Design for Manufacturing, Reliability, and Economics

Team 4

VTT Rotor: Back EMF Test Fixture

Members:

Russell Hamerski – rh10g

Andrew Panek – ajp11k

Thomas Razabdouski – trs09

Tim Romano – tr10j

Andre Steimer – as10f

Faculty Advisors: Dr. Lou Cattafesta

Sponsor: Brandon Pritchard

Instructors: Dr. Nikhil Gupta, Dr. Chiang Shih

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ABSTRACT

Senior design Team 4 of the FAMU-FSU College of Engineering was tasked by Danfoss Turbocor to create a test fixture that can measure the back EMF of rotors that are manufactured by an outside company. The test fixture needs to insert an 80 pound magnetic rotor into a stator and rotate the rotor at a minimum of 1000 RPM. Through consistent meetings with Turbocor to finalize specifications, designs, and technical drawings, a prototype was agreed upon. Separate components were ordered and custom parts were manufactured from raw materials, and then put together on schedule and under the $4,000.00 budget given to the senior design team. The test fixture is expected to run reliably and with little maintenance needed on a manufacturing line for the foreseeable future. This report outlines the manufacturing assembly process, reliability of the test fixture, and economic analysis of the project. It should be noted that at this time assembly is not 100% complete and therefore no finalized assembly pictures can be provided.

ACKNOWLEDGEMENTS

Senior Design Team 4 is pleased that this Design for Manufacturing, Reliability, and Economics, given by Dr. Nikhil Gupta and Dr. Chiang Shih, was completed in conjunction with the assembly and testing of the final prototype. This report could not have been completed without the cooperation and combined effort of Russell Hamerski, Andrew Panek, Thomas Razabdouski, Tim Romano, and Andre Steimer. Team 4 would also like to thank Dr. Nikhil Gupta, Dr. Chiang Shih, and our advisor, Dr. Lou Cattafesta, for their guidance and assistance in reaching this milestone. Finally, Team 4 would like to thank the sponsor of this project, Danfoss Turbocor, and our liaison, Mr. Brandon Pritchard, for assisting us throughout the fall and spring semesters and answering any and all technical questions posed by Team 4.

1. Introduction

Danfoss Turbocor is planning to launch a new compressor model during 2015. Current production plans call for the use of a rotor that is to be manufactured by a third party company. Turbocor requires a way to quality check these rotors and ensure they are up to their standards. To do this, Turbocor must measure the back electromotive force delivered when the rotor is spun inside a stator. Electromotive force, or EMF, typically refers to the voltage generated when a rotor is spun due to the relative motion of the magnetic fields of the rotor and the stator.[1] Measuring this voltage can be used as a method to determine the speed that the rotor is rotating at. The reason it is generally referred to as a back EMF force is because the voltage pushes against the current that induces it. Taking measures of this back EMF gives Turbocor the ability to verify the quality of these rotors. Down the road, Turbocor plans to manufacture these rotors in-house, but until this takes place, this method of quality assurance is necessary.

To implement this testing procedure successfully and efficiently, a test fixture must be created that can be integrated into Turbocor's existing product manufacturing line. This test fixture will be used to perform the back EMF measurements on each rotor prior to assembling it into the new compressors. Turbocor developed an existing test fixture approximately 10 years ago for use on one of their smaller compressor models. While the test fixture for this application will be similar, there are additional constraints when compared to the older one that make this implementation more difficult. There is a large magnetic force induced when the rotor is inserted into the stator. This is not of concern in the smaller compressor models as a human can easily overcome the magnetic force. In the new, larger compressor model, this magnetic force is significantly greater, and it is not safe to manually insert the rotor by hand. In addition, a method of centering the rotor inside the stator must be developed. This is absolutely essential to the testing process as any deviations in the centering can cause a test to fail or give inaccurate results.

The existing, smaller test fixture served as a guide to the team for designing a new test fixture to test a larger rotor. It is important to note that the current fixture absolutely cannot be modified to test the new rotor for the new compressor due to the larger physical size and electromagnetic force. In addition, to the age of the previous test fixture and the increased frequency of testing needed by Turbocor once the new compressor is released, a more reliable unit is needed. The setup and operation of the previously developed test fixture does give this senior design group an opportunity to view the essential features and operation of the test fixture. A picture of the previously utilized back EMF test fixture can be seen in Figure 1.

