Interim Design Report

VTT Rotor: Back EMF Test Fixture

Danfoss Turbocor

Team 4

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VTT Rotor: Back EMF Test Fixture

Danfoss Turbocor

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Abstract

This report will summarize the senior design project undertaken by group four that was proposed by compressor manufacturer, Danfoss Turbocor of Tallahassee, Florida. Turbocor requires a method of quality control for the compressor rotor that will be utilized by the largest compressor that they will release in the near future. Currently the compressor rotor is being manufactured by a third party, and Turbocor wants to insure that the product meets the required specifications needed. The objective that must be met by group four is to build a test fixture that can rotate the rotor within the provided stator at a given rpm, and obtain readings by means of an oscilloscope to verify that the back electromotive force, or back EMF, is within a specified tolerance. This back EMF is generated due to the relative motion of the magnetic fields between the rotor and the stator. The rotor must be centered within 0.5mm of the centerline of the stator, or the back EMF would not be correct. Additionally, there is a resistive force of approximately 70lbf (311.4N) between the rotor and the stator upon insertion that must be overcome. This will be done through the use of a ball screw attached to the stator housing.

I. Introduction

Danfoss Turbocor plans to launch a new compressor model in 2015. Current production plans call for the use of a rotor that will be manufactured by a third party company. Therefore, a method to check the quality of these rotors to ensure they are up to Turbocor standards needs to be developed. To test these rotors, Danfoss Turbocor must measure the back electromagnetic force delivered when the rotor is being rotated inside of the stator. Electromotive force, or EMF, typically refers to voltage generated when a rotor is spun. Measuring this voltage can be used as a method to determine the rotational speed of the rotor, which is called back EMF. The reason it is referred to as a back EMF force is because the voltage pushes against the current that induces it. By measuring this back EMF, Danfoss Turbocor will be able to verify the quality of the rotors. Eventually, Turbocor plans to manufacture these rotors in-house, however, until they switch over to manufacturing these themselves, they require this method of quality assurance.

To successfully and efficiently implement this testing procedure, a test fixture must be created that can be integrated into the already existing manufacturing line. The equipment will be used to perform the back EMF measurements on each rotor prior to its assembly into the compressor. A previous test fixture has been developed by Turbocor for use on one of their smaller compressor models. The test fixture for this application will be similar; however, there are additional constraints that make the implementation more difficult. One of the biggest challenges is to determine a method of centering the rotor within the stator. This is essential because if the rotor is slightly off center, it cannot be tested properly. Additionally, there is a large magnetic force induced when the rotor is pushed into the stator. This is not of concern in the smaller compressor models as the small force can easily be overcome by a human; however, in the new larger compressor model this force is significant and it is not safe to manually load the rotor. Due to the magnetic nature of the components used in the assembly of the compressors, magnetic material should be avoided in areas within the magnetic field of the rotor.

The smaller test fixture will serve as guide for the new design to test a larger rotor. However, the current fixture cannot be modified to test the new rotor due to an increase in size, electromagnetic force and a need for a more reliable unit as discussed previously. The overall setup of this previously developed test fixture does give this senior design group an opportunity to view the essential features of the test fixture. A picture of the previously utilized back EMF test fixture can be seen in Figure 1.[3]

The sponsor for this project is Danfoss Turbocor.

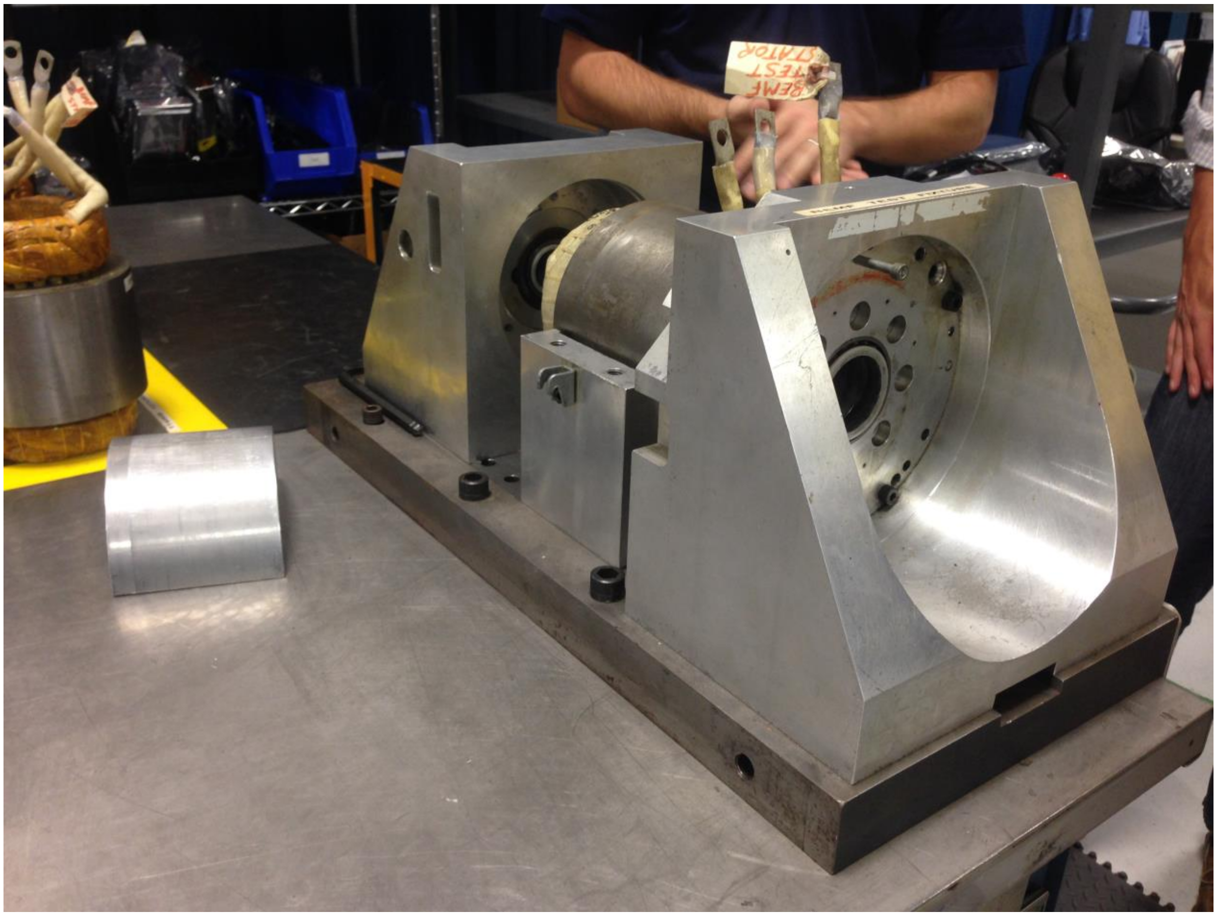


Fig. 1. Designed Back EMF Test Fixture for smaller compressor model.[2]

In the test fixture for the smaller compressor model, there is a locking feature that locks the stator into place and can be unlocked, should the stator need to be replaced. This is an essential feature of the new design. The old design utilizes a bearing to ensure the centering of the rotor within the stator. This is an effective way to ensure that the rotor is centered; however, there is a high cost associated with the replacement of bearings over the life cycle of the test fixture. Turbocor made it clear that they wanted to avoid using bearings to directly support the rotor during the test because the rotor will not be supported during the operation of the actual compressor, and wanted the test to emulate the operation as much as possible. It is important to note that a bearing is being used in the new design. This bearing is attached to the motor to aid in the support of the weight of the rotor. This way, the motor's shank will not risk failure, as it will be supported by the bearing. The bearing will not have to be replaced as it will only support the motor shank instead of the actual rotor.

