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Team 05: High Speed Motor Test Stand

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1.1 Project Scope

Danfoss is tasking Team 05 with designing a system that can measure motor efficiency at standard operating speeds for motors inside various Danfoss Turbocor compressors. Team 05 will determine the best way to measure output power for efficiency calculations and the best way to couple the motor shafts for operation at high speeds. They will design and implement a safety shield in order to maintain safe operating conditions while testing the system

Only the Danfoss facility will use the motor testing system. The assembly line will not use the system to test each compressor; instead, the research and development team will utilize it. The stakeholders include Danfoss, research, and product development.

1.2 Customer Needs

Danfoss Turbocor research and development team requires a high-speed motor testing system capable of measuring the power output and efficiency of the Turbocor compressors. The system will operate at a range of 13,000 to 40,000 rpm. Improvements are to be made to the existing system based off of need when testing. The system will have a stand since the current motor testing system sits on the floor. It will also need some sort of structure surrounding the entire system for safety purposes. Finally, the team will select and add a torque transducer to the test stand to accurately measure the efficiency of the compressor.

1.3 Functional Decomposition

From the project scope and customer needs, the Danfoss High Speed Motor Test Stand Team can determine the functions of the stand. The team decides on three main functions. The high speed motor test stand will measure motor efficiency, hold the weight of the motor testing system, and protect the operator from harm while testing is in progress. Each of these main functions will also have subfunctions, which will be discussed below.

A subfunction is what needs to be done in order for the main function to take place. For the test stand to be able to measure motor efficiency, it will first need to be able to operate at standard motor speeds. For the motors used in this project, standard motor speed is between 13,000 to 40,000 rpm. Then, it will have to measure torque with a torque transducer.

To hold the weight of the motor testing system, the stand will need to be built with a suitable material. It will also maintain stability.

A safety shield will attach to the motor test stand to protect the operator during testing. The safety shield will be built with a suitable material. After the safety shield is built, the stand will have easily accessible E-stops added to it.

1.4 Target Summary

After defining the functions and their subfunctions, the Danfoss High Speed Motor Test Stand team can now establish the targets for each subfunction. By establishing targets for the project, it will help the team in the further stages of the design process because they will have clear goals to aim for, and it will help eliminate concepts. Each subfunction discussed in the previous section will have a target that the design must satisfy.

The first main function for the high speed motor test stand, as discussed above, is to measure motor efficiency. This function has two subfunctions: operate at standard operating speeds and measure torque with a torque transducer. The standard operating speeds of a Danfoss compressor can range from 13,000 to 40,000 rpm; however, the target for this subfunction is 7,000 to 40,000 rpm. This is because the previous Senior Design Team that worked on this project only achieved 7,000 rpm, and one of the goals set by the sponsor is to achieve a speed higher than the previous team (Aponinuola, De La Rose, Jurko, & Pullo, 2017). To measure torque, the torque transducer must be able to measure a torque of up to 100 newton meters and be able to operate at 40,000 rpm.

From the Functional Decomposition, the second main function is to hold the weight of the motor testing system. This function also has two subfunctions. To be able to hold the weight of the motor testing system, the stand must be built with a suitable material and be able to maintain stability. The material used for the test stand must be able to withstand the weight of two Danfoss compressors, which total 272 kilograms. The stand must also maintain stability while operating underneath the weight of the system. If the system is unstable, the two compressor motor shafts become misaligned, and when the misalignment is too great the compressors completely shut down. This shutdown occurs when the radial force exceeds 890 newtons.

Safety of the operator using the high speed motor test stand is one of the main concerns of this design project; therefore, the third main function is to protect the operator while testing is in progress. To protect the operator, the system will have a safety shield which must be at least 0.61 meters long, 0.61 meters wide, and 0.5 meters in depth in order to cover all moving parts of the high speed motor testing system. The safety shield will need to be built with a suitable material that can handle the impact energy of a projectile hitting it. Team 05 calculates this energy using the equation below.

$$E = \frac{1}{2}mv^2$$

The variable 'm' represents the mass of the projectile, and 'v' represents the velocity of the projectile. For the worst-case scenario, the team uses the coupler, with an outer diameter of 0.08128 meters and a mass of 0.907 kg, as a possible projectile and 40,000 rpm to calculate the velocity. By converting the revolutions per minute to radians per second and then multiplying it by the radius of the coupler, the velocity of the projectile is 170 meters per second. From the energy equation above, the impact energy of the coupler is 13 kilojoules. The material used must be able absorb an impact energy of 13 kJ. The stand will also need accessible E-stop buttons. An E-stop is defined as "a function that is intended to invert harm or to reduce existing hazards to persons, machinery, or work in progress" (Nix, 2017). For each operator station that can produce mechanical motion, there must be one emergency stop function (Nix, 2017). Finally, for the testing system to be safe to operate, it must prevent the operator from handling the tester while testing. OSHA standards state that rotating parts cannot come into contact with any part of the body. The target set for this subfunction is 0.172 meters because that is the average size of a woman's hand. Team 05 uses this metric because a woman's hand on average is smaller than a man's, and a hand is the most likely body part to come into contact with the tester. The safety shield must be designed so that no operator can come within 0.172 meters of the motor shaft.

The Target Catalog, Table 2 shown in Appendix C, shows all the metrics discussed above. The table also contains the relating subfunctions and main functions.

1.5 Concept Generation

Table 1
System and Concept Description

System	System Title	Concept	Concept Title
System 1	Motor Torque	Concept 1.1	TMHS 311 Torque Transducer
		Concept 2.1	TMHS 310 Torque Transducer
		Concept 3.1	UTM II - 100 Nm Torque Transducer
		Concept 4.1	Froude AG80 Dyno
		Concept 5.1	PCB Rotary Transformer
System 2	Coupling System	Concept 1.2	Zero Max Double Clamp A1C Coupling
		Concept 2.2	Custom Zero Max Carbon Fiber Coupling
		Concept 3.2	SU 90-6 Coupling
System 3	Safety	Concept 1.3	Frame over Rotating Parts
		Concept 2.3	Frame over Entire System
System 4	Frame Adjustments	Concept 1.4	Alignment Set-Screws

System 1.

One of the high speed motor test stand functions, mentioned in the Functional Decomposition, is to measure motor efficiency. To measure motor efficiency, motor torque will need to be measured. There are two fundamental ways that torque can be calculated. One way is called the indirect method. This typically involves doing a calculation based on the theoretical operation of the system. For example, given a gear train with an input shaft and output shaft, the indirect method would use the input torque and gear ratio to calculate the output torque. Another way is called the direct method. The direct method involves some direct measurement of the torque applied by the output shaft of the motor. With this method, the torque is transduced by attaching a resistive sensor to a shaft that is then coupled with the motor shaft (Schicker & Wegener, 2002).

Concept 1.1

One way to measure the motor efficiency is to use a torque transducer. Team 05 will research multiple torque transducers because the sponsor desires to measure motor torque using a torque transducer. An important consideration when choosing a torque transducer is the mechanical design of the transducer. Since the compressor motor is a high speed motor, a transducer that uses non-contact bearing should be chosen. Otherwise, the bearings would have to be replaced often which would become a maintenance burden under continuous operation. The high speed of the motor places another, less restrictive, constraint on the selection of a torque transducer. The standard method of a signal transmission in a torque transducer is through use of a slip ring, where the electrical signal is conducted through a rotor by brushes that are in physical contact with the rotor as it spins. A transducer that conducts the signal using a slip ring would likely wear prematurely, and thus should be avoided if possible. Other technologies exist that use contactless conduction for the electrical signal and would require less maintenance. One possible torque transducer for this project is the TMHS 311 from Magtrol, represented by Figure 1. This in-line rotary torque transducer is capable of rotary speeds of up to 32,000 rpm and is rated for a torque of 100 Nm. It has non-contact bearings with a non-contact conduction technology suited for high speed operation. This option would provide a fixed center for the test stand. In hopes to eliminate fighting between the compressors, this option allows each compressor a level of independence that is only possible with a fixed toque transducer. The vibrations from one compressor will no longer be transferred to the other compressor. Instead, it will only be fighting against the fixed torque transducer. The only limitation this torque transducer has is that it is only rated to 32,000 rpm. Although that is slightly lower than the max achievable speed by the compressors, it should be suitable for testing. As you increase rpms, the torque rating of the transducers goes down. This option provides the highest rpm while maintaining the required torque rating that the compressors can reach. This torque transducer can be attached to a fixed mount or adjustable mount. With a fixed mount, the alignment of the shafts could become increasingly difficult if the height is not perfect when machined and manufactured. The assembly is much easier than an adjustable mount, and it takes less time to set up. The fixed mount is also very rigid which means that small vibrations from the compressors will not affect the torque transducer's alignment. With the adjustable mount, the aligning the transducer with the motor shaft will be simpler than with the fixed mount, maintaining that the adjustable mount is level. The adjustable mount design can be seen below by Figure 2.