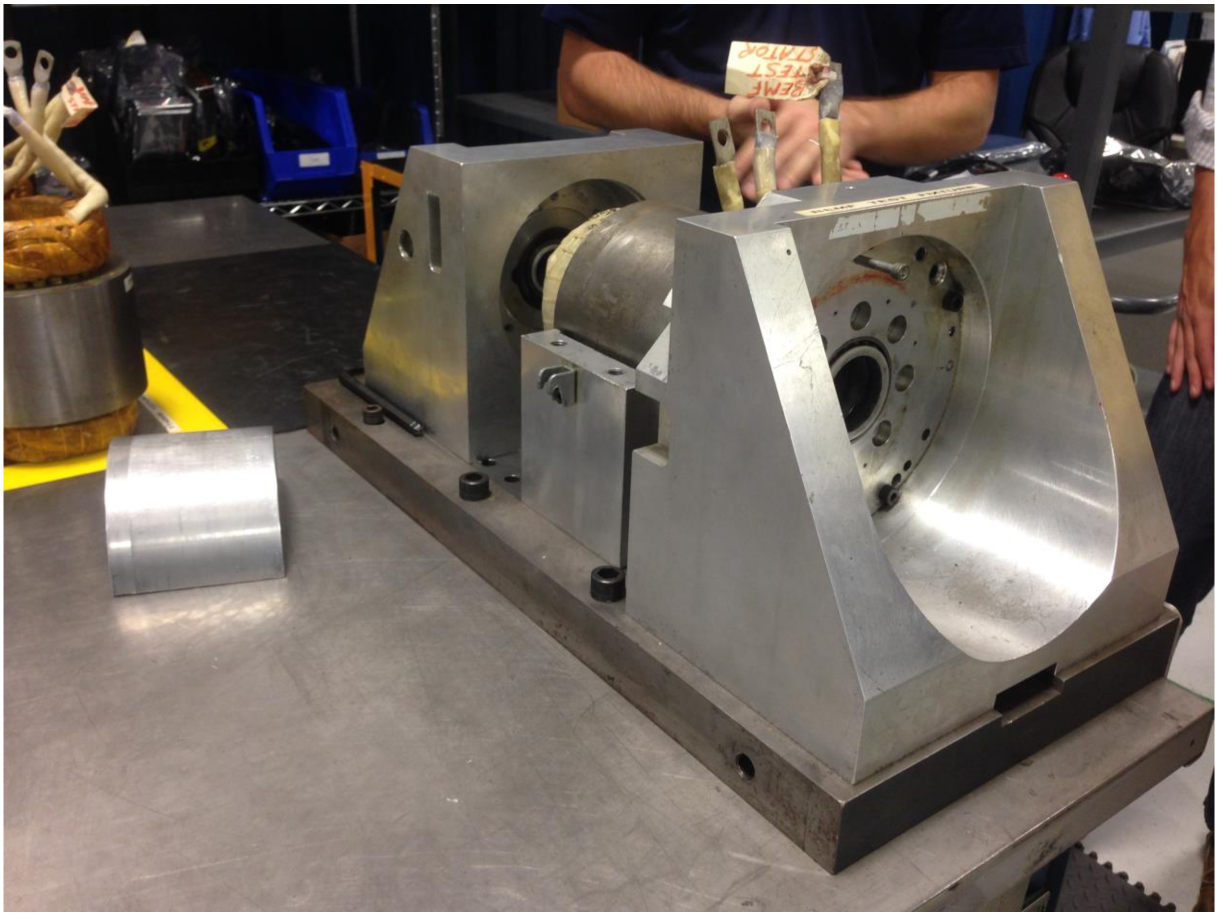


Figure 1: Previous test fixture for smaller rotors.

In the test fixture for the smaller compressor model, there is a locking feature that locks the stator in place, allowing for replacement of the stator as needed. This is an essential feature that is included in the new design. The older test fixture also utilized a bearing to ensure the rotor being tested is centered inside the stator. While this method of centering the rotor is effective, the high cost associated with replacing bearings over the life cycle of the test fixture led to the need of a new design. In addition, Turbocor stated that in the compressor, the rotor would not be supported by a bearing, and wanted the rotor to emulate its use in the compressor as much as possible. It is important to note that while a bearing is being used in the new test fixture design, it will be attached to the motor and support the motor shank rather than the actual rotor. This way, the motor shank will not risk failure and will not have to be replaced due to the decreased stress placed on it when compared to the previous test fixture.

2. Design for Manufacturing

Before starting the assembly, the senior design group's off-the-shelf components had to be ordered and the custom components had to have the raw materials sent out for machining. Florida State University's water jet was needed to turn the raw aluminum block ordered into a housing for the stator. This process took approximately three hours with a two-week lead-time. In addition, the machine shop at Danfoss Turbocor spent approximately 30 hours turning the raw aluminum materials into the required components such as the live center housing and baseplate.

Once the orders for the off-the-shelf components were placed, they arrived on time and error-free. All components were laid out on a table set aside for the group in the Danfoss Turbocor manufacturing facility. The first week of assembly started with the group focusing on the motor, extruded aluminum base, and the live center housing. The extruded aluminum base was the very first item put together, as every other component stems from here and cannot be placed without it. After this step, the ball screw was attached to the extruded aluminum base, as seen in Figure 2. Construction of the live center assembly commenced after this, with the support being heated in order for successful insertion of the live center adapter into the upright support. To heat it, the upright support was placed on a hot plate for approximately 10 minutes. This allowed the aluminum to expand and allow for easier insertion of the live center adapter. Following this insertion, the live center top and bottom baseplate pieces were attached to the upright support while the live center was placed in its adapter. Finally, the front plate for the live center housing was attached, securing the live center in place.