II. DESIGN AND ANALYSIS

A. The Rotor

The rotor being supplied is 799mm long, weighs 70 pounds and has a magnetic section with a length of 180mm. One key feature of the rotor is a key way that is machined into the left end of the rotor that will allow torque to be transferred from the motor connection to the rotor. An isometric view of the rotor can be seen in Figure 2, and this key way can be seen on the top left of this figure. On the opposite end of the rotor the recess for the sixty degree conical live center opening can be seen, this allows the rotor to be supported on both ends but still rotate freely as the motor spins the rotor to the desired operating speed. The magnetic section of the rotor is the location that the stator must surround in order for an electromotive force to be generated. This magnetic section consists of strong permanent magnets that are wrapped in a carbon fiber sleeve.

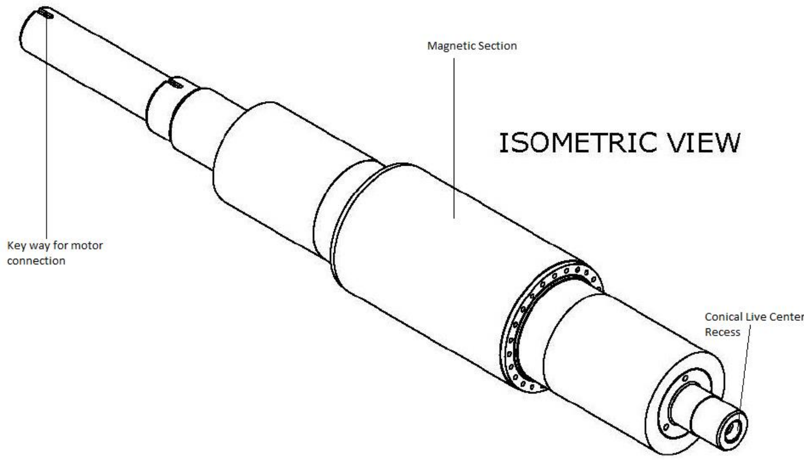


Fig. 2. Isometric view of rotor, from left to right, showing the key way for motor connection, magnetic section, and the conical live center recess.

B. Live Center

The most effective way to center the rotor within the stator is through the use of a live center. A live center, or lathe center is a tool that has a conical shape that is typically used in lathe work in order to provide a stable axis that can be easily replaced, while also providing an accurate method of centering. A live center typically consists of a sixty degree conical shape on one end that will align with an opening on the work piece that is shaped to accept the conical end at the given angle. The advantages of using a live center include the enabling high speed rotation while handling heavy loads, centering the work piece accurately from work area to work area, and feasibility of replacement.

Fig. 3: Live Center [4]

The live center chosen for this application is rated for 5,500 RPM and has the capability to support 660 pounds. It will be placed in an adapter to make the tapered end straight and then placed into a custom-designed housing that will hold the live center at an appropriate height to keep the rotor level. The adapter ensures that the hole drilled in the housing for the live center can have a constant diameter rather than a varied one that a tapered end would require. This reduces the accuracy and machining required for the live center housing, and thus, reduces the cost. [4]

C. Linear Guides

The linear guides allow the stator to move over the rotor, as well as moving the live center into place on the rotor. The linear guide consists of a carriage riding on a track, usually through the use of bearings. Linear guides significantly reduce friction, and thus, ensure that a heavy part can be easily pushed or pulled. A total of two linear guides will be used, and each linear guide will have two carriages, one for the stator and the other for the live center. The linear guides are both from Misumi, with the part number of SXR28-1240. The track is 1240mm long, with a carriage length of 67mm and width of 48mm.

Fig 4: Linear Guides[6]

D. Stator

Provided by Turbocor, the stator will reside within the custom-made stator housing. The stator itself weighs roughly 70 pounds and has a diameter of 230mm. When the stator is pushed over the magnetic portion of the rotor, there will be a resistive force of approximately 70 pounds. The force will then reverse itself and become an attractive force once the stator is halfway over the magnetic section of the rotor. This is very important because this magnetic force will then act to align the stator and the magnetic portion of the rotor horizontally.

E. Stator Housing

The stator housing will have to be custom-made, as the stator will have to rest within the housing with no chance of allowing the stator to rotate. The housing consists of two pieces—an upper piece and a bottom piece. Connected by four screws; the two pieces will be tightened so that the stator will not rotate. The stator housing is 166mm long, 320mm wide and 280mm tall. The stator housing will be fastened to stator housing spacers that will allow the linear guides to be bolted directly to the stator housing. These spacers are necessary because without them, the bolts for the linear guides would have to be screwed down through the top of the entire height of the stator housing, which is not cost efficient.

F. Extruded Aluminum

The extruded aluminum like most of the parts will be purchased through Misumi, and will serve as the base plate and mounting point for all the other components of the design. The part number is HFS8-90180-1750, which references an aluminum extrusion that is 1750mm long, 90mm high and 180mm wide. This aluminum extrusion is designed for high rigidity and low deflection which is critical for the project, as a lack of concentricity between the stator and rotor will yield unusable test results.

G. Ball Screw

A ball screw, in contrast with a lead screw, utilizes ball bearings whereas the lead screw is strictly metal on metal. Thus, the ball screw is more efficient as it requires less effort to move and has lower wear properties. The intent of the ball screw is to provide the operator with the mechanical advantage required to move the stator into the working position by transferring rotary motion into linear motion. The ball screw part number is BSBR1510-1100, and is from Misumi. It has a 15mm diameter with a 10mm lead, and costs $344.91 for just the ball screw. This ball screw also requires the use of bearing blocks, which come at a combined cost of $218.54, for a total of $563.45. The bearing blocks will sit on either side of the ball screw and aid in the alignment of the ball screw.

Fig. 5: Ball Screw[6]

H. Motor

The motor used in the design is from Marathon Electric. It is a 2 HP, 1800 RPM, 3 phase AC motor. The shank diameter is 0.875 in (22.225 mm), and has a start-up torque of 24.5 foot-pounds. The cost of the motor is $455.00. In order to control the motor, a GS2 AC drive was selected. It operates at 230 V, is 3 phase, and 2HP, and has a cost of $255.00, for a total of $710.00 for the motor and drive. The purpose of the drive is so that the operator can slowly ramp up the angular velocity of the motor during operation.[7]

Fig. 6: Marathon Electric 2HP Motor[7]

I. Design Concepts

In order to overcome the magnetic resistance between the rotor and the stator, multiple methods were researched, and three were chosen for further research and then evaluated using a weighted decision matrix. These three methods were a rack and pinion, a pneumatic actuator, and a ball screw.

The rack and pinion converts a rotary input into a linear output in a direction perpendicular to the axis of rotary input. Therefore, the crank input needs to be located on the side of the design. Back drive is a more significant issue with the rack and pinion. The two most viable options to prevent back drive is to utilize a mechanism that locks the crank into place, and a separate mechanism such as a ratchet and pawl that will prevent back drive on its own. With the rack and pinion, the rack would be connected to the stator housing, and the pinion would be fixed about an axis. When rotated, the pinion would move the rack linearly and thus the stator would be able to be moved into place.