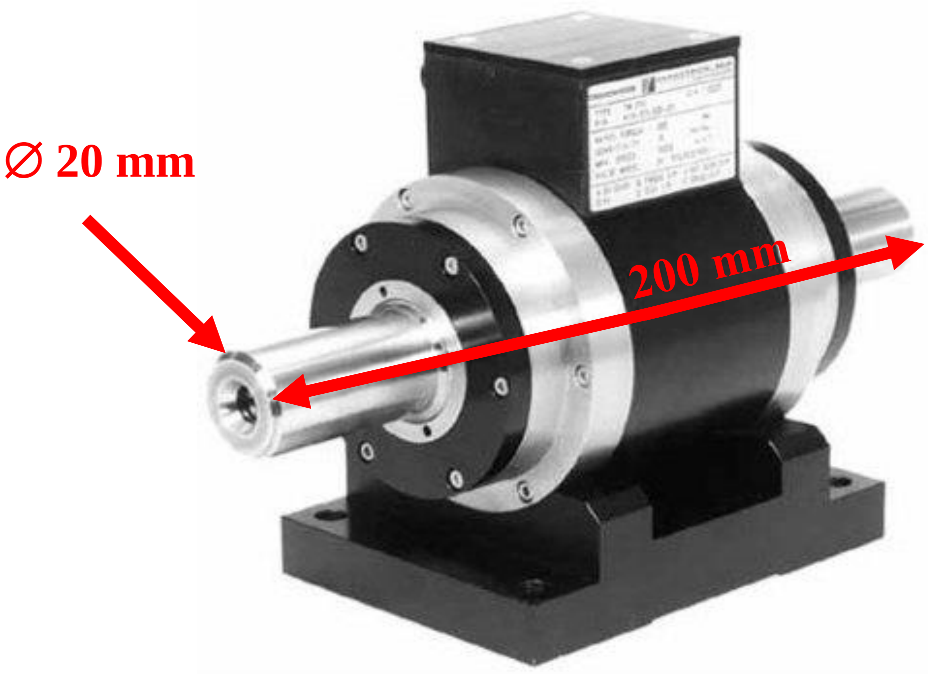

Figure 1. TMHS 311 Torque Transducer.

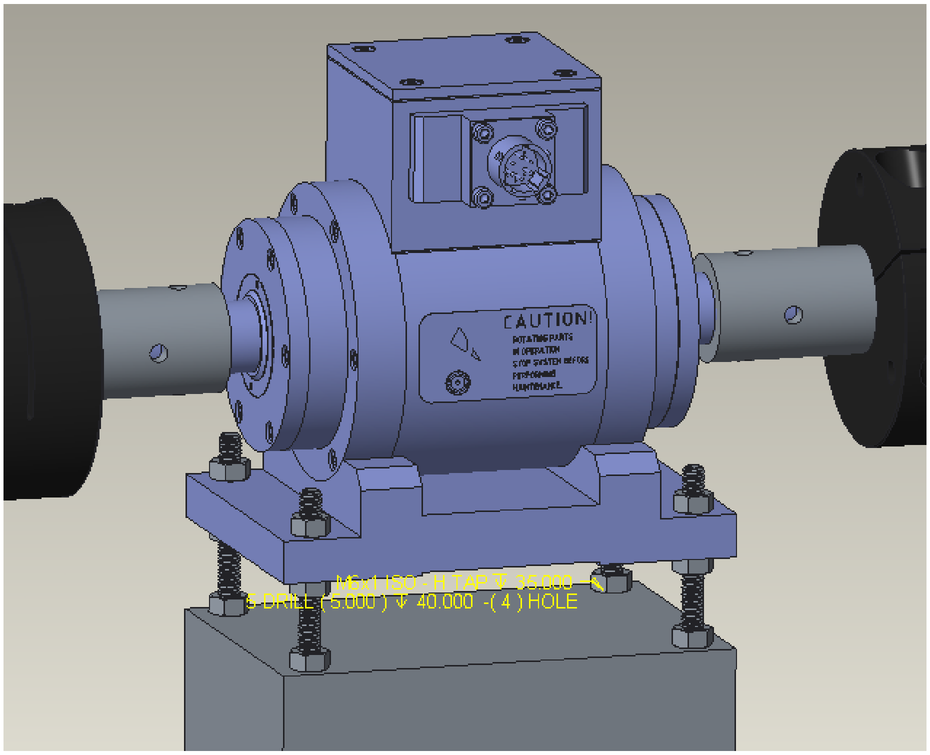

Figure 2. Adjustable mount design

Concept 2.1

The second torque transducer option is the TMHS 310 also by Magtrol. Similar to the transducer mention in Concept 1, it is an in-line rotary torque transducer that is capable of rotary speeds of up to 32,000 rpm and is rated for a torque of 50Nm. This option is the cheaper version of Concept 1, offering many of the same advantages. This transducer also has non-contact bearings with a non-contact conduction technology suited for high speed operation. While this is the cheaper option, its torque rating falls short of the max torque achievable by the compressor. This was provided as a cheaper alternative to the sponsor by last year's senior design team; however, it was never purchased. This transducer can also be mounted with a fixed or adjustable amount, which is explained above in Concept 1.

Concept 3.1

Another possible transducer is the UTM II – 100 Nm by Unipulse, represented by Figure 2. This option provides the team with an alternative to the fixed transducer. Previous teams had issues with vibrations when running the test at higher speeds. With the proper alignment, it is possible that this option could be feasible. The UTM II can reach speeds of 15,000 rpm and is capable of readings up to 100 Nm. One major benefit of this option is that it eliminates the need for a torque transducer mount, as this sensor rotates freely due to its no slip ring. Shown by the schematic represented by Figure 3, the torque transducer is floating, as it is connected on each side by just the flexible couplers. This option still presents a risk of compressor vibrations being transferred between compressors, which can cause fighting between compressors and the testing system to shut down.

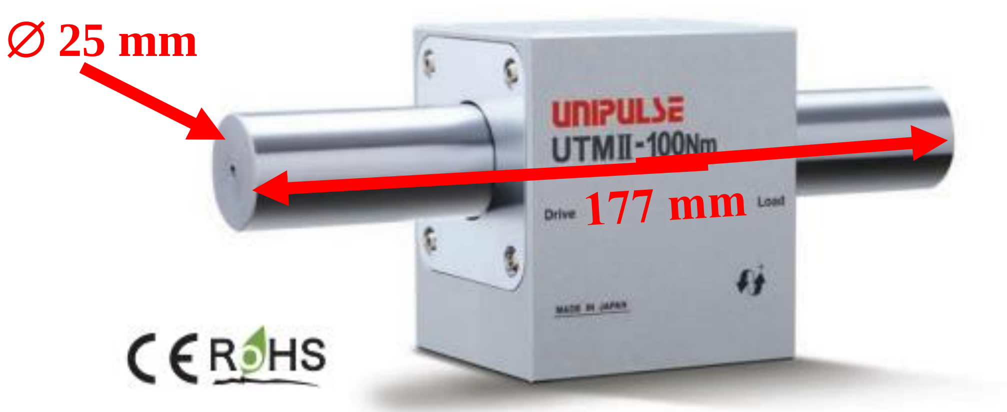

Figure 3. UTM II – 100 Nm Torque Transducer.