After the live center housing was complete, the senior design group focused attention on the motor. The bearings for the motor were attached which would eventually allow attachment of the rotor being tested. While these steps took place over the first of two designated assembly weeks, the stator housing had some finishing touches applied to it by the Turbocor machine shop after it underwent the cutting by the water jet. Some final holes were applied and the housing was cut in half horizontally in order to create the two separate upper and lower stator-housing pieces.

The second week concluded the assembly of the test fixture. The stator housing and stator were bolted onto the test fixture, along with the motor and motor drive. As previously mentioned, the two-part stator housing allows for replacement of the stator if necessary. Next, the linear guides were attached using fasteners in conjunction with the extruded aluminum. The electronics were attached after this and the test fixture was connected to the power supply. Testing and adjustment of the emergency stop feature were then done.

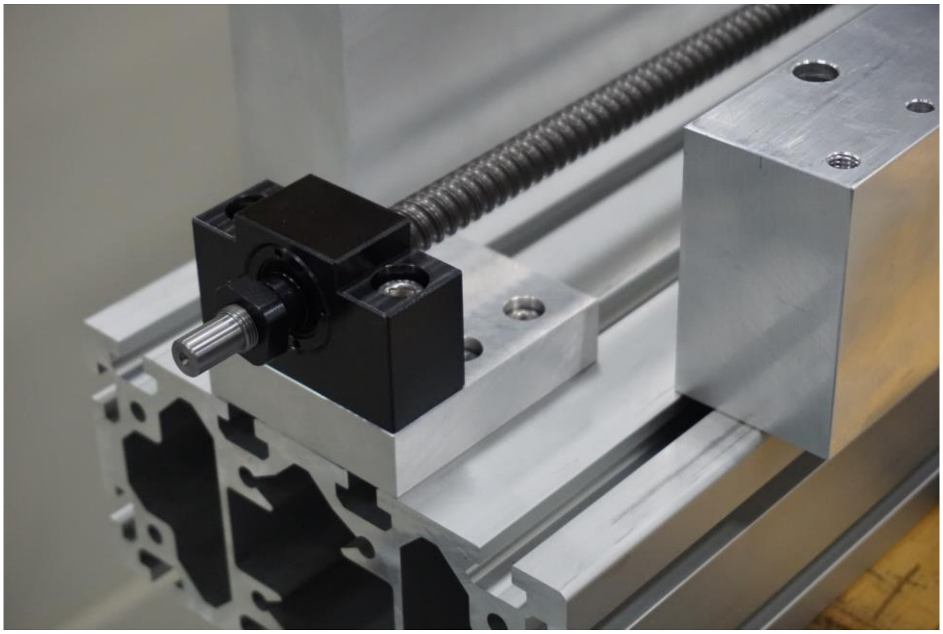


Figure 2: The ball screw attached to the extruded aluminum baseplate during assembly.

Unfortunately, a few design issues came up that were not foreseen by the senior design group. The original plans called for the custom components to be machined at Turbocor's in-house machine shop. However, the stator housing proved troublesome however as the raw aluminum was too thick for Turbocor's tools to effectively cut through. Florida State University's High Performance Materials Institute was then tasked by the senior design group to complete the cut for the stator housing as that facility contained a water jet that could cut through the material.

Problems also arose when assembling the motor support to the test fixture. The dimensions of the motor support that connects to the bottom of the motor were taken and applied to the baseplate of the motor supports when designing the housing on the computer using Pro Engineer. The group had to overcome a challenge as the X and Y dimensions were applied backwards and so the motor support only will when turned 90 degrees relative to the original orientation. As it turns out, this was actually not a problem as the original intention of the motor support was to allow the motor to slide backwards and forwards in line with the extruded aluminum. This idea would only work if the motor was perfectly centered on the test fixture, and incorrect assembly would render the test fixture useless. The motor support as it is now applied allows the motor to slide to the right and left of the extruded aluminum, giving the operator a chance to center the rotor. This can be seen in Figure 3.