The pneumatic actuator would use pressurized air to push the stator housing into and out of position over the rotor. If this concept were to be implemented, these hoses would be connected to the shop air that is available at Turbocor. When connected, the pressure of the air could be regulated to provide the proper pressure (and thus force) needed to move the stator into position. Once in position, either a locking mechanism to keep the stator into place would be utilized, or the pressure would be kept constant to exert a constant force sufficient to prevent movement of the stator. More than likely, a locking mechanism would need to be utilized as the force exerted on the stator during the insertion process due to the magnetic field is not constant. Proper safety regulations would have to be followed if this design option were to be implemented.

The last option was the ball screw. With this design, a crank would be connected to the ball screw, which would be rotated by the operator. The ball screw would be connected to two fixed blocks that are connected to the base plate of the test fixture. Additionally, it would be connected to another moving block located on the threaded portion of the ball screw. This moving block would need to be fastened to the stator housing. To be effective, linear actuators would be used to support the stator housing. The purpose of the linear guides is to reduce the friction that would be present without them. Additionally, the linear guides aid in the alignment of the stator, and will remove any moment that is generated due to the distance between the connection between the ball screw and stator housing and the point of application of the magnetic force.

J. Evaluation of Designs

The three design options of rack and pinion, pneumatic actuator, and ball screw, were put into the weighted decision matrix in Table I. The three methods were evaluated based on safety, simplicity, ease of use, cost, and durability. Safety was given the highest weight because if the test fixture does not meet safety standards or is deemed unsafe to operate it will not be able to be implemented on Turbocor's manufacturing line. It can be seen that the ball screw received the highest weighted sum of all design considered. It is also important to note that the ball screw would receive the highest score regardless of the weights chosen for the different categories because no other design has a higher score in any of the categories with the exception of the pneumatic device in the durability category.

TABLE I. WEIGHTED DECISION MATRIX TO OVERCOME MAGNETIC FORCE

Design	**Decision Categories**					
	Safety	***Simplicity***	***Ease of Use***	***Cost***	***Durability***	***Weighted Sum***
Weight	15	5	10	5	5	/370
Rack and Pinion	6	4	6	8	6	210
Pneumatic Actuator	2	2	4	2	8	130
Ball Screw	**8**	**6**	**8**	**8**	**6**	**300**

K. *Final Design*

The final design has been reviewed by Danfoss Turbocor, and barring minor changes, will be manufactured and implemented this coming spring semester. The final design can be seen in figure 4. The final design posed many challenges throughout the design process, and each challenge brought a unique design solution. The first major design challenge was overcoming the magnetic resistance during the insertion process of the rotor into the stator before the test can begin. The resistance force was approximately 70 pound, however all calculations and parts were selected using 200 pound (890N) to insure that there is no chance of failure. To overcome this magnetic resistance force, a ball screw will be used that will drive the stator down the length of the rotor and move it into the working position.

Once into the working position, the stator will be surrounding the magnetic portion of the rotor. The axial alignment must be concentric between the two parts for the test to be successful and provide accurate results. This is the responsibility of the live center and the motor connection, and is the second design challenge that the group faced. The alignment of the rotor down the axis of the stator will be held in place by the live center and the motor connection, both of which will be fixed vertically and will support the rotor during the test. The location of the rotor within the stator is extremely critical, and thus the live center housing and the motor connection base, which are responsible for the vertical and horizontal alignment of the rotor, will be machined in-house by Turbocor in order to provide the most accurate alignment possible. The live center is more than capable of supporting the rotor with its ability to support 660 pound (2936N) and rotate at 5,500rpm, and will be locked into place using linear guide clamps to prevent the live center from sliding back and releasing the rotor.

One of the most important parts of the test fixture is the baseplate that will support all of the components, and will be the main building block of the test fixture. The base plate will consist entirely of extruded aluminum that is 90 mm tall, 180 mm in width, and 1750 mm long, and can be seen in Figure 3 to the right. This extruded aluminum design is intended for high rigidity and low deflection down the length of the extrusion, which is a necessity in order to maintain concentricity between the rotor and the stator during operation of the test fixture. Extruded aluminum also comes with slots that accept a small fastener so that a bolt can be inserted into them and pulled tight against the aluminum. Extruded aluminum is also considerably lighter and cheaper than a comparable plate of milled aluminum that would be used for the same purpose, thus making the extruded aluminum option the logical choice.

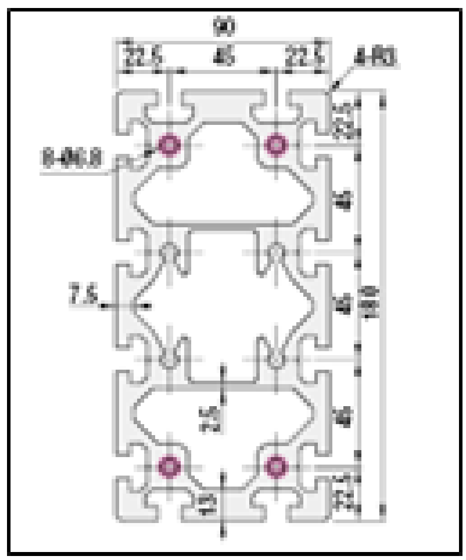


Fig. 7: Extruded Aluminum Cross Section[6]

The majority of the components of the final design will be off-the-shelf items that will be purchased through the parts retailer Misumi. The only parts that will not be purchased from Misumi will be the live center housing, stator housing, and motor support. Having fewer custom parts is beneficial as it reduces the overall cost of the project. Should parts need to be replaced, there is no necessity for drawings or access to a machine shop because the parts can be ordered and assembled. One of the more unique parts will be the 3D printed nylon motor connection, which will be responsible for transferring torque from the motor to the rotor. This 3D printed part will be ordered through the company FineLine, and is critical because it must be soft enough to not damage the rotor, yet strong enough to handle the 24.5 foot pounds of startup torque of the motor. The live center adaptor is another part that simplifies the design as it allows the hole in the live center housing to be drilled with a constant diameter instead of a tapered one, thus making the machine work for the live center housing considerably less expensive.

The aluminum stator housing will be machined from large blocks of rough cut aluminum, as well as the live center housing, and the motor supports. The stator housing will be mounted to stator housing spacers that will also be machined from aluminum. The Stator housing spacers will be mounted to the linear guide carriages. There will be two sets of linear guide carriages, one set for the stator, and one set for the live center housing. The live center housing will be locked into place using linear guide clamps to constrain the live center during the operation of the test fixture.[4,6,7]