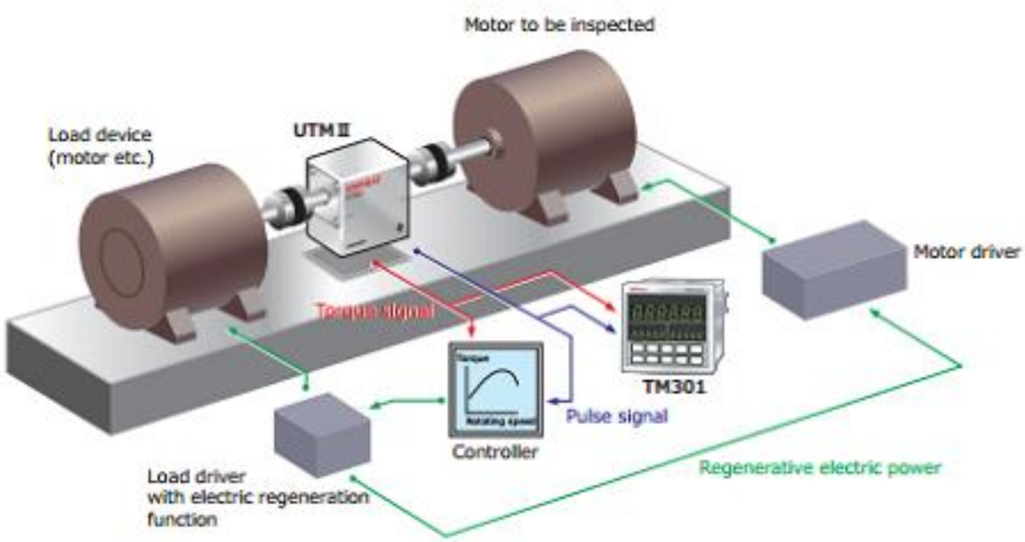

Figure 4. Schematic of the UTM II – 100 Nm Torque Transducer

Concept 4.1

Another idea to measure the motor efficiency is to use a car dyno. This would replace using another compressor as the generator. The dyno is designed to test electric motor rigs making it ideal for this application. The specific model Team 05 is discussing is the Froude AG80 dyno shown in Figure 5. The steel shaft is supported on deep grove ball bearings which are grease lubricated, and the heat is dissipated by a water cooling system integrated within. It uses twin magnetizing coils that are used to create a magnetic field which absorbs torque. This specific model, the AG80, can handle up to 30 kW of power, 95 Nm of torque, and can spin up to 14,000 rpm. It would bolt directly onto the compressor motor shaft. Instead of having two motors coupled, only one motor would couple to the dyno.

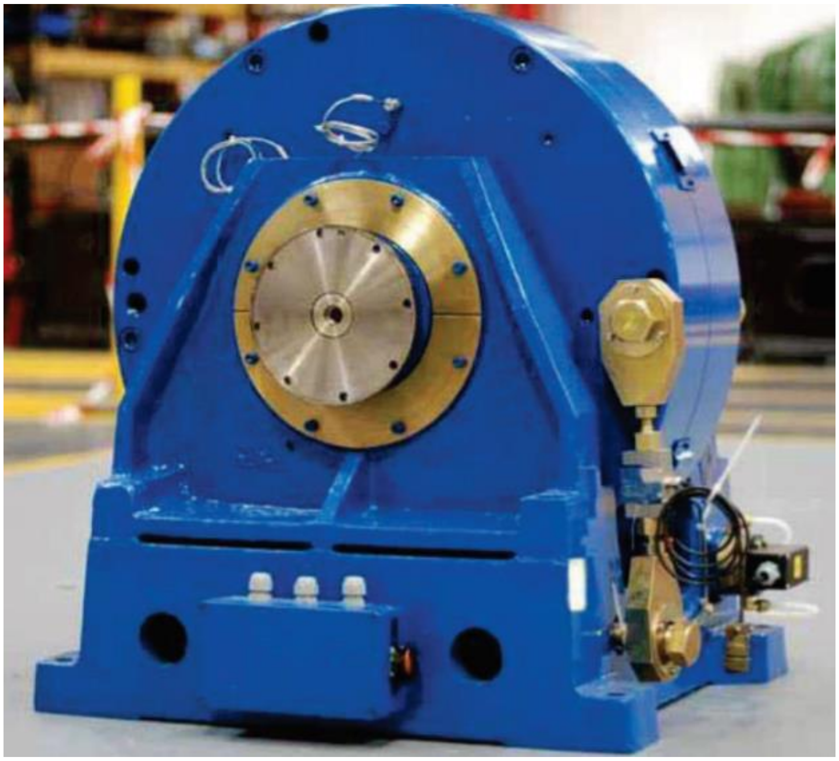

Figure 5. Froude AG80 dyno.

Concept 5.1

The final concept to measure motor efficiency is to utilize a rotary transformer. Like the previous concept, the transformer would function as the generator for the compressor motor instead of another compressor. A rotary transformer works similar to a regular transformer by having primary and secondary coil windings separated into two cores. The magnetic flux created in the two cores results in a torque measurement. The transformer has a flange with splined shaft which allows for easier coupling. It can be bought with a speed sensor as it can be a 2 in 1 system. The model the team is considering is the PCB Piezotronics 4115k-04A shown in Figure 6. The maximum torque this motor can handle is 55 Nm and has an overload limit of 170 Nm, and it has a maximum speed of 15,000 rpm.

Figure 6. PCB rotary transformer.

System 2.

Both the 2016 and 2017 design teams looked into the coupling system. The coupling system is the method in which the motor shafts of the two compressors are attached. Both teams chose a coupler, but this year's team will further research couplers to find out if there are better options.

Concept 1.2

The Zero Max Double Clamp A1C Coupling, Figure 7, was selected by the 2017 senior design team for a variety of reasons. This model can reach speeds of up to 15,000 rpm. While it is not capable of reaching the desired speed of 40,000 rpm, the sponsor wants the team to start testing with this coupler to ensure that the method to measure motor torque is viable. The Double Clamp A1C model is a variation of a composite disc coupling, otherwise known as an Oldham coupling. Oldham couplings are made up of three discs which are joined by a tongue and groove joint. Tongue and groove joints are used to join two bodies together. The groove is a slot along one edge of the body, and the tongue is a ridge that is a little less than the depth of the groove.

The middle disc rotates about the center of the input and output discs and, in this case, contains springs which are used to reduce the backlash of the mechanism. Because of this configuration, the Double Clamp A1C can tolerate up to 2 degrees of angular misalignment, 0.44 mm of parallel misalignment, and 1.6 mm of axial misalignment. At the minimum bore size, it’s weight is 0.3 kilograms. This is very light and could reduce the vibrations in the system.

Figure 7. Double Clamp A1C Coupling.

Concept 2.2

Another option would be a coupling made of carbon fiber. Zero Max is willing to make the team a custom-made carbon fiber double clamp coupling. The carbon fiber coupling would be able to reach speeds of 40,000 rpm and would be able withstand the high speeds and high torque. It would be another variation of an Oldham coupling and would cost around $2,000. This model would ideally be able to tolerate the same amount of angular, parallel, and axial misalignment as the A1C. The carbon fiber model would also be lighter than the Double Clamp which would assist with vibrational issues from slight misalignments.

Concept 3.2

The SU coupling, represented by Figure 8, is another form of disc coupling. It is torsionally rigid, which eliminates backlash and doesn't require any lubrication or maintenance. The couplings come in multiple sizes. The 90-6 size meets most of Team 05's goals. It is capable of withstanding 480 Nm of torque, satisfying the requirement of 100 Nm. It has a maximum balanced speed of 22,700 rpm, which is below the goal of 40,000 rpm. It can tolerate 0.75 mm of axial misalignment and 1.5 degrees of angular misalignment, which are within the sponsors requirements of 0.5 mm of axial misalignment and 1 degree of angular misalignment. It does not accommodate parallel misalignment. It has a weight of 1.54 kilograms which could substantially affect the vibrational issues in the system.

Figure 8. SU coupling.

System 3.

Safety of the operator is very important to consider when designing this test stand. Without certain safety precautions, handling a machine with an exterior motor shaft that can reach speeds of 40,000 rpm can lead to serious injury. The High Speed Motor Test Stand Team will design a safety shield to make the tester safe to operate.