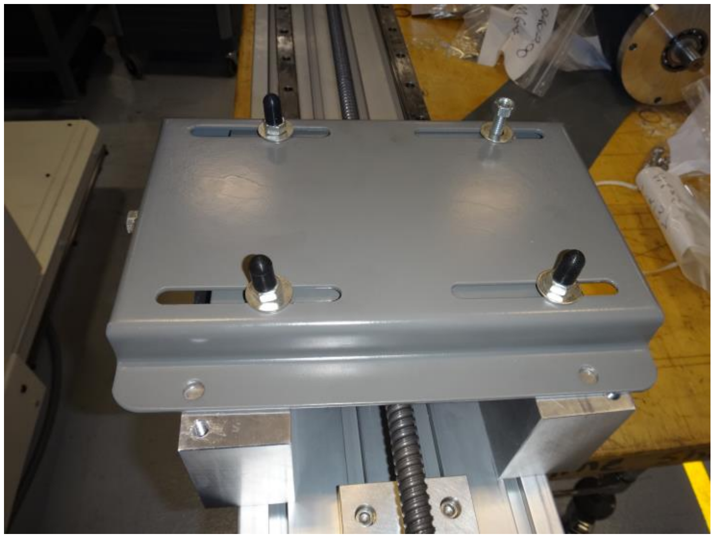


Figure 3: The modified motor support allowing for lateral adjustment of the motor.

Another issue that came about during the assembly involved the process of attaching the linear guides to the extruded aluminum base of the test fixture. The original conceptualization had M6 bolts connecting to M6 fasteners inserted into the extruded aluminum. This proved impossible, as the M6 bolt heads were too big to fit into the counter bore of the extruded aluminum. To fix this, M5 extruded aluminum fasteners were ordered and used in place of the M6 ones, as the bolt heads of the M5 screws fit inside the counter bore.

Although the assembly of the test fixture has taken approximately two weeks just as this senior design group predicted, the time frame for assembly relative to the point in the year was different than originally predicted. The original plans called for assembling the test fixture in late January, as part orders and technical drawings for manufacturing custom components were submitted in early December (just before the winter break between the fall 2014 and spring 2015 semesters). This was done with the intent of having our needed parts delivered and custom components machined and returned around the time the team returned from winter break. In case of any errors in manufacturing, delays in getting parts, or simply finding errors or flaws in the design, the senior design group would have had a substantial amount of time before the end of the semester to adjust accordingly. However, assembly was delayed until March to adjust some of the technical drawings at the request of the machine shop.

The final prototype has undergone multiple redesigns in order to simplify the test fixture. The result of these redesigns is given in Figure 4, which shows an exploded view. All in all, there are 32 major components in the final prototype, including 21 ordered straight from suppliers. Due to the multiple redesigns, the senior design group has determined that in order to meet the requirements of the project, the test fixture cannot be simplified any further without compromising any of the features or ease-of-use. The most significant component that required examination and selection was the one that would enable movement of the stator in order to overcome the magnetic force of the rotor. Three different options were considered: a rack and pinion, a pneumatic actuator, and a hand-driven ball screw. After using a weighted decision matrix and considering the pros and cons of each method, the ball screw was eventually chosen, as it had the highest score of the three and thus was the best choice for the project.

More complexity in the final prototype would be possible but not appropriate for the application it is to be used for. The test fixture is required to quickly and easily test rotors for quality control purposes. An example of adding unneeded complexity would be powering the method for overcoming the magnetic force, which would be the ball screw. Although it would be possible to connect a motor to the ball screw to crank it, for simplicity and reliability reasons it would not be necessary and was not wanted by Turbocor. This additional motor would have to have its own control system, and is not needed when an operator can crank the stator into position in under a minute. Additionally, all OSHA safety standards must be met and specifically, OSHA 29 CFR 1920 must be met at all times meaning noise levels must be maintained less than 80 dB.[2] An additional motor would significantly contribute to the noise signature of the design.