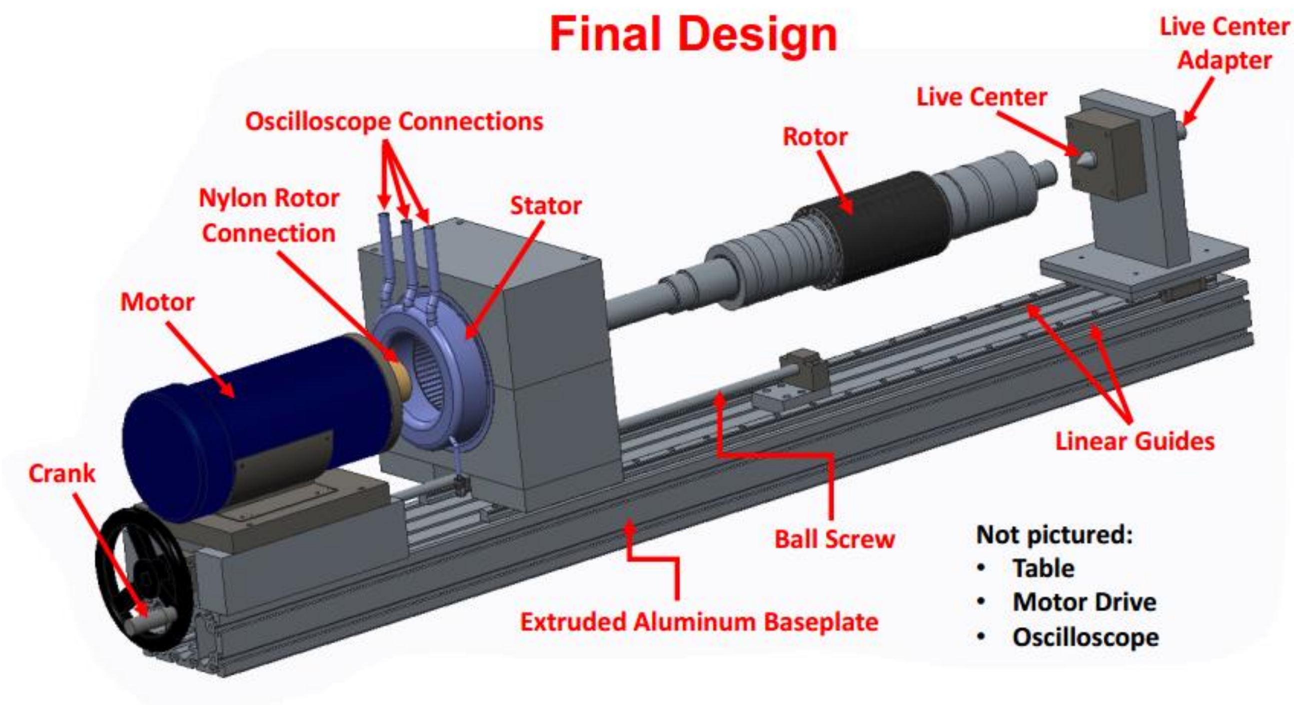


Fig. 8: Back EMF Test Fixture Final Design

L. Procedure

It is important to note that, when in use in the factory, the oscilloscope will already be attached to the oscilloscope connections on the stator. The first step is to have the rotor lowered into position between the stator and the live center using nylon straps. This position can be seen in Figure 4 above. The longest side of the rotor will then be inserted through the stator to connect to the coupler. The live center will then be pushed so that the live center connects with the rotor. A linear guide stop will then be placed so that the linear guide housing will not move. Next, the nylon straps will be removed from the rotor, as it will be held into place by the coupler and live center. Next, the wheel attached to the ball screw will be turned until the stator is in place over the magnetic section of the rotor. The drive will then ramp up the angular velocity of the motor until it reaches 1700 rpm. Subsequently, the user will verify if the rotor is within specification by looking at the oscilloscope output. Once verification is complete, the drive will ramp down the angular velocity of the motor until it stops, at which point, the user will turn the wheel so that the stator moves back to its initial position. Nylon straps will then be put around the rotor, the linear guide stop will be removed and slid back, and the rotor will then be removed.

III. Risk and Reliability

A. OSHA Regulations

In order to comply with OSHA safety regulations, a warning sticker will be placed on the test fixture warning the operator that the test fixture will operate at high rotational velocities. Additionally, an emergency stop will be placed so that it will be easily accessible when operating the test fixture. This emergency stop will cut power to the motor and drive, resulting in the cessation of the motor.[1]

B. *Failure of the Motor Shank*

In order to not risk the failure of the motor shank, a bearing is being attached to the motor, and a connection for the shank will be 3D printed out of nylon. Therefore, the weight of the rotor will be transferred to this bearing, and thus, the motor housing. This is intended to reduce the force that the internal motor bearings will have to support and reduce the wear on the internal bearings. The exterior bearing on the motor shank will also be much easier to service and replace.

C. *Failure of the Motor Connection*

The motor connection is a critical point in the test fixture design namely because it is responsible for transferring the torque from the electric motor to the compressor rotor. Due to the importance of this component, it is critical that finite element method analysis be performed on this part to insure the integrity of the component is up to the task at hand. This FEM can be seen in appendix 2. After performing FEM there is no doubt this component will be able to transfer the 24.5 lbf-ft torque that the motor will output during startup.

D. *Failure of the Live Center*

There is zero expectation of failure from the live center, but in the event of failure, either from the internal bearings within the live center, or the live center nose cone breaks off, or if the live center housing is pushed back and the rotor is released, the most probable occurrence would be that the rotor will be attracted to the stator due to the magnetic fields between the two and the rotor will cling to the interior of the stator and stop rotation. In the event that anything goes wrong there will also be an immediate power shut off switch that will make the test fixture completely inoperable. The live center housing is constructed so that the live center may be removed and replaced if needed.

IV. PROCUREMENT

In order to begin the procurement process, procurement forms must be filled out and given to Turbocor. From there, Turbocor will order the part from the vendor indicated through one of their suppliers. All supplies will be shipped directly to Turbocor. The aluminum will be ordered by Turbocor, delivered to Turbocor, and machined by Turbocor to the specifications given by the senior design group. There is roughly a three week lead time for the majority of the ordered parts and another three week lead time for machine work. The group is currently waiting to receive final design approval from Turbocor so that a purchase order can be developed and parts ordering can take place.

V. COMMUNICATION

A. *Group Communication*

Senior Design Team 4 communicated through various media. The primary form of communication was through text messaging. Files were primarily shared through Dropbox, however e-mail was also used. Group members were always easily reached through the media listed above, and at no point was there a lack of communication.

B. *Sponsor Communication*

Communication with Turbocor was done through e-mail. The liaison, Brandon Pritchard, was always easily reached, and quickly responded to any e-mail sent. Meetings were conducted on a biweekly basis, at which the progress on the group was discussed and any concerns were addressed. In the event that a meeting needed to be cancelled, the issues at hand were handled via email.

C. *Advisor Communication*

The advisor, Dr. Louis Cattafesta, was reached through e-mail. Like our sponsor, Dr. Cattafesta quickly responded to any e-mail sent. Each presentation was performed in front of Dr. Cattafesta prior to presentation to the class. Meetings throughout the semester were scheduled with Dr. Cattafesta in order to address concerns with the project, as well as to ask for any advice. These meetings were typically biweekly; however, in the event that they were deemed unnecessary the meeting would be moved to the subsequent week.

VI. PROJECT MANAGEMENT

A. *Gantt Chart*

The Gantt chart for the fall semester is split into four distinct sections. These are the Preliminary Design Stage, the Advanced Design Analysis Stage, the Final Design Stage, and the Parts Ordering Stage, and can be seen in Figure 6. The first design stage is the Preliminary Design Stage, which encompasses research, the initial design conception, design development, and redesign. The initial design conception is brainstorming, where each group member comes up with ideas to accomplish the project objective. Design development involves selecting the feasible ideas from the initial design conception stage and developing them further.

Redesign is the last step of the Preliminary Design Stage in which the developed ideas are modified prior to being presented to the sponsor.

