 Grammar  
40 Technical Content (questions addressed, Pwr graph, results summary)  
20 Effectiveness  
100 Total

---

**MET 314 Air Motor/Gear Pump Lab Data Sheet**  
Name: _________________________________

<table>
<thead>
<tr>
<th>RPM</th>
<th>Pump $P_{in}$</th>
<th>Pump $P_{out}$</th>
<th>Water Flow Rate</th>
<th>Air Motor Temp $T_{in}$</th>
<th>Air Motor Temp $T_{out}$</th>
<th>Air Volume Flow Rate</th>
<th>Air Flow Meter Temp</th>
<th>Air Flow Meter Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1-1: Technical Specifications of a Dayton Speedaire model no. 4Z231 motor

<table>
<thead>
<tr>
<th>Item</th>
<th>Air Motor</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP</td>
<td>1.8</td>
<td>Stall Torque</td>
</tr>
<tr>
<td>Running Torque @ Max Pressure</td>
<td>36 in.-lb.</td>
<td>RPM @ Max. Torque</td>
</tr>
<tr>
<td>Max. Air Flow</td>
<td>78 cfm</td>
<td>Max. Air Pressure</td>
</tr>
<tr>
<td>No Load RPM</td>
<td>3000</td>
<td>Keyway Length</td>
</tr>
<tr>
<td>Shaft Diameter</td>
<td>5/8”</td>
<td>Keyway Width</td>
</tr>
<tr>
<td>Shaft Length</td>
<td>1.12”</td>
<td>Overall Length</td>
</tr>
<tr>
<td>Mounting</td>
<td>Hub</td>
<td>Overall Width</td>
</tr>
<tr>
<td>Port Size</td>
<td>¼” NPT</td>
<td>Overall Height</td>
</tr>
<tr>
<td>Rotation</td>
<td>REV</td>
<td>Operating Temp. Range</td>
</tr>
<tr>
<td>Housing Material</td>
<td>Cast Iron</td>
<td>Includes Muffler</td>
</tr>
</tbody>
</table>

Notes:
Appendix G – Testing Data

**G-1: Calibration Test Deliverable**

<table>
<thead>
<tr>
<th>Weight (g)</th>
<th>Weight (lbs)</th>
<th>Readout Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
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</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**G-2: Interference Test Deliverable**

<table>
<thead>
<tr>
<th>RPM</th>
<th>High</th>
<th>Low</th>
<th>Range</th>
<th>% if Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>900</td>
<td></td>
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<tr>
<td>1000</td>
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<td></td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>1200</td>
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</table>
### G-3: Weight Test Deliverable

<table>
<thead>
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<th>Part</th>
<th>Estimated Weight</th>
<th>Actual Weight</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque Arm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Column</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mount</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load Cell Mount</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load Cell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fasteners</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Motor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Assembly</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### G-4: Construction Test Deliverable

<table>
<thead>
<tr>
<th>Construction or Deconstruction</th>
<th>Time (Minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td></td>
</tr>
<tr>
<td>Deconstruction</td>
<td></td>
</tr>
<tr>
<td>Deconstruction</td>
<td></td>
</tr>
<tr>
<td>Deconstruction</td>
<td></td>
</tr>
</tbody>
</table>
## G-5: Torque Test Deliverable

<table>
<thead>
<tr>
<th>PSI</th>
<th>RPM</th>
<th>Readout</th>
<th>Torque (ft-lb)</th>
<th>Torque (in-lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
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<tr>
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</tr>
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<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
# Appendix H – Evaluation Sheets

## H-1: Calibration Test Table of Values

<table>
<thead>
<tr>
<th>Calibration Weight (lb)</th>
<th>CH 1 Value (lb)</th>
<th>Percent Error</th>
<th>CH 2 Value (lb)</th>
<th>Percent Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.220462</td>
<td>0.21</td>
<td>4.981904762</td>
<td>0.33</td>
<td>33.19333333</td>
</tr>
<tr>
<td>0.440924</td>
<td>0.47</td>
<td>6.186382979</td>
<td>0.62</td>
<td>28.88322581</td>
</tr>
<tr>
<td>1.10231</td>
<td>1.1</td>
<td>0.21</td>
<td>1.24</td>
<td>11.10403226</td>
</tr>
<tr>
<td>2.20462</td>
<td>2.31</td>
<td>4.561904762</td>
<td>2.41</td>
<td>8.521991701</td>
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<tr>
<td>4.40924</td>
<td>4.49</td>
<td>1.798663697</td>
<td>5.1</td>
<td>13.54431373</td>
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<tr>
<td><strong>Average</strong></td>
<td><strong>3.54777124</strong></td>
<td><strong>19.04937936</strong></td>
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<td></td>
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## H-2: Interference Test Table of Values