Concept 1.3

One option for the safety shield is to use a frame that only covers the moving parts of the motor testing system, mainly the rotating motor shaft. Figure 9 further shows this concept. The team has multiple ideas to gain access to the tester covered by the safety shield. The shield can be free standing, meaning that it is not attached to anything. This allows for the individual using the tester to simply lift the shield off the system if they need to access any parts beyond it. The team will have to design the shield to be lightweight so the operator can easily lift it. If the shield is bolted down, possibly to the frame or the stand, the shield can have a door on the front for accessibility. The door can be a sliding door or a hinged door. The shield can be made of multiple materials including wire mesh, acrylic glass, and polycarbonate. Most wire mesh used to guard machinery are constructed with 10-gauge wire, which can handle a load of about 1,500 newtons. Acrylic glass is often chosen over regular glass in applications where non-shattering is desired. Acrylic glass's impact strength depends on its thickness. Polycarbonate is a great material when a high impact resistance is a requirement. For example, polycarbonate is one of the few materials used for bullet proofing.

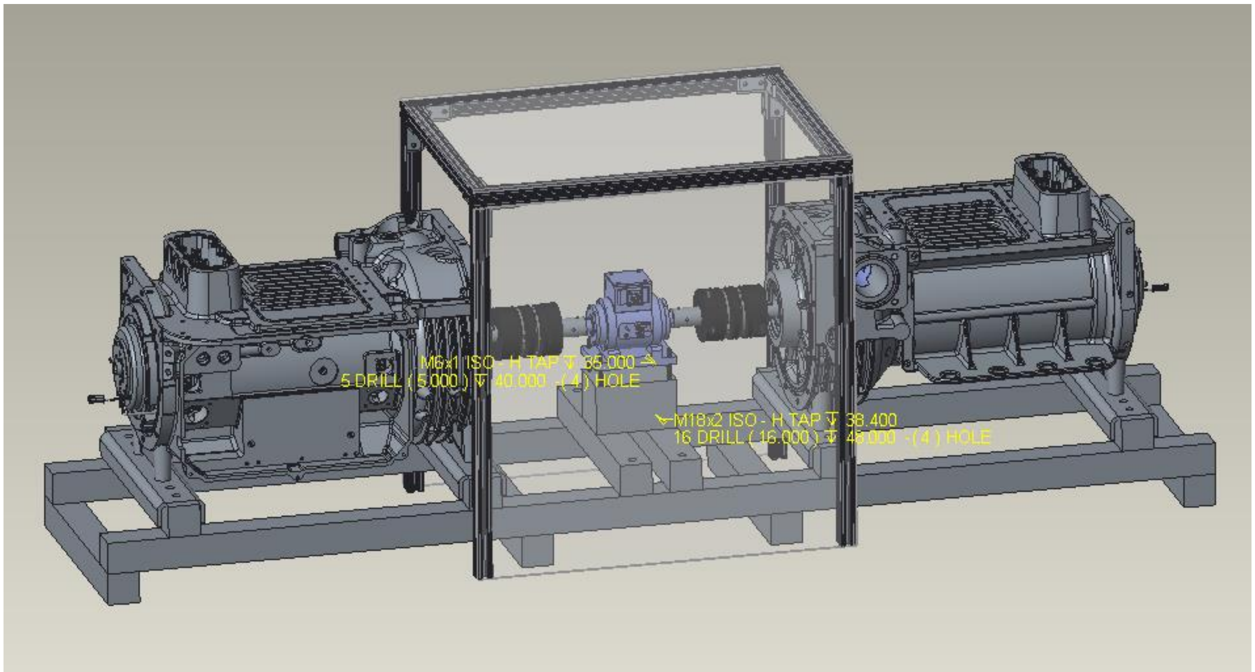

Figure 9. Concept 1 safety shield

Concept 2.3

Instead of just covering the rotating motor shaft, the safety shield could cover the entire system, including the two compressors, the frame, and the motor shaft. This idea is shown below by Figure 10. This design will be fixed and will have multiple access doors so that the operator can have access to all parts of the motor test stand. While the design shown below has a wire mesh guarding, other materials can be utilized instead. These materials include and they are further discussed above in Concept 1.

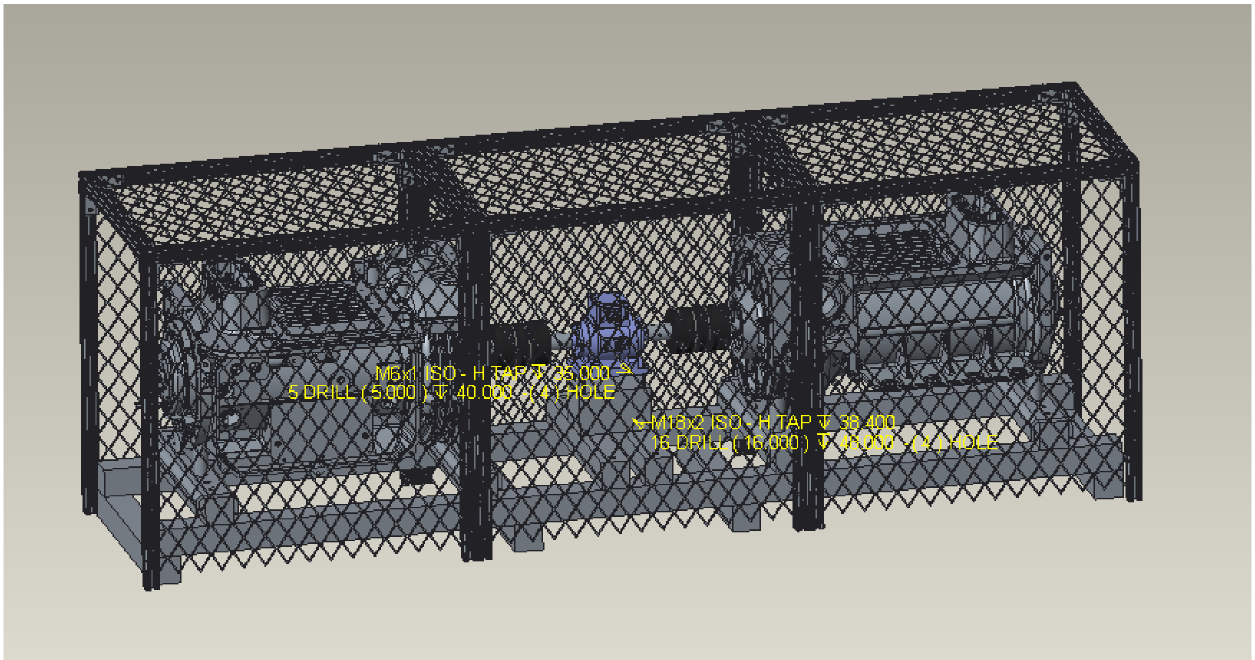

Figure 10. Concept 2 safety shield

System 4.

The motor testing frame was already designed and implemented by the previous years' senior design teams, but this year's team will most likely need to make adjustments to this frame depending on what motor torque testing device is chosen. The previous senior design team's frame design, Figure 11, used 50.8 mm x 50.8 mm steel tubing and welded brackets with a 3/8-24 tapped hole. A 63.5 mm set screw was used to set the rails, which are connected to the compressor feet, in place in the lateral direction. Adjustments in the 'z' or vertical direction, were accomplished via shims, represented by Figure 12. The overall design proved to work well; however, the shims proved to be marginally successful. Possible changes to the frame design are discussed below.