The second design stage is the Advanced Design Analysis. This stage involves taking the feedback from the sponsor, and adding it to the existing designs that were developed during the preliminary design stage, thus making the designs work more efficiently, save space, and perform better. The initial prototype was selected based on feedback from the sponsor and research performed by the group. The next step in the Advanced Design Analysis is performing further research to verify the initial prototype's feasibility. The last step in this stage is Final Prototype Selection which is where the team is currently. The last stage is the Final Design Stage, and the stages that make up this stage can best be illustrated in the Work Breakdown Structure (WBS) block diagram seen in Figure 5. The final stage of the project for the fall semester is the Parts Ordering stage which involves creating a bill of materials, getting Turbocor approval, ordering parts, and developing a testing procedure.

Currently, Team 4 is in the Parts Ordering Stage. The components to be used in the test fixture have been selected and approved by Turbocor and the process to order them through Turbocor partners is well underway. Steps still to be completed include creating the Bill of Materials and developing the testing procedure for the technicians that will use the test fixture.

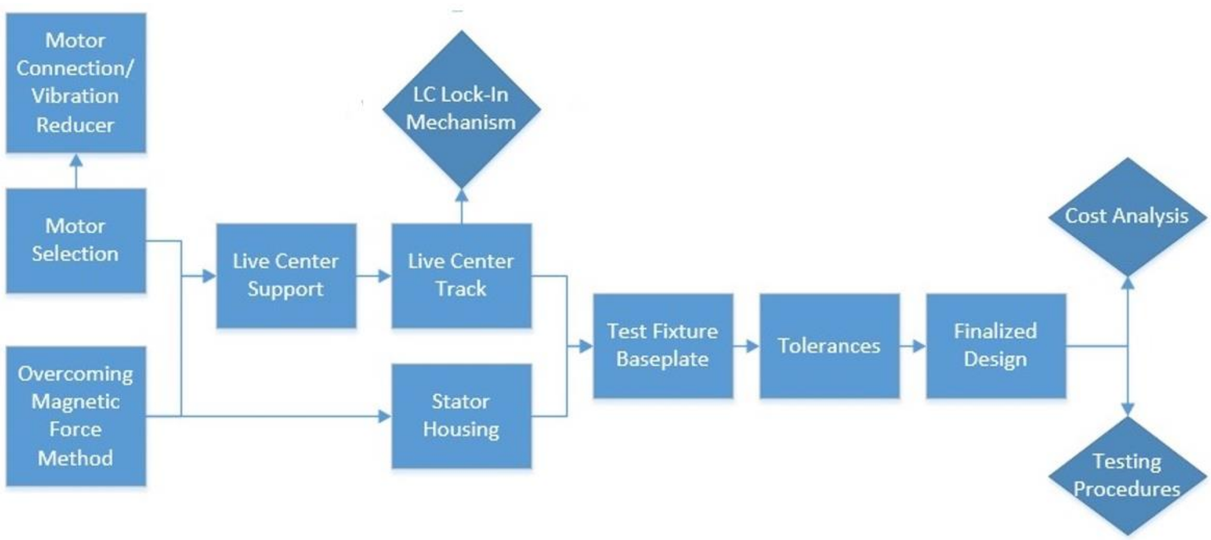
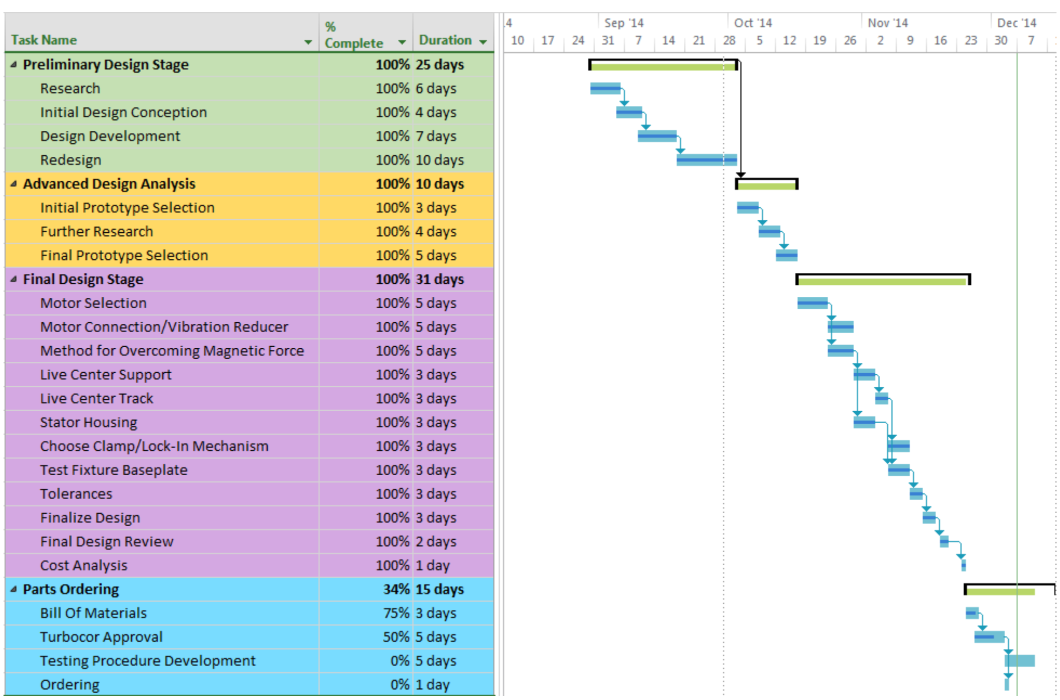


Fig. 9: Work Breakdown Structure Block Diagram



Task Name	% Complete	Duration
Preliminary Design Stage	100%	25 days
Research	100%	6 days
Initial Design Conception	100%	4 days
Design Development	100%	7 days
Redesign	100%	10 days
Advanced Design Analysis	100%	10 days
Initial Prototype Selection	100%	3 days
Further Research	100%	4 days
Final Prototype Selection	100%	5 days
Final Design Stage	100%	31 days
Motor Selection	100%	5 days
Motor Connection/Vibration Reducer	100%	5 days
Method for Overcoming Magnetic Force	100%	5 days
Live Center Support	100%	3 days
Live Center Track	100%	3 days
Stator Housing	100%	3 days
Choose Clamp/Lock-In Mechanism	100%	3 days
Test Fixture Baseplate	100%	3 days
Tolerances	100%	3 days
Finalize Design	100%	3 days
Final Design Review	100%	2 days
Cost Analysis	100%	1 day
Parts Ordering	34%	15 days
Bill Of Materials	75%	3 days
Turbocor Approval	50%	5 days
Testing Procedure Development	0%	5 days
Ordering	0%	1 day

Figure 10: The Gantt chart for the Fall Semester

B. Resources

There are several tasks that need to be completed in order to successfully design and manufacture the back EMF test fixture and fulfill the requirements of the senior design class. The following roles have been assigned to each team member, and will be discussed more in depth in the subsequent paragraph:

- Team Leader – Russell Hamerski
- Webmaster – Andre Steimer
- Secretary – Thomas Razabdouski
- Financial Advisor – Tim Romano
- Lead Engineer – Andrew Panek

The team leader is responsible for keeping the team on schedule, delegating responsibilities, and keeping all team members accountable for their responsibilities. The team leader is also responsible for ensuring all deliverables that need to be completed are of high quality, which includes reports, designs, CAD work, and presentations. The secretary acts as the assistant to the team leader, and is responsible for maintaining minutes of all meeting which include internal, external, and staff meetings. Additionally, the secretary is responsible for the proofreading and editing of all deliverables as a secondary check after the team leader. The financial advisor is responsible for maintaining the budget of the project and working with Turbocor to order all parts and materials required for the back EMF test fixture. The webmaster is required to build and maintain the project's website; he needs to ensure the website will exhibit sufficient information regarding the project's goal and progress.