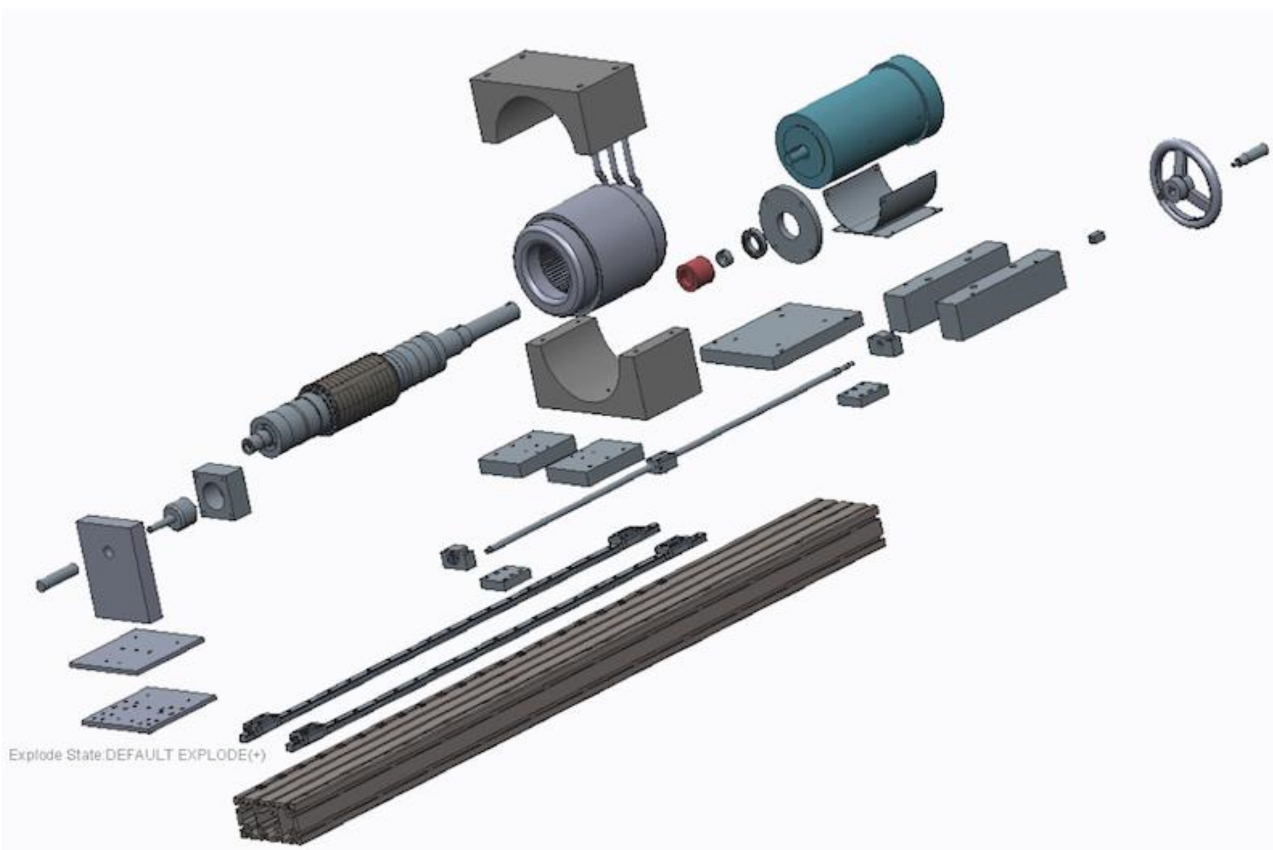


Figure 4: Exploded view of the Back EMF Test Fixture.

3. Design for Reliability

The final prototype has been run through a gauntlet of tests since completion, as any errors in the operation of the test fixture could lead to downtime in the manufacturing line and destruction of the rotor being tested. When used once, the test fixture successfully operates in the method it is designed to. Once the rotor is lowered into place, the motor and rotor can be sped up using the variable frequency drive and useful readings of the back EMF can be obtained from the oscilloscope. The requirements of the project from Turbocor outlined a need of testing rotors anywhere from 10-20 times per day, and the senior design group sees no problems with the test fixture fulfilling this requirement. As discussed earlier, the previous test fixture that was designed for smaller rotors required a significant amount of maintenance as that design called for a bearing that directly supported the rotor weight. The new design features a bearing that instead supports the motor shank and in turn, undergoes less stress while being used. The motor shank has been analyzed using finite element analysis as seen in Figure 5. The shank undergoes 5.83 MPa of stress while it is designed for approximately 60 MPa. This indicates a factor of safety of over 10. Other examples of the finite element analysis done on the motor shank can be seen in Appendix B.

Each test should only be in the neighborhood of 1-3 minutes. Even if used 3 minutes a day, 20 times a day, the bearing should not require replacement (barring an unforeseen catastrophe). As long as the maintenance outlined in the operation manual is done correctly, there should not be any problems with using the device 100 times, 1000 times, or 10,000 times.

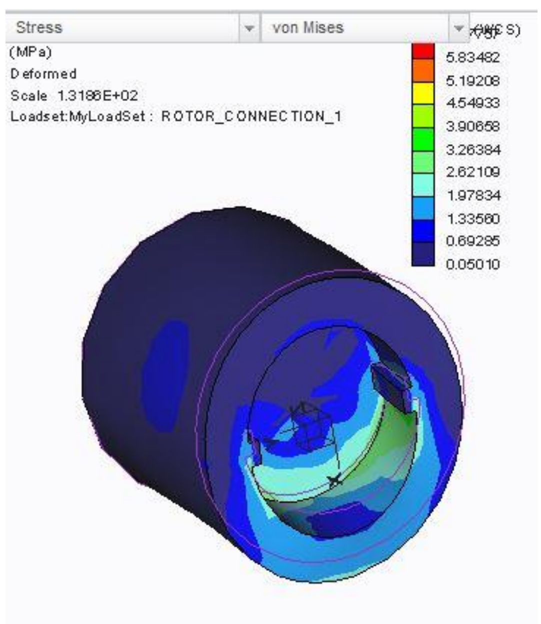


Figure 5: Finite element analysis performed on the motor shank, showing a maximum of 5.83 MPa on the part. The shank should be able to withstand 60 MPa.