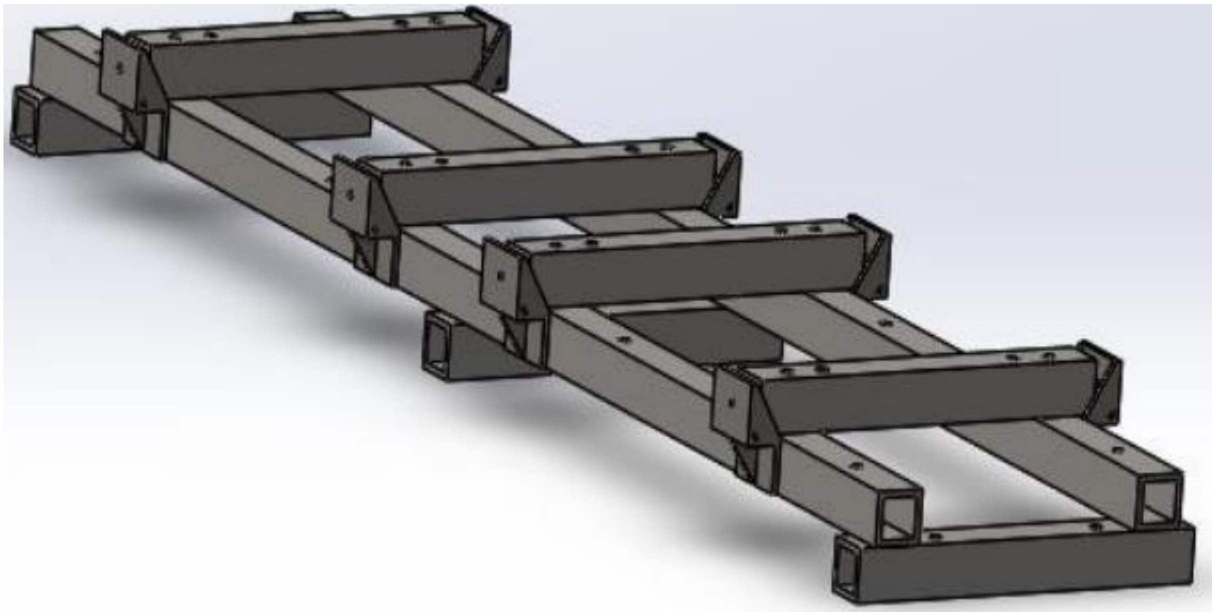

Figure 11. 2017 Senior design team frame design.

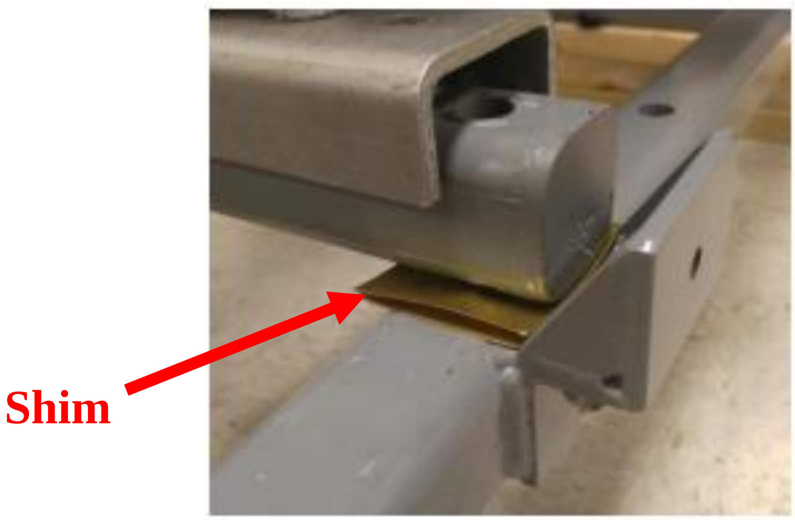

Figure 12. Application of the shim.

Concept 1.4

One alternative to using the shims is to use set screws to lift the compressor. Team0 5 can tap eight holes in the 50.8 mm x 50.8 mm steel tubing support brackets that support the four crossbeams which connect to the feet of the compressor. This will allow a new set screw to raise each leg in the z or vertical direction. The crossbeam tubing that connects to the feet of the compressor must also be set in place in the z direction so vibrations don't cause it to move up and down during testing; therefore, there needs to be a way to fasten the cross beam to the support beam either with a bolt and nut or another method of fastening.

1.6 Concept Selection

In order to determine Team 05's final concept, the group compares each concept to each other from each system from Concept Generation using methods such as the Target Catalog and the Pugh Chart. This helps to eliminate some of the options. After discussing the concepts with the sponsor, advisor, and professor, the High Speed Motor Test Stand Team selected the final design for each system.

Transducer.

For selecting a concept to measure motor efficiencies, the proposed concepts need to be evaluated against the constraints that are in place. Ideally, the motor testing stand should be able to work for all TT model Danfoss compressors, which vary in size from 300-700 kW. This means that each component of the stand should to be able to operate in a wide range of operating conditions. Specifically, the maximum speed that any TT model can run at is 40,000 rpm and the maximum torque that a TT model can apply is 100 Nm. These specifications put constraints on the concepts that were selected in the concept generation phase.

Table 2

Transducer Pugh Chart

Pugh Chart - Transducer						
Selection Criteria	**Current Requirements**	**Concept 1.1**	**Concept 2.1**	**Concept 3.1**	**Concept 4.1**	**Concept 5.1**
		TMHS 311	TMHS 310	UTM II	AG80 Dyno	PCB Rotary Transformer
Maximum Speed (rpm)	40,000 rpm	+1	+1	0	0	0
Maximum Torque (Nm)	100 Nm	+1	0	+1	0	+1
Sum of Positives		+2	+1	+1	0	+1

To decide which transducer to select, Team 05 utilized a Pugh Chart. The transducers were compared to the maximum speed and the maximum torque requirements which are 40,000 rpm and 100 Nm respectively. Team 05 considered these requirements of equal importance so chose not to use a weight system. A positive one was added to Concept 1.1, the TMHS 311 torque transducer, for both criteria because of its maximum speed of 32,000 rpm and its torque capacity of 100 Nm. Concept 2.1, the TMHS 310 torque transducer, was given a positive one for its maximum speed of 32,000 rpm and was given a zero for its torque capacity of 50 Nm which did not meet the requirements. A positive one was also awarded to concept 3.1, the UTM II torque transducer, for its torque capacity of 100 Nm. It was given a zero for its low maximum speed of 15,000 rpm. Concept 4.1, the Froude AG80 Dyno, was given a zero for its torque capacity of 95 Nm and its maximum speed of 14,000. Concept 5.1, the PCB rotary transformer, was also awarded a one and a zero for it's torque capacity and maximum speed which were 170 Nm and 15,000 rpm respectively.

Utilizing Table Table 2, the concept that was chosen was the TMHS 311 Torque Transducer. The rated specifications of each torque measurement device were the metrics used to select a concept. The TMHS 311 can handle the maximum torque applied by the motor while still being able to operate close to the desired 40,000 rpm. While not able to reach the absolute maximum speed of the motor, the TMHS 311 can come close enough to act as a proof of concept for the motor testing device. No transducer was found that is versatile enough to be able to handle the maximum torque of the motor and the maximum speed.

Coupler.

The selected primary coupling to be used to couple the Magtrol torque transducer to the motor shaft will be from R+W America. As mentioned in Appendix D, these couplings were recommended to be used with the torque transducer from the transducer manufactures. This will allow us to use this coupler with confidence as these are precision couplings that can be used for non-standards applications including custom requests for different tolerances and keyways. This also includes a range of inner diameters between 12-32mm. The coupling that was selected is the EK2-60A Elastomer Coupling with Clamping Hub. The reason the EK2 series was specifically chosen was due to its ease of mount feature compared to the rest of the elastomer couplings from R+W America. This model works by using high strength aluminum for the two clamping hubs and a thermally stable polymer for the elastomer insert. These couplers have the following desirable properties: easy to assemble, concentrically machined hubs, vibration dampening, backlash free, and it's a press fit design. The standard version can spin up to 11,000 rpm, but the team has selected the 31,000 rpm option that was specifically speed balanced. The rated torque it can handle is a

60Nm, but maxes out at 120 which meets the team's requirements. By not having an overly stiff coupler it will allow for some misalignment.

Figure 13. R+W America coupler.

Safety Shield.

For the safety shield, the team selected a partially enclosed system, see Figure 9, which covers all moving parts. The team decided to choose a partially enclosed system instead of a fully closed system for a few reasons. The most important reason being that a fully enclosed system does not allow for easy accessibility to the compressors being tested. The compressors, being so heavy, have to be loaded onto the test stand with a crane that lowers each compressor onto the test stand. Therefore, the fully enclosed system would have to have doors on the top to allow access for the crane, but even then, it would be difficult to change out compressors with every test. Another reason is the cost. The partially enclosed system uses less material than the fully enclosed system, which means the total cost for the material for the partially enclosed system is less than material for the fully enclosed system. While cost is not a huge factor for the team to consider since there is a large budget, the sponsor believes the less expensive the better. Since both the fully enclosed system and the partially enclosed system keep all moving parts away from the operator, the cheaper option is favorable. The safety shield will be attached to the test stand, which most likely means the team will have to make some adjustments to the test stand to accommodate for this. The team also discussed letting the safety shield be free-standing, but the team agreed it would be safer for the operator if it was fixed to the stand. If it is fixed, the chance of the operator coming into contact with any moving parts is low.