There is significant engineering design and analysis required for this project. The lead engineer will be in charge of ensuring this design and analysis is completed in a timely manner and meets the constraints given to us by Danfoss Turbocor. All team members will be involved in the analysis of the design; however, major engineering decisions will be made by the team leader and lead engineer with input from the other team members. Per the October 30th meeting with Danfoss Turbocor, multiple tasks were divided among team members as it was critical that all design work be completed before the final design review on November 25th. Russ also took the lead on the final motor selection for the test fixture. Thomas was in charge of the final screw selection and making the decision on whether a ball or lead screw is used. Tim was in charge of choosing the motor connection and vibration dampener. Tim also overlooked the financial data to ensure all Turbocor budget constraints were met. Andre and Andrew also worked on the CAD for the motor, motor housing, stator housing, and the selected screw. In addition to this, Andre invesigated different options for the live center and live center housings, while Andrew made decisions on whether a linear bearing is used in the final design and chose said linear bearing. These tasks were in addition to the continued support roles that were delegated at the beginning of the semester. As of December 5th, the group is on schedule and has completed all tasks that needed to be done by this point. As a whole, the group is still finalizing the decision on the table used for the test fixture and is collaborating on the ordering process with Turbocor.

C. Budget

The budget determined by Turbocor was $4000.00. Currently, the projected expenditure for the parts that will be purchased is $2723.04. While this does not include the cost of aluminum for machining, the estimate of $508.00 can be used for the total price of aluminum. The price of aluminum at this point is an approximation based on the price per pound of raw, general purpose aluminum; the density of aluminum; and the volume of the culmination of all the parts that will be made of aluminum. During the final design presentation, it was determined that the test fixture was under budget. Due to this, Turbocor supported the purchasing of stronger linear bearings than were initially selected at a slightly higher cost. In addition, the use of longer linear guides was approved with two carriages per track, which would be used for both the stator housing and live center housing, also at a higher cost. This brought the final budget to $3231.04 in addition to the cost of the table as well as nuts and bolts. The finished product is roughly expected to be $3500.00 with the inclusion of the table and hardware. A budget break down can be seen in appendix 1A.

VII. RESULTS AND DISCUSSION

At the beginning of the fall 2014 semester, it was agreed upon between the senior design team and Turbocor that a final design review would be held before the end of the semester where the design and all components would be selected and approved. The original date for this was to be November 20th, 2014, but was later pushed back to November 25th due to delays in getting component prices and specifications from different manufacturers. Per this final design review, all the main components of the test fixture have been approved and the design has been deemed satisfactory by Turbocor. The use of extruded aluminum for the baseplate rather than a solid aluminum piece that would have to be milled has substantially cut down on costs from approximately $3800 to $3231.04. This has allowed the selection of stronger linear bearings for the ball screw and longer linear guides that can accommodate the stator housing and live center assembly, rather than just the stator housing. This is useful as it prevents the need for an intricate track system to be milled into the baseplate, simplifying manufacturing and alleviating tolerance concerns between a milled track system and milled live center housing.

As discussed in the previous sections, multiple components have been selected based on price and performance. Items such as the ball screw were picked based on lead and diameter, while others such as the motor and motor drive were based on Turbocor's given specifications and needs. During the last week of the semester, the orders for the selected components will be officially submitted through Turbocor. In addition, the drawings for the custom components such as the housings for the live center and the stator will be submitted to the Turbocor machine shop. This should ensure that, by the time the spring 2015 semester begins, the majority of our components should have arrived and be in the possession of either the team or Turbocor. While the fall semester has consisted mainly of designing and number crunching for the test fixture, the spring semester should be much more hands-on. Upon the start of the semester, assembly of the test fixture can begin. Overall, the spring semester will be made up of assembly, testing, and implementation of the test fixture. In the case any part does not meet specifications, there will be enough time before the end of the semester for new components to be selected and implemented. The assembly of the test fixture should coincide with the writing of the instruction manual and troubleshooting guide that will be required for the device.

VIII. CONCLUSION

Danfoss Turbocor requires a test fixture to be developed that will measure the back EMF generated when the rotor is rotated within a stator. This is needed to verify the quality of the rotors as they are manufactured by a third party company. The key requirements of the design is that it must center and align the rotor within the stator to a tolerance of 0.5 mm, and it must contain a design feature that will overcome a 60-80 lbf magnetic force that is exerted when the rotor is inserted into the stator. Additionally, the rotor must spin at a minimum of 1,000 RPM and the angular velocity must remain constant and repeatable so that tests may be compared to one another. Several important design considerations needed to be made in order to move forward with an initial prototype. Instead of moving only the rotor or only the stator, it was decided that both the rotor and stator would move in the final design in order to minimize the spatial footprint of the final design. The decision was made to utilize a live center to keep the rotor centered within the stator over a ball bearing, as the live center will have less durability issues. Additionally, Turbocor has indicated that a ball bearing is not preferred in the final design. The main design decision that needed to be made was the method of overcoming the magnetic force exerted during the insertion process. A weighted decision matrix indicated that the most suitable choice for this was the use of a ball screw due to its safety, low cost, simplicity, and ease of use.

In order to stay on course, weekly meetings are held at Turbocor every week to ensure that there is a good line of communication between the team and the sponsor. Various team member roles were delegated to ensure all work related to the project is completed in an efficient manner. A Gantt chart was constructed based on the work breakdown structure to ensure all deadlines for the senior design class and Turbocor were met. The final design review was held November 25^{th}, 2014 at Turbocor. The next steps include submitting orders for the selected components and completing the drawing packages that can be submitted to the Turbocor machine shop. In addition, a table must be selected on which the design will sit.

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Appendices:

Appendix 1:

VTT Rotor: Back EMF Test Fixture: Final Design Cost Analysis

Estimated Total Cost:	**$3231.04 + Cost of Table, Bolts**
Cost of Purchased Components:	**$2723.04**
Estimated Cost of Machined Components:	**$508**

Motor, Total: $852 + Cost of Machined Components

Purchased Components:
Motor – AC E2007A Marathon Electric Motor - $455 from automationdirect.com
Motor Drive – GS2-22P0 2.0 HP AC Drive - $251 from automationdirect.com
Motor Base – MTA-BASE-W145T - $18 from automationdirect.com
Rotor Connection – 3D Print part - $146 by finelineprototyping.com

Machined Components:
External Bearing – Provided by Turbocor
(2x) Motor Supports – Aluminum
External Bearing Support – Aluminum
Shank to Bearing Adapter – Aluminum

Ball Screw, Total: $609.10 + Cost of Machined Component

Purchased Components:
Ball Screw – Rolled Ball Screw BSBR1510-1100 - $344.91 from misumi-ec.com
Ball Screw Fixed Bearing Block – BSWE12 - $87.14 from misumi-ec.com
Ball Screw Support Bearing Block – BTN12 - $90.59 from misumi-ec.com
Crank – PHL200-17 Offset Hand wheel - $86.46 from misumi-ec.com

