Final Report
Team 4: High Speed Motor Test Rig

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Abstract

In order to deliver a practical design for Danfoss Turbocor's High Speed Motor Test Rig, senior design team 4 will design a system that can qualify the motor performance parameters while withstanding angular speeds up to 50,000 RPM and operate up 100 Nm of torque and allow up to no more than 2 mm of axial shaft misalignment. This design can be achieved with an effective mounting system, flexible shaft-to-shaft coupling, an accurate torque transducer, and a precision laser alignment system. It is noted that system relies on the allowable misalignment and the R&W BKC coupling does accommodate the axial misalignment to 1 mm and also the radial misalignment while withstanding 80,000 rpm of speed. To be sure that the alignment precision is as good as possible the SKF TSKA 31 laser alignment tool is going to be utilized to ensure an alignment up to 5μm, which is accurate enough to coincide with the coupler misalignment allowance. The system is being designed to be effective, accurate, efficient, and safe for those operating the rig.

I. Introduction

A. Background

The HVAC market has been increasing in size and has been continuously producing new compressor systems. Danfoss Turbocor has been continuously innovating to stand out as one the leaders in such a market. Despite the fact that Turbocor started out in Australia back in 1993, they did not go about installing their first compressor (the TT300) until the year of 2001 in California, USA. In recent years, however, Turbocor stands as a leader in the oil-free, centrifugal compressor product market. They have been supplying the world with the most efficient refrigerant compressors for the HVAC industry (over 35,000 compressors to be exact).

Danfoss Turbocor is in need of a motor-generator system that can be used to qualify compressor motor performances. They seek to qualify the efficiency, power, and heat management. A motor-generator functions by coupling the shaft from a motor to a generator. This typically is used to produce power from the generator. Turbocor wishes to use two compressors in place of the typical motor and generator. One compressor will use its motor to back drive the other compressor by coupling their shaft together. For this project the impellers will be removed. Motor generator systems usually use a simple method that involves special tools to align the shafts together. The compressors that will be used in Turbocor's system will reach speeds much higher than average motor-generator systems. Therefore this project requires special design efforts to be made to the alignment process.

B. Objective

Turbocor has delegated Team 4 with the task of designing and constructing a High Speed Motor Test Rig. Team 4 has been focusing on how to deal with the high speed of the compressors (12,000 - 40,000 RPM) that Turbocor produces while choosing the proper coupler and alignment system that can efficiently work with said systems. Detail must be focused upon the alignment system. This is because the compressors use magnetic bearing, which by nature have different tolerances to load versus typical ball bearings.