To decide what material to use for the safety shield, the team implemented a Pugh Chart to compare the three materials discussed in Concept Generation: wire mesh, polycarbonate, and acrylic glass. The Pugh Chart is represented by Table 3.

Table 3
Safety Shield Material Pugh Chart

Pugh Chart - Safety Shield Material				
Selection Criteria	**Current Solution** Wire Mesh	**Concept 1.3** Polycarbonate	**Concept 2.3** Acrylic	**Weight (1-5)**
Impact Strength	DATUM	+1	-1	5
Cost		-1	-1	2
Weight		-1	+1	2
Amount of Coverage		+1	+1	4
Sum of Positives		2	2	
Sum of Negatives		2	2	
Weighted Sum of Positives		9	6	
Weighted Sum of Negatives		4	7	

Team 05 decided that the selection criteria should include the impact strength, cost, weight, and amount of coverage provided by the material. These criteria were selected because of the customer needs and functional decomposition. The current solution that last year's team was using as a safety shield uses wire mesh. Depending on the wire material, the impact strength can differ, but most wire mesh guarding for machinery is made of powder coated steel. The average impact strength for this material is 20 kJ/m^2. Polycarbonate has an impact strength of 35 kJ/m^2, and acrylic glass has an impact strength of 15 kJ/m^2. For the cost and weight criteria, a sheet with dimensions of 48” x 96” x ¼” (when applicable) was used since this is a very common size. The average cost of a wire mesh panel of this size is $112, the average cost of a polycarbonate sheet is $281, and the average cost of an acrylic glass sheet is $145. The weight of the wire mesh panel is 32 pounds, the weight of a polycarbonate sheet is 47 pounds, and the weight of an acrylic glass sheet is 23 pounds. With all of this information, the Pugh Chart was filled out. For amount of coverage, a positive one was added to both the polycarbonate and acrylic glass material because the wire mesh can allow small pieces of material through.

Since the sum of positives and sum of negatives was the same for polycarbonate and acrylic, a weight of 1 through 5, 5 being the most important, was added to the Pugh Chart. The most important criterion for the safety shield is the impact strength, because it must be able to absorb the energy created by a projectile to be effective thus safe; therefore, a weight of 5 was given to this criterion. A weight of 4 was given to amount of coverage because it is important that no material can get through the safety shield, but if the impact resistance is not high enough, this will not matter. Weights of 2 were given to weight and cost because they are something to consider when choosing a material, but not the most important. After these weights were calculated, it was determined that polycarbonate is the best material to use, which is highlighted in green in the Pugh Chart.

1.7 Project Plan

Gantt Chart

Looking at the Gantt chart, which can be viewed in Appendix E, starting the year of 2018, the first task is to purchase the coupling which will be done soon after classes end in Fall 2017. This is to save time because the part needs to be purchased and shipped from the supplier, which could take up to six weeks, and will hopefully arrive as we return for the 2018 spring semester. This break will allow for brainstorming to spec the torque transducer and order it as we will start to work on the project again. A very large time frame was given to spec the transducer in order to make sure that only one transducer will be ordered without doubting that it will be functional for the duration of this project. A week into picking up again from winter break, the dates from 1/22 to 2/24, the shaft extension and the safety shield should be fabricated and machined allowing us to continue to the next step which is assembly. This will allow us enough time to make sure that the shaft extension is properly balanced. At this point the coupler, the torque transducer, shaft extension and safety shield should all be ready to assemble. The following three weeks, 2/26-3/16 are dedicated to assembly, this will include creating the code and hardware to set up the torque transducer. This is required as the transducer doesn't come with mounting or data collection accessories. The physical assembly of everything should be done by 3/23, which is a week after the transducer equipment is done. The testing phase is planned to take 4 days assuming best case scenario. This phase includes making sure that the system can run at our target rpm and troubleshooting any vibrations in the system. There is a month of slack time from 4/2-5/4 which will be distributed to the tasks that may experience unexpected backups.

Next Steps.

Couplings.

Selecting flexible couplings is now the main priority. Since Team 05 already had plans to purchase the Magtrol torque transducer, the team's communication liaison, Jacob Quigley, contacted them to find the couplings that they recommend using with their torque transducers for high speed applications. They then referred Jacob to R+W America where he found Elastomer couplings that meet the torque and speed requirements needed and possessed similar specifications as the zero-max couplers that last year's team used. The hope is these couplings will be approved for purchase before the end of the semester and can be tested for functionality in early January.

Torque Transducer.

It is most likely that the torque transducer will not be purchased until after couplings are approved by the sponsor due to budget constraints. Therefore, the timing of the testing of the couplings is crucial to the overall timeline of the project. The sponsor has approved the TMHS 311 torque transducer that was chosen for our design concept. However, all purchases beyond the couplings are delayed until the couplings are approved.

Design Approval.

The design, shown in Figure 14, has not been officially approved by the sponsor yet due to the conflict concerning the couplings. However, Team 05 has agreed on a general concept that includes a balanced shaft that is in proper stack tolerance. This was the main improvement to the team's design relative to the previous two years.

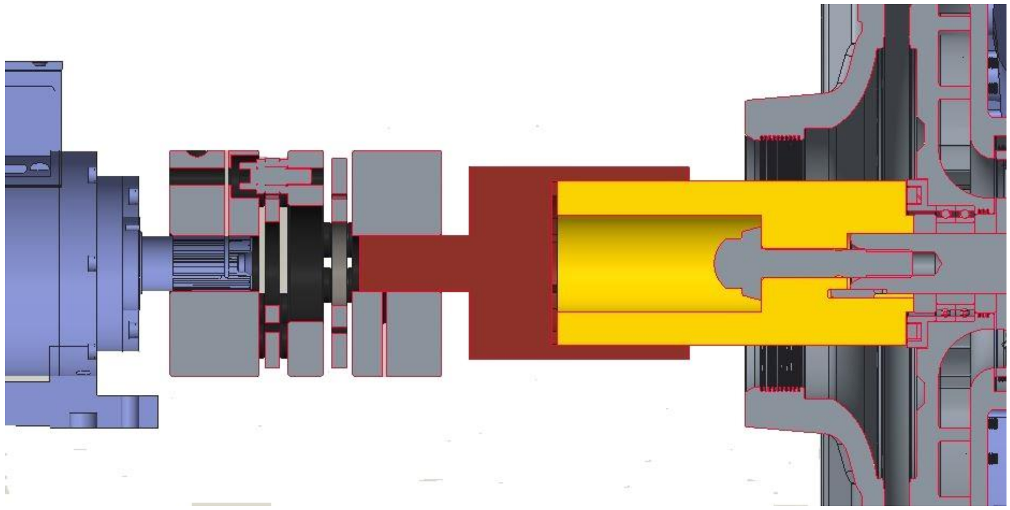

Figure 14. Current design to connect motor shaft to transducer.

The previous senior design teams connected the couplings directly to the shaft. To connect directly to the shaft, the 1st stage impeller and shaft bolt were removed. The shaft is balanced with the 1st stage impeller and shaft bolt on the shaft, when those parts are taken off the shaft is no longer balanced.

Also, the shaft bolt is torqued to 50Nm to keep the parts that make up the shaft in the proper stack tolerance. Therefore, without the shaft bolt the shaft is not in its proper stack tolerance, leaving the parts freely in the compressor without any axial constraint. Two of the most crucial metrics of the shaft are its concentricity and tolerance stack, both of which were compromised with the previous team's designs.

Machine Parts.

The design above consists of a "dummy" 1st stage impeller, which will be referred to as the shaft extender, that will be torqued to the shaft at 50Nm by the shaft bolt to keep the other parts in their correct tolerance stack. The shaft extender is essentially a splined shaft with a hole for the shaft bolt to be torqued down by a deep well socket wrench. The shaft extender is also designed with a shaft collar for additional tightening to the shaft itself, to prevent from any slippage that may occur. The shaft extender pieces need to be machined by Danfoss. Then the shaft will need to be rebalanced in the balancing cell at Danfoss turbocor, with the shaft extender on the shaft instead of the 1st stage impeller, keeping the shaft in its proper balance and stack tolerance. The shaft extender is shown by Figure 15.