This test fixture was designed for maximum reliability with minimal maintenance required, and there are not any imperative reliability concerns in the final test fixture. The operation manual developed for the test fixture outlines how to operate the device for reliably and safely. If the operator follows this outline, there should not be any outstanding issues to be concerned about. The most important point emphasized in the manual is the importance of using the emergency stop function only in an actual emergency. Some operators may be tempted to use it when the test is complete, rather than ramping the speed of the motor down using the variable frequency drive. Repeated use of the emergency stop function when not necessary may cause damage to either the drive or the motor over a long period of time. Using it only when required, however, poses no known threat to the reliability or lifespan of the test fixture.

Future work from a reliability standpoint includes implementing the test fixture in the manufacturing line in a way that will guarantee easy operation. This involves considerations such as access to a crane in order to lower the rotor into place. Close, efficient access to a crane is imperative as the rotor's size and its magnetic force make it too large to be loaded by hand, and damage (and downtime) could occur if the operator attempts this. Several considerations were given to the different ways in which the test fixture may fail, and these can be seen in an FMEA diagram provided in Appendix C.

4. Design for Economics

The cost of the components and raw materials alone come in at approximately $3,734.49, well under the $4,000.00 budget given by Turbocor. Figure 5 gives a visual representation of how the money was allocated. The complete details of the components and materials ordered are available in Appendix D. It is important to note that the cost of the components and raw materials do not include the cost of labor for machining the raw materials into the custom components. The machine shop at Turbocor completed approximately 30 hours of work to finish the test fixture's parts while FSU HPMI spent approximately three hours turning the raw aluminum block into a usable housing for the stator using their water jet.

The cost of this labor was not included in the senior design group's budget. It must be remembered, however, that if these resources were not available to the team, the labor necessary would have to be included in the budget and the cost of the total project would increase substantially based on the hourly cost of the labor. For example, at a going rate of $20 an hour for a machine shop technician, 33 hours of labor would add a cost of $660.00 to the senior design group, putting this project over budget. However, it should also be noted that the $4,000 budget outlined by Danfoss Turbocor was given as an outline only and if it became necessary to go over this budget they had no issue with spending additional resources.

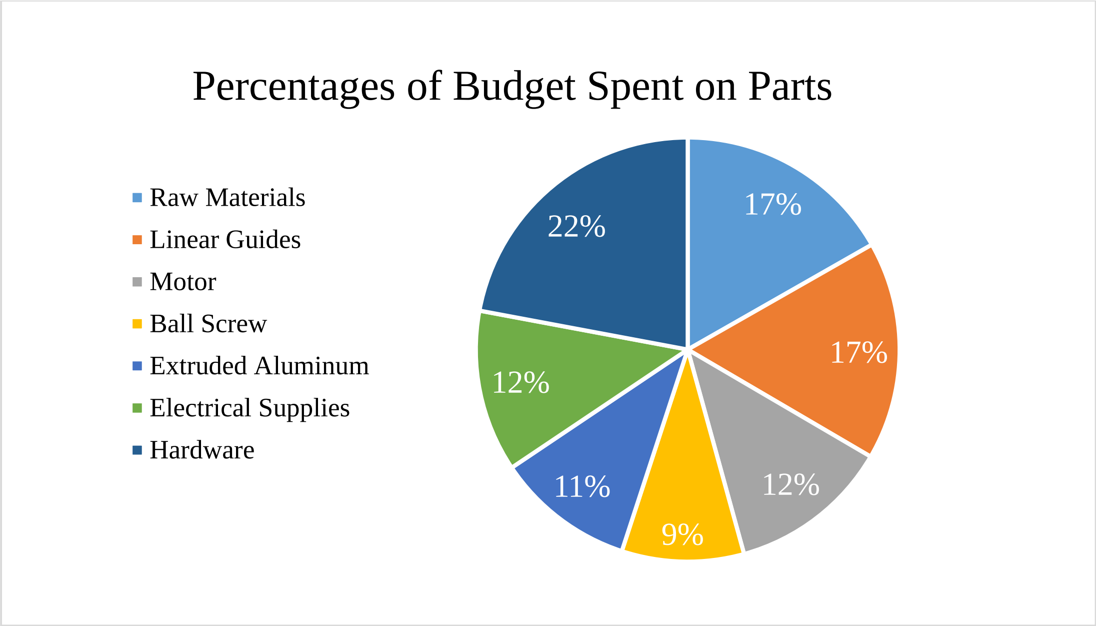


Figure 6: A visual representation of how the $3,734.49 spent was allocated.

The cost of the test fixture is relatively minor compared to the rotors being tested, which are approximately $12,000 each. The test fixture itself is custom tailored to the rotors Danfoss Turbocor is receiving for their new compressor and is "1 of 1". As far as research can tell, there are not mass-produced test fixtures that measure back EMF available for purchase, and there certainly is not one tailored to the specific rotor being implemented in the Turbocor's upcoming VTT Compressor. A comparison to a similar device is impossible as the only relatively similar device known to exist is the previous one Turbocor employed for testing smaller rotors.