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<th>High</th>
<th>Low</th>
<th>Range</th>
<th>% of reading</th>
</tr>
</thead>
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<tr>
<td>800</td>
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<td>1.59</td>
<td>0.11</td>
<td>6.470588235</td>
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<tr>
<td>900</td>
<td>1.9</td>
<td>1.79</td>
<td>0.11</td>
<td>5.789473684</td>
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<tr>
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<td>2.26</td>
<td>2.19</td>
<td>0.07</td>
<td>3.097345133</td>
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<tr>
<td>1100</td>
<td>2.19</td>
<td>2.14</td>
<td>0.05</td>
<td>2.283105023</td>
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<tr>
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<td>2.36</td>
<td>2.31</td>
<td>0.05</td>
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<tr>
<td><strong>Average</strong></td>
<td><strong>0.078</strong></td>
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<td><strong>3.951831229</strong></td>
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</table>

(Valve Half Closed)

<table>
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<th>Low</th>
<th>Range</th>
<th>% of reading</th>
</tr>
</thead>
<tbody>
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<td>0.07</td>
<td>5.785123967</td>
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<tr>
<td>900</td>
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## H-3: Weight Test Table of Values

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<th>Part</th>
<th>Estimated Weight</th>
<th>Actual Weight</th>
<th>%Error</th>
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</thead>
<tbody>
<tr>
<td>Torque arm</td>
<td>0.28</td>
<td>0.2</td>
<td>28.57143</td>
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<tr>
<td>Arm Connector</td>
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</tr>
<tr>
<td>Column</td>
<td>0.12</td>
<td>0.1</td>
<td>20</td>
</tr>
<tr>
<td>Mount</td>
<td>1.61</td>
<td>2</td>
<td>19.5</td>
</tr>
<tr>
<td>Load Cell Mount</td>
<td>0.08</td>
<td>0.2</td>
<td>60</td>
</tr>
<tr>
<td>Load Cell</td>
<td>0.01</td>
<td>0.1</td>
<td>90</td>
</tr>
<tr>
<td>Fasteners</td>
<td>0.5</td>
<td>0.3</td>
<td>66.66667</td>
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<tr>
<td>Total Assembly</td>
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<td>2.9</td>
<td>24.82759</td>
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<tr>
<td>Air motor</td>
<td>9.94</td>
<td>7.2</td>
<td>38.05556</td>
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</table>
**H-4: Construction Test Table of Values**

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<tr>
<th>C or D</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>13.18</td>
</tr>
<tr>
<td>Construction</td>
<td>13.03</td>
</tr>
<tr>
<td>Construction</td>
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<tr>
<td>Average</td>
<td>13.0466667</td>
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<tr>
<td>Deconstruction</td>
<td>6.83</td>
</tr>
<tr>
<td>Deconstruction</td>
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<tr>
<td>Deconstruction</td>
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<td>Average</td>
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</table>

**H-5: Torque Test Table of Values**

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<th>PSI</th>
<th>RPM</th>
<th>Readout</th>
<th>Torque (ft-lb)</th>
<th>Torque (in-lb)</th>
<th>PWR</th>
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<td>1900</td>
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<td>1.35</td>
<td>16.2</td>
<td>2565</td>
</tr>
<tr>
<td>40</td>
<td>1800</td>
<td>2.94</td>
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</table>
Appendix I – Resume

Objective
To become an essential part of the team with hope to further the development of my knowledge and the overall experience of said team.

Skills
Hard working, fast learner, works well with others, well organized, prompt, and a problem solver.

Experience

Elmview
November 2016-Present
Supervisor: Kristen Jarvis (509) 925-6688
Caregiver: Assist in the everyday lives of clients, including: medications, meals, shopping, transportation, personal care, cleaning, and support.

AC Moate Industries
June 2014-September 2014
June 2013-September 2013
June 2015-September 2015
Supervisor: Nick Marx (206) 510 – 8241
Laborer: Flatbed wrecker tow truck driver, shoveling, asphalt removal, clean up, paving, sealcoat, crack fill, striping, driver, mechanics assistant, flagger, Quality control, squidgy, rotary brush maintenance and operation.

Express Employment Professionals
December 2014-January 2015
Supervisor: Bridget (253) 474 - 2537
Driver: Drive cars to and from various lots preparing them for their next destination.

Rotary Offset Press
June 2012-September 2012
Supervisor: Kerry Norton (206) 422 - 6881
Post Press: Feed machines, bundle paper, stack skids, load trucks, clean, mailed and labeled papers, and worked a pallet jack.

Education

Central Washington University
August 2011-June 2016
Mechanical Engineer Technologies Major
Interdisciplinary Studies Honors Minors

Todd Beamer High School
September 2007-June 2011
Ignite Mentoring Program
AFJROTC: Captain, Flight Sergeant, and an Information Tech Sergeant

Certifications
Solid Works December 2013