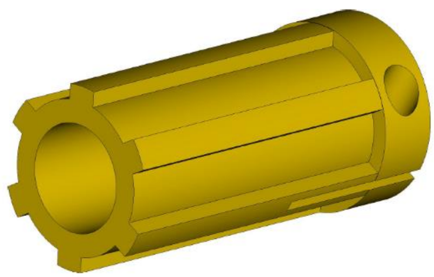

Figure 15. Shaft extender.

The coupler connector, shown by Figure 16, is the female end of the shaft extender spline shaft. The coupler connecter will also be machined at Danfoss Turbocor. It would be ideal to be able to have the shaft rebalanced with the coupler connector on as well, however since the coupler connector is not fastened to the shaft rather just held together by the friction of the spline, it may be too great of a safety concern. For this reason, Team 05 might have to explore other options for balancing.

Figure 16. Coupler connector.

The mount for the torque transducer is simply a block that has the four holes needed to mount the torque transducer at the proper height. Shims will be used for any minimal height adjustments needed. The block needed will be fabricated by the machine shop at Danfoss Turbocor per the drawings given to them by the senior design team with approval from the sponsor.

Alignment.

Alignment is the most crucial part of the set up for the testing process. The laser alignment tool last year's team selected works well, however they were previously connecting the alignment attachment to the flexible couplings rather than the shaft itself. This was because the shaft was recessed too far inside the compressor for the alignment attachment to be put on. Although they didn't know this at the time, the flexible couplings allowed for a degree of misalignment that was not being accounted for by the laser alignment tool. This was another reason the High Speed Motor Test Stand Team designed the shaft extender, ensuring it extended out of the compressor enough to properly attach the laser alignment tool.

Build Plan.

The coupling connectors will be put onto both shaft extensions, then the coupling connectors will be fastened to the flexible couplings themselves via the shaft collar on the flexible coupling. Next, the flexible couplings will be fastened to the torque transducer by sliding both compressors towards each other on the stand until they meet at the torque transducer. The shaft collar will be tightened on the flexible couplings onto both ends of the torque transducer. At this point, both compressors will be connected to the torque transducer.

For testing, the torque transducer mount needs to be fastened to the test stand with the correct height. Then the torque transducer shaft must be properly aligned with coupler connector that is connected to the shaft on the compressor using the laser alignment tool. Next, the compressor must be fastened securely to the test stand. Finally, the other compressor needs to be properly aligned with the laser alignment tool to the torque transducer then fastened securely to the test stand.

Appendices

Appendix A: Code of Conduct

Mission Statement

The Danfoss High Speed Motor Test Stand Team is dedicated to work together in a positive environment through the entirety of this project. Each team member will always be respectful and professional with other team members. Each member will utilize his or her strengths in order to contribute as much as possible to this project.

Team Member Roles

Team Manager – Emily Simmons

The Team Manager will ensure that each team member is aware of his or her responsibilities through every stage of the design project. She will also make sure that all members are completing assigned tasks in a timely manner. The Team Manager is responsible for editing each deliverable before the submission deadlines. This includes all reports, presentations, and any other documents required by the project. Once the Team Manager has edited a deliverable, she will be in charge of submitting it on time. Lastly, the Team Manager will always inform the other team members of the project's progress.

Lead ME – David Balbuena

The Lead ME will be in charge of the technical part of the project. This includes data analysis, programming, and any calculations that need to be done. The Lead ME will be held responsible for these tasks even when the work is done by another team member. In the event that another team member does any calculations, the Lead ME will thoroughly check their work for correctness.

Design Lead & Communication Liaison – Jacob Quigley

The Communication Liaison will be the main contact between the senior design team and the sponsor. The responsibilities of the Communication Liaison are but not limited to ensuring that the wants and needs of the customer are well understood, ensuring that the sponsor is aware of the current state of the project, and providing the sponsor with feedback and answering/ finding the answers to any questions that may come up.

The Design Lead will be tasked with creatively designing a mounting stand for the torque transducer and its connections. The Design Lead will also ensure that the safety of the test stand is improved. All parts will be made by the Design Lead taking into account the machinability and cost of the process. All part drawings will be done by the Design Lead, and he will schedule drawing reviews with all team members before any submissions or purchases.

Financial Planner – McLaren Beckwith

The Financial Planner will be responsible for the supervision of the project's budget as well as maintaining a record of all of the relevant team purchases. All expenditures must be reviewed by the financial planner for approval. Pending approval, the planner is responsible for analyzing alternative products and verifying that the order is satisfactory. Once the transaction is complete, a record of the purchase must be created and maintained by the planner.

Web Designer – Charles Daher

The Web Designer will be in charge of creating the template for the 2017 High Speed Motor Test Rig website. He will update the website as necessary with information describing the project, project deliverables, and sponsor and team member information. He will make sure that the website is easy to navigate, esthetically pleasing, and always up to date with the project's progress.

Organizational Chart

Team Member Names	Team Member Roles					
	Team Manager	Lead ME	Design Lead	Communication Liaison	Financial Planner	Web Designer
David Balbuena		✓				
McLaren Beckwith					✓	
Charles Daher						✓
Jacob Quigley			✓	✓		
Emily Simmons	✓					

All Team Members:

- Contribute equally
- Listen and be open-minded to others' ideas
- Provide constructive feedback
- Deliver on commitments

Communication

Communication between team members will be done in person on Tuesdays and Thursdays in class, through a group messaging app called GroupMe, and on Google Drive when preparing presentations and papers that the team will all collectively be collaborating on. If a member of the team is having difficulty with communication, (i.e. not responding to messages/

not doing their part) Jacob and/or Emily will be tasked with trying to effectively communicate the task at hand. If this is a continuous problem, it will be addressed with Dr. McConomy.

Communication between the senior design team and the sponsor at Danfoss will be done mostly through the Communication Liaison, Jacob. Verbal communications between Jacob and the sponsor pertaining to the project will be relayed to the team members using GroupMe. The Communications Liaison will also handle all emails and will be responsible for sharing the information to all group members.

Team Dynamics

Each team member will have their own responsibilities during the project. They are in charge of making sure their portion of the project is progressing in a timely manner and are ultimately responsible for making sure it is completed by the specified deadline. One of the most important things is that a team member should communicate with the team if they are having difficulty completing a task.

Ethics

The team will be adhering to the National Society of Professional Engineers' Code of Ethics. Team members are required to model their behavior to the highest standard of honesty and integrity for the benefit of the client, the team and the profession.

Dress Code

During presentations, team members will be expected to dress in business formal attire. Client meetings will be held in business casual attire. There will be no required dress code for routine team meetings. All dress code expectations are subject to change with a unanimous team decision.

Weekly and Biweekly Tasks

Weekly meetings will be held between team members during class time. In these meetings, the group will make sure all the team members are up to date on the progress of the project. Project updates and any new information will be discussed here. At least one meeting per week with all team members will be expected with strict attendance. The team will communicate with the sponsor biweekly, either in person or through Jacob Quigley. If needed the team will plan for more meetings depending on the project direction.

Decision Making

All decisions will be made together as a team. Ideally, in the event that two group members disagree, an intelligent conversation would be had including all team members, leading to a resolution. If there is still a disagreement, a vote would be taken amongst team members. Team 05 has an odd number of group members so this should solve the issue. In the unlikely event that only a certain amount of team members could vote and it resulted in a tie, the tiebreaker would go to whoever is leading that discipline. For example, if it were a discrepancy on the background color of the webpage, Charles would have final say since he is the Web Designer.

Conflict Resolution

If the team members have any discord, the following steps will be employed:

- Ideas will be discussed with all members to analyze the pros and cons.
- The leader of each department will decide what the final result will be.
- If needed, the team manager will intervene.
- Instructor will facilitate the resolution of conflicts.

Amendment Process

This code of conduct can be amended only if all team members sign off on the amendment.

Statement of Understanding

By signing this document, the members of the Danfoss High Speed Motor Test Stand Team agree to the code of conducts and understand its principles.