A summary of the specific monetary values spent on the different component categories shown in Figure 5 is displayed in Table 1. Hardware for assembling the test fixture came in as the most expensive category at $816.53 while the ball screw was the least expensive category at $344.91.

Table 1: Summary of how the budget was allocated.

Category	**Amount Spent**
Raw Materials	$620.42
Linear Guides	$616.66
Motor	$455.00
Ball Screw	$344.91
Extruded Aluminum	$391.12
Electrical Supplies	$456.75
Hardware	$816.53

5. Conclusion

The senior design group has delivered the back EMF test fixture based on the design agreed upon with Danfoss Turbocor. Although the start of the assembly was pushed further back than originally scheduled, the actual assembly itself took approximately two weeks as expected. The components and electronics came together as designed and should perform reliably with minimal maintenance for many years to come in the manufacturing facility. FEA and FMEA has been performed by the team to ensure that all possible failure modes have been taken into account. The information provided in this report outlines in detail the assembly process that Team 4 underwent including some of the difficulties that were faced by the team throughout the assembly process. The test fixture was under budget, even with a few unexpected roadblocks in the assembly, such as the extruded aluminum fasteners not fitting as designed. Future work involves finding the best location for the test fixture to guarantee efficient, quick operation with a crane for loading and unloading the rotor.

References

[1] Acroname. "Back-EMF Motion Feedback." Acroname. Brainstem, 2014. Web. 23 Sept. 2014. <http://www.acroname.com/articles/emf-motion-feedback.html>.

[2] Pritchard, Brandon. VTT Rotor Back EMF Test Fixture Equipment Specification. Rep. no. A.0. Vol. 1. Tallahassee: Danfoss Turbocore, 2014. Print.

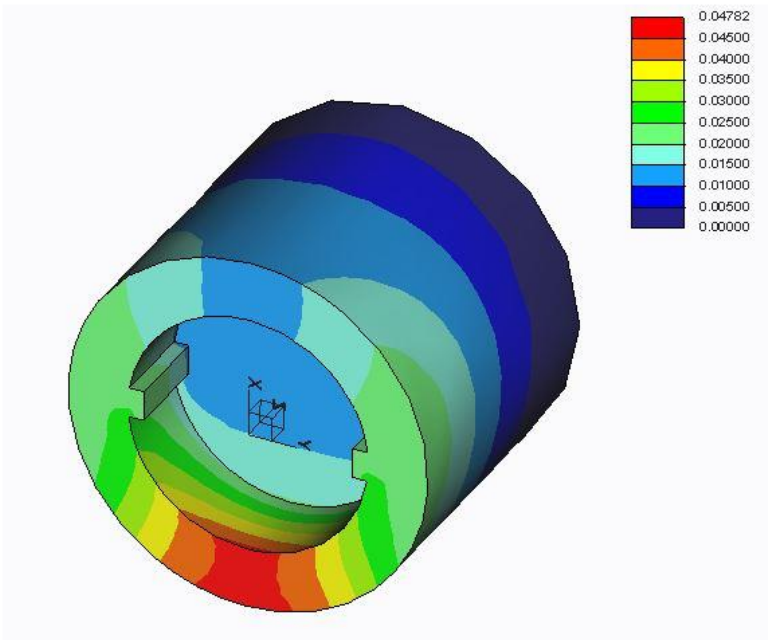
Appendix A

Summary of components of the Back EMF Test Fixture:

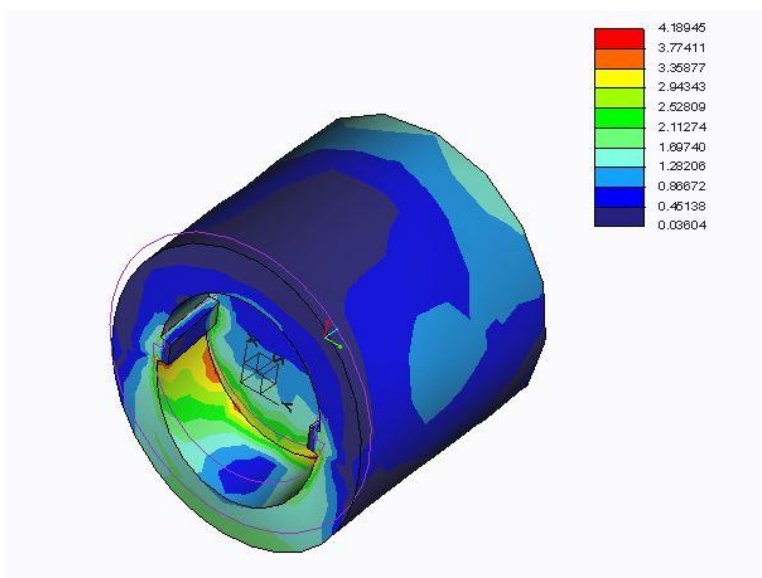
Description	Quantity
Heavy Load Linear Guides	2
Linear Guide Claming Units	2
Extruded Aluminum Baseplate	1
M5 Extruded Aluminum Fasteners (x100)	1
Handwheel	1
Rolled Ball Screw (1100 mm)	1
Fixed Side Support Unit	1
Support Side Support Unit	1
2 HP AC Motor, 1800 RPM	1
2 HP AC Motor Drive, 3 Phase	1
Adjustable Motor Base, 145T Frame	1
Live Center	1
Live Center Adapter	1
Fuse 25A 300VAC Class T 10 Pack	1
Fuse 0.1A 250VAC Class A 5 Pack	1
VFD Remote Keypad Mount	1
Power Supply 24 VDC 3.75A (90 Watt)	1
MUSH PB 30mm Metal Red NC Push-Pull	1
Guarded PB 30mm Metal Green 24V MOM LED-3H	1
Legend Plate 30mm On/Off Plastic	1
Legend Plate 30mm E-Stop Plastic	1
Bearing Block Support	1
Motor Bearing Support	1
Stator Housing Bottom	1
Stator Housing Top	1
Linear Guide Spacer	2
Live Center Baseplate	1
Live Center Front Plate	1
Linear Guide Connector	1
Live Center Upright Support	1
Motor Base Support	1
Table	1

Appendix B

Finite element analysis showing displacement of the rotor connection at the ground point, with a maximum deflection of 0.04782 mm:



The Von Mises stress experienced by the rotor connection with a simulated rotor weight of 160 lbf, twice the real world weight. The maximum stress is approximately 4.18 MPa in the corner:



Appendix D

Summary of components ordered and their respective prices:

Description	Vendor Part Number	Quantity	Unit Price	Total Price
Heavy Load Linear Guides	SX2R28-1240	2	$308.33	$616.66
Linear Guide Claming Units	SVCK28	2	$78.18	$156.36
Extruded Aluminum Baseplate	HFS8-90180-1750	1	$391.12	$391.12
M5 Extruded Aluminum Fasteners (x100)	PACK-HNTTSN8-5	1	$33.10	$33.10
M6 Extruded Aluminum Fasteners (x100)	PACK-HNTTSN8-6	1	$33.10	$33.10
Handwheel	PHLW200-17	1	$86.46	$86.46
Rolled Ball Screw (1100 mm)	BSBR1510-1100	1	$344.91	$344.91
Fixed Side Support Unit	BSWE12	1	$87.14	$87.14
Support Side Support Unit	BTN12	1	$90.59	$90.59
2 HP AC Motor, 1800 RPM	E2007A	1	$455.00	$455.00
2 HP AC Motor Drive, 3 Phase	GS2-22P0	1	$251.00	$251.00
Adjustable Motor Base, 145T Frame	MTA-BASE-W145T	1	$18.00	$18.00
Live Center	ZLC 07018-MT2	1	$128.95	$128.95
Live Center Adapter	185041	1	$23.93	$23.93
6061 Configurable Plate	A6061P-6F-MMA-NNN-212-160-38.1-CAR	1	$119.63	$119.63
6061 Configurable Plate	A6061P-6F-MMA-NNS-166-120-32-CAR	2	$71.09	$71.09
6061 Configurable Plate	A6061P-6F-MMA-NNS-80-70-20-CAR	2	$29.36	$58.72
6061 Configurable Plate	A6061P-6F-MMA-NNS-200-200-10-CAR	2	$55.06	$110.12
6061 Configurable Plate	A6061P-6F-MMA-NNS-100-100-49-CAR	1	$67.30	$67.30
6061 Configurable Plate	A5052P-6F-MMA-NSN-210.4-80.5-49.1-CAR	2	$96.78	$193.56
Fuse 25A 300VAC Class T 10 Pack	TJN25	1	$71.75	$71.75
Fuse 0.1A 250VAC Class A 5 Pack	AGC-1	1	$6.50	$6.50
VFD Remote Keypad Mount	GS-CBL2-IL	1	$28.50	$28.50
Power Supply 24 VDC 3.75A (90 Watt)	PSM24-090S	1	$99.00	$99.00
MUSH PB 30mm Metal Red NC Push-Pull	HT8 CBRB	1	$62.00	$62.00
Guarded PB 30mm Metal Green 24V MOM LED-3H	HT8 GDF3	1	$68.00	$68.00
Legend Plate 30mm On/Off Plastic	HT8 SP25	1	$4.50	$4.50
Legend Plate 30mm E-Stop Plastic	HT8 RP79	1	$4.50	$4.50
N12 30mm COVER 8X3.25X2.81 IN PUSH BUTTON	PB3	1	$53.00	$53.00
			Total:	$3,734.49