Machined Component:
Bearing Block Connectors – Aluminum
Crank Connector - Aluminum

Baseplate, Total: $424.22

Extruded Aluminum – HFS8-90180-1750 Extruded Aluminum- $391.12 from misumi-ec.com
EA Nuts – Pre-Assembly Nuts for HFS8 Series (100 pack) - $33.10 from misumi-ec.com

Live Center, Total: $152.88

Live Center – Super Rolling Live Center ZLC 07018-MT2 - $128.95 from zlivecenter.com
Live Center Adapter – Morse Taper to Straight Shank Inside 2MT - $23.93 from mscdirect.com

Linear Guides, Total: $684.84

(2x) Linear Guides – Heavy Load SX2R28-1240 Guides - $308.33 each from misumi-ec.com
Linear Guide Clamp – SVCK28 Clamping Unit - $78.18 from misumi-ec.com
Live Center Housing, Total: All Machined Components

Live Center Housing Top Baseplate – Aluminum
Live Center Housing Bottom Baseplate – Aluminum
Live Center Housing Support – Aluminum
Live Center Housing Front Plate – Aluminum

Stator Housing, Total: All Machined Components

Top of Stator Housing – Aluminum
Bottom of Stator Housing – Aluminum
(2x) Stator Housing Spacers – Aluminum

Table, Total: Unknown

Table – Need to check out FSU Surplus

List of all parts that need to be machined, and dimensions:
Part, Length x Width x Height (mm), Volume (mm^3)

Motor Related (3,017,300 mm^3)
(2x) Motor Supports, 270 x 60 x 81.5 mm - 1,320,300 mm^3
External Bearing Support, 170 mm diameter x 16 mm thick - 363,200 mm^3
Shank to Bearing Adapter, 35 mm diameter x 14 mm thick - 13,500 mm^3

Ball Screw Related (226,700 mm^3)
(2x) Bearing Block Connectors, 80 x 70 x 20 mm - 111,200 mm^3
Crank Connector, 15 x 17 x 17 mm - 4,300 mm^3

Live Center Related (2,641,120 mm^3)
LC Housing Top Baseplate, 200 x 200 x 10 mm - 400,000 mm^3
LC Housing Bottom Baseplate, 200 x 200 x 10 mm - 400,000 mm^3
LC Housing Support, 38.1 x 160 x 220 mm - 1,341,120 mm^3
LC Housing Front Plate, 50 x 100 x 100 mm - 500,000 mm^3

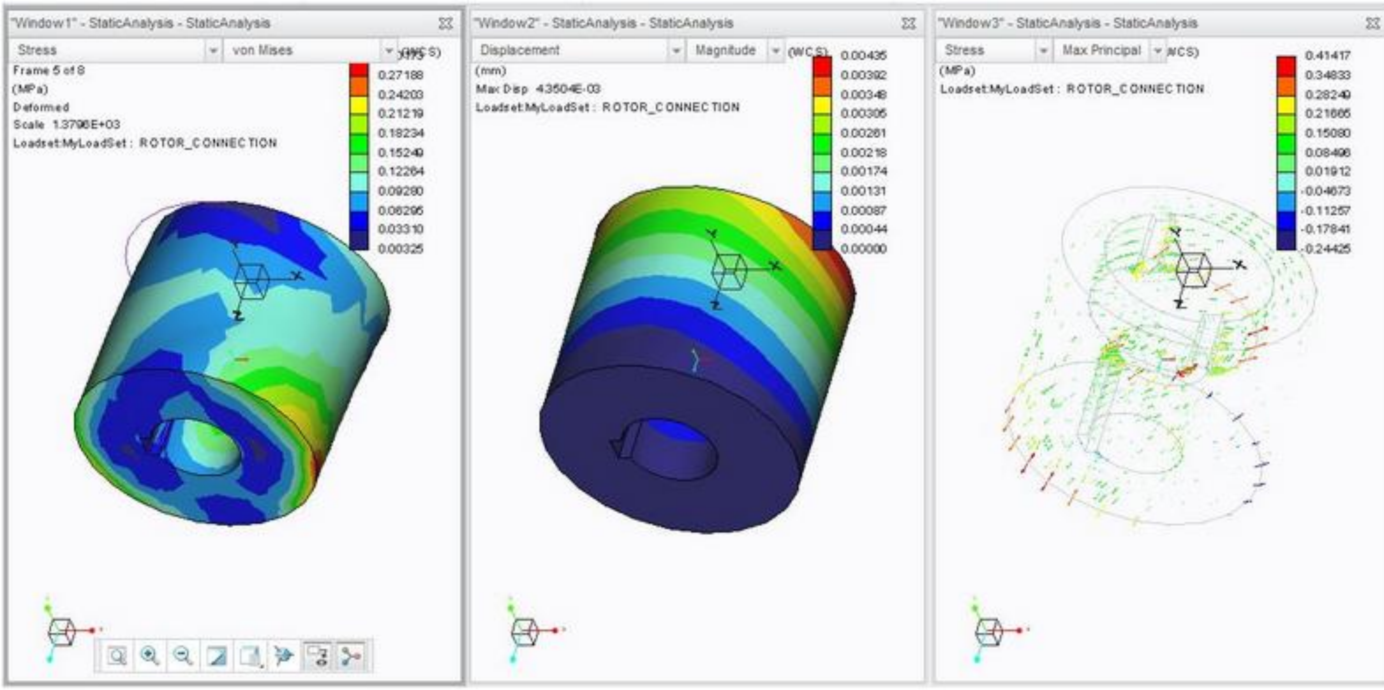
Stator Housing Related (15,511,040 mm^3)
Top of Stator Housing, 166 x 320 x 140 mm - 7,436,800 mm^3
Bottom of Stator Housing, 166 x 320 x 140 mm - 7,436,800 mm^3
(2x) Stator Housing Spacers, 166 x 120 x 32 mm - 637,440 mm^3

Total Volume = 21,400,000 mm^3 or 0.0214 m^3
Total Weight ~ 58 kg or ~127 lbf

Cost at $4 per pound: $508

Appendix 2:

FEM Analysis of Motor Connection:



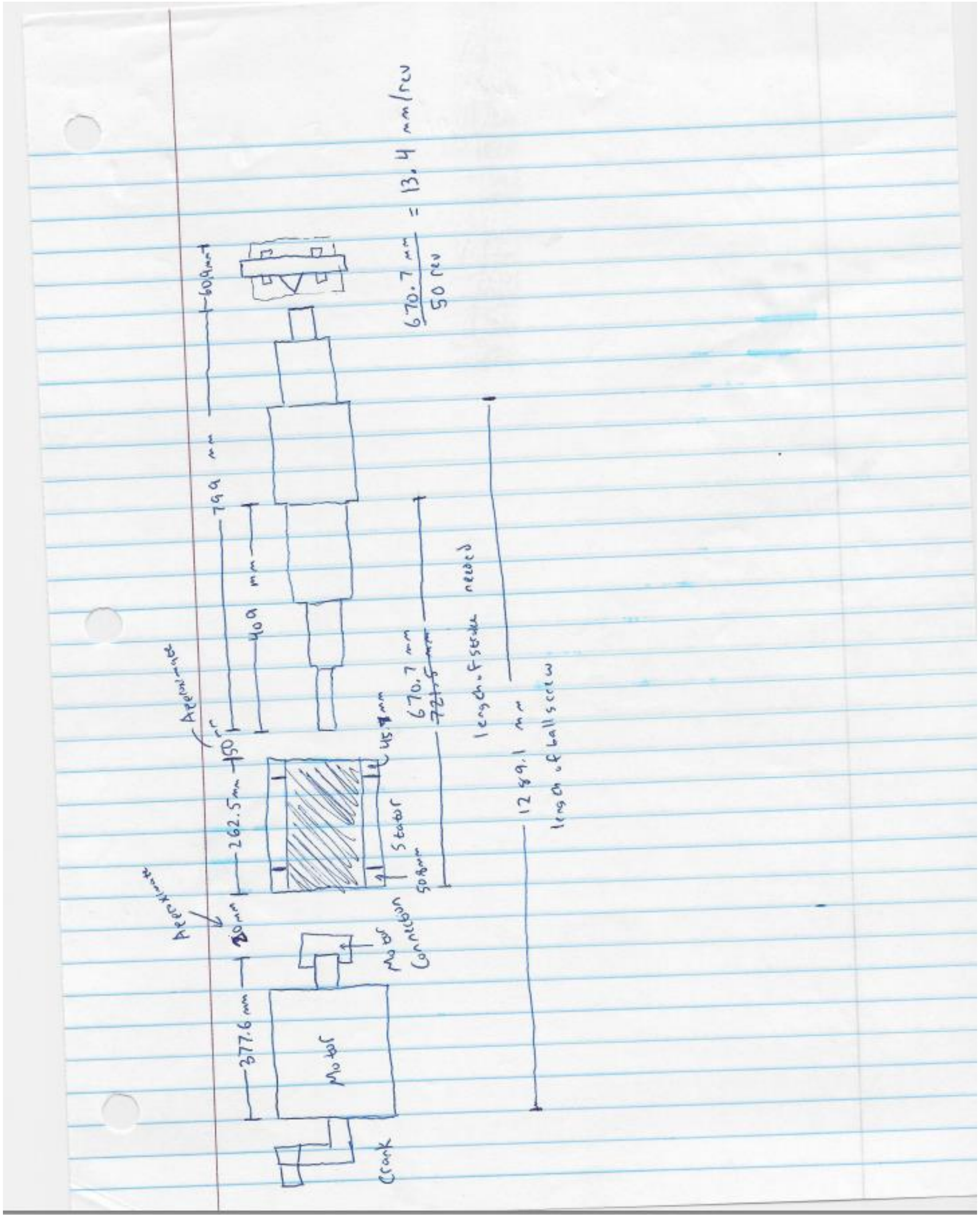
Appendix 3:

Ball Screw Analysis:

Lead	0.1				
Pitch Diameter	0.685	Distance to Move	400	15.7480315	
Force	200	Revolutions		157.480315	
Friction Coefficient (Screw)	0.23				
Collar Diameter	0.75				
Thread Pitch	0.1				
Area Factor (Wi)	0.5				
Minor Diameter (in)	0.6201				
Major Diameter (in)	0.75				
Nc	1028.474606				
Unsupported Length (mm)	2032				
Minor Diamter (mm)	15.75054				
Critical Buckling Force	5775421.373				
End Fixity Factor	2.23				
Friction Coefficient (Collar)	0.1				
Unsupported Length (in)	80				
Cs	4				
Lead Angle vs Friction (u)	Torque(Thrust Collar)	Torque(Screw)	Total Torque	Screw Efficiency (in*lbf)	Screw Efficiency (J)
0.046468597	7.5	19.14269169	26.64269169	167.4009689	18.91376985
Shear Stress for Thread Stripping(Screw) (psi)	Shear Stress for Thread Stripping(Nut) (psi)	RPM Before Resonance (RPM)	Critical Buckling Force	Shear Stripping Area(Screw)	Shear Stripping Area(Nut)
2053.280995	1697.652726	822.779685	4620337.098	0.09740508	0.117809725

Appendix 4:

Rough Calculations for Initial Designs



$$H(HP) = \frac{T\omega}{63000}$$

mass = 32 kg

$I = 0.15228\ kg \cdot m^2$

$T = I\alpha = 0.15228\ (kg \cdot m^2)\left(15.71\ \frac{rad}{s}\right)$

$$\alpha = \frac{\Delta\omega}{\Delta t} = \frac{1500\ RPM}{10\ sec}\left(2\pi\ \frac{rad}{rev}\right)\left(\frac{1}{60\ sec}\right) = 15.71\ \frac{rad}{s}$$

= 2.39 Nm

= 1.76 ft·lbf

$$H = \frac{2\,(1500)}{63000} = \underline{0.05\ HP}$$

$I = 0.04\ kg \cdot m^2$

m = 32 kg

$T = I\alpha$

$$\alpha = \frac{\Delta\omega}{\Delta t} = \frac{1500\ RPM}{5\ sec} \cdot \frac{2\pi}{60} = 31.41\ rad/s^2$$

T = 0.9268 lbf·ft

$2hp \Rightarrow \frac{63000H}{\omega} = T$

T(2hp) 128 ft lbf

AL to AL $\mu_s = 1.05 - 1.35$

$A = 200mm\,(200mm) = 40000\,mm^2 = 0.04\,m^2$

$F_x = 80\cos(60) = 40\,lb$ with FOS of 2 = 80 lb

$F_y = 80\sin(60) = 69.28$ FOS of 2 = 140 lb

$F_f = F_x \Rightarrow F_f = \mu_s N = 1.05(N) = 140lb(32.2)$

$F_f \Rightarrow N = 133.3\,lb = 4293\,N$

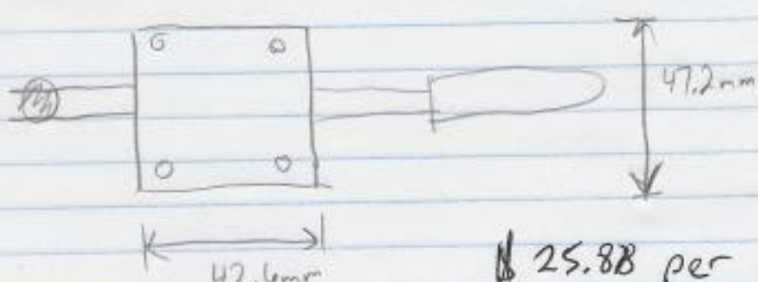
weight of aluminum ≈ 25 lbs = 805 N

need to make up 3488 N

two clamps means $\frac{3488N}{2} = 1744\,N$

need clamp part number 2017 UR

has toggle lock to prevent improper tightening



\$25.88 per clamp

2017-UR

Ø 40mm

Ball Bearings $L_{10} = \left(\frac{C}{P}\right)^3$

6200 Bearing → 1,150 Dynamic Load Rating

$P = 100$ lbs

$L_{10} = \left(\frac{1150 \text{ lb}}{100 \text{ lb}}\right)^3 = 1520.875$ mill rev

Rev per year ⇒ Say 20 tests per day

10 minutes per test

2000 rpm

= 400,000 rev/day

≈ 146 million rev/year

Design Life = 10.4 years

6203 Bearing = 2,150 Dynamic Load Rating

$P = 100$ lbs

$L_{10} = \left(\frac{2150}{100}\right)^3 = 9938$ mill rev

Design Life = 68 years