Name	Signature	Date
Emily Simmons		09/21/17
David Balbuena		09/21/17
McLaren Beckwith		09/21/17
Jacob Quigley		9/21/17
Charles Dahn		9/21/17

Appendix B: Functional Decomposition

Table 4

Functional Decomposition

		Main Functions		
		Measure Motor Efficiency	Hold the Weight of Motor Testing System	Protect Operator while Testing
Sub-Functions	Operate at standard motor speeds	●		
	Attach a safety shield			●
	Measures torque with a torque transducer	●		
	Build with appropriate material		●	●
	Add accessible E-stops			●
	Maintain stability		●	
	Prevents operator from handling tester while testing			●

Appendix C: Target Catalog

Table 5
Target Catalog

Main Function	Sub-Functions	Type of Target	Target
Measure motor efficiency	Operate at standard motor speeds	Speed	7,000 - 40,000 rpm
	Measures torque with a torque transducer	Speed, Torque	40,000 rpm, 100 Nm
Hold the weight of motor testing system	Build with appropriate material	Mass	272 kg
	Maintain stability	Radial Force	890 N
Protect operator while testing	Attach a safety shield	Length	0.61 m x 0.61 m x 0.5 m
	Build with appropriate material	Impact Energy	13 kJ
	Add accessible E-stops	Number of E-stops	1 E-Stop
	Prevents operator from handling tester while testing	Length	0.172 m

Appendix D: Project Scope Revision

Team 05 met with the sponsors at Danfoss on 11/16/17 in hopes of getting the design and purchasing plan approved for the torque transducer. Unfortunately, when getting the request for quotations (RFQs) to present to Danfoss to get approval for the budget, Team 05 came across an oversight by the 2016-17 Senior Design team who chose the couplers for this project. Choosing the couplings is a very difficult task, the 2015-16 Danfoss Senior Design team was tasked with choosing couplings that minimize vibrations and fighting between compressors. They chose a coupling that was extremely heavy and bulky that could only achieve a max test speed of 700 rpm. This coupling did not satisfy the specified requirements. The 2016-17 Danfoss Senior Design team was thought to have selected couplings that met the requirements of the sponsor. Danfoss initially considered the Zero-Max couplings because a sales representative told a member of the 2016-17 Senior Design team that they had the ability to manufacture special carbon fiber couplings that were capable of speeds up to 50,000 rpm. These couplings would have had the same capabilities as the Double Clamp Type Aluminum A1C Hubs – 6P30-A1C, which were rated to 9,500 rpm and capable of 90Nm continuous torque and a max peak torque rating of 170Nm.

The 2016-17 Senior Design team then proceeded with the information from the sales rep at with the assumption that the 2017-18 team would purchase the carbon fiber couplings. When this information was relayed to Danfoss, they decided to test a cheaper coupling to verify a proof of concept. Ensuring that they could achieve high speeds, with minimal vibrations and fighting between compressors. Since the 2016-17 Team was considered successful in choosing couplings, the 2017-18 Team's Senior Design project was selecting a torque transducer. When Team 05 requested a quote for the 50,000 rpm custom carbon fiber couplings, the team was informed that last year's conversation was had between a sales representative at Zero-Max and not an engineer. After speaking to the head manufacturing engineer and the lead coupler design engineer, it was confirmed that there are not coupling applications that meet the requirements of Danfoss from Zero-Max. When Team 05 relayed this information to Danfoss in the concept approval and purchase planning meeting, it was disappointing to the sponsor and the direction of Team 05's project immediately changed to selecting the proper couplings for this high speed test.

Team 05 is not discouraged because they do have a plan to meet with Danfoss before the end of the year in hopes of getting couplings purchased for testing in early January. Since they have found a torque transducer that will meet the requirements of the high speed high torque test, they decided to reach out to their sales team to find out which couplers are recommended for their high-speed torque transducers. Magtrol, the torque transducer manufacturer Team 05 wanted to use, referred the team to R+W America. They have elastomer couplings that are rated to 120Nm and 32,000rpm. They are roughly the same size and weight as the zero-max couplings and have similar specifications.

It seems like the long-term solution may be to have two couplings and two torque transducers, one capable of reaching speeds up to 32,000rpm and with a torque capability of 100Nm. And one set for higher speeds of up to 50,000rpm with a torque capability of 20Nm. Since the torque rating doesn't need to be as high for testing at high speeds, this was approved by the sponsor. However, it is likely they will only choose one coupling and one torque transducer for proof of concept due to time constraints of this project.

Appendix E: Project Plan Gantt Chart

Table 6

Project Plan Gantt Chart

Project Plan Gantt Chart

Danfoss

PROJECT TITLE	High Speed Motor Test Stand	**COMPANY NAME**	Danfoss
Team	Team 05	**DATE**	12/8/17

						January																			
						WEEK 1					WEEK 2					WEEK 3					WEEK		
						M	T	W	TH	F	M	T	W	R	F	M	T	W	TH	F	M	T	W
Task No.	TASK TITLE	TASK OWNER	START DATE	DUE DATE	Complete	8	9	10	11	12	15	16	17	18	19	22	23	24	25	26	29	30	31
1	Component Configuration																						
1.1	Purchase Coupling	McLaren	1/8/18	1/19/18	x																		
1.2	Spec Torque Transducer	David	1/8/18	1/12/18	x																		
1.3	Purchase Torque Transducer	McLaren	1/15/18	2/23/18	x																		
1.4	Design Shaft Extension	Charly	1/8/18	1/26/18	x																		
1.5	Machine Shaft Extension	Jake	1/29/18	2/23/18	x																		
1.6	Fabricate Safety Shield	Jake	1/22/18	2/24/18	x																		
2	Assembly																						
2.1	Torque Transducer Signalling Process	David	2/26/18	3/7/18	x																		
2.2	Torque Transducer Hardware Set Up	Emily	3/8/18	3/16/18	x																		
2.3	Implement Shaft Extension	Jake	3/19/18	3/21/18	x																		
2.4	Implement Coupling	Charly	3/22/18	3/23/18	x																		
3	Testing																						
3.1	System Validation	Team	3/26/18	3/30/18	x																		
3.2	Troubleshoot Vibrational Problems	Team	3/26/18	3/30/18	x																		
3.2.1	Maximize Operating Speeds	Team	3/29/18	3/30/18	x																		
4	Supplementary Tasks																						
4.1	Cooling Research & Design	Emily	4/2/18	5/4/18	x																		
4.2	Slack Time	Team	4/2/18	5/4/18	x																		

						February																			
						WEEK 4		WEEK 5					WEEK 6					WEEK 7					WEEK		
						TH	F	M	T	W	TH	F	M	T	W	TH	F	M	T	W	TH	F	M	T	W
Task No.	TASK TITLE	TASK OWNER	START DATE	DUE DATE	Complete	1	2	5	6	7	8	9	12	13	14	15	16	19	20	21	22	23	26	27	28
1	Component Configuration																								
1.1	Purchase Coupling	McLaren	1/8/18	1/19/18	x																				
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3	Testing																								
3.1	System Validation	Team	3/26/18	3/30/18	x																				
3.2	Troubleshoot Vibrational Problems	Team	3/26/18	3/30/18	x																				
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4	Supplementary Tasks																								
4.1	Cooling Research & Design	Emily	4/2/18	5/4/18	x																				
4.2	Slack Time	Team	4/2/18	5/4/18	x																				

						March																					
						WEEK 8		WEEK 9					WEEK 10					WEEK 11					WEEK 12				
						TH	F	M	T	W	TH	F	M	T	W	TH	F	M	T	W	TH	F	M	T	W	TH	F
Task No.	TASK TITLE	TASK OWNER	START DATE	DUE DATE	Complete	1	2	5	6	7	8	9	12	13	14	15	16	19	20	21	22	23	26	27	28	29	30
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4	Supplementary Tasks																										
4.1	Cooling Research & Design	Emily	4/2/18	5/4/18	x																						
4.2	Slack Time	Team	4/2/18	5/4/18	x																						

						April																			
						WEEK 13					WEEK 14					WEEK 15					WEEK 16				
						M	T	W	TH	F	M	T	W	TH	F	M	T	W	TH	F	M	T	W	TH	F
Task No.	TASK TITLE	TASK OWNER	START DATE	DUE DATE	Complete	2	3	4	5	6	9	10	11	12	13	16	17	18	19	20	23	24	25	26	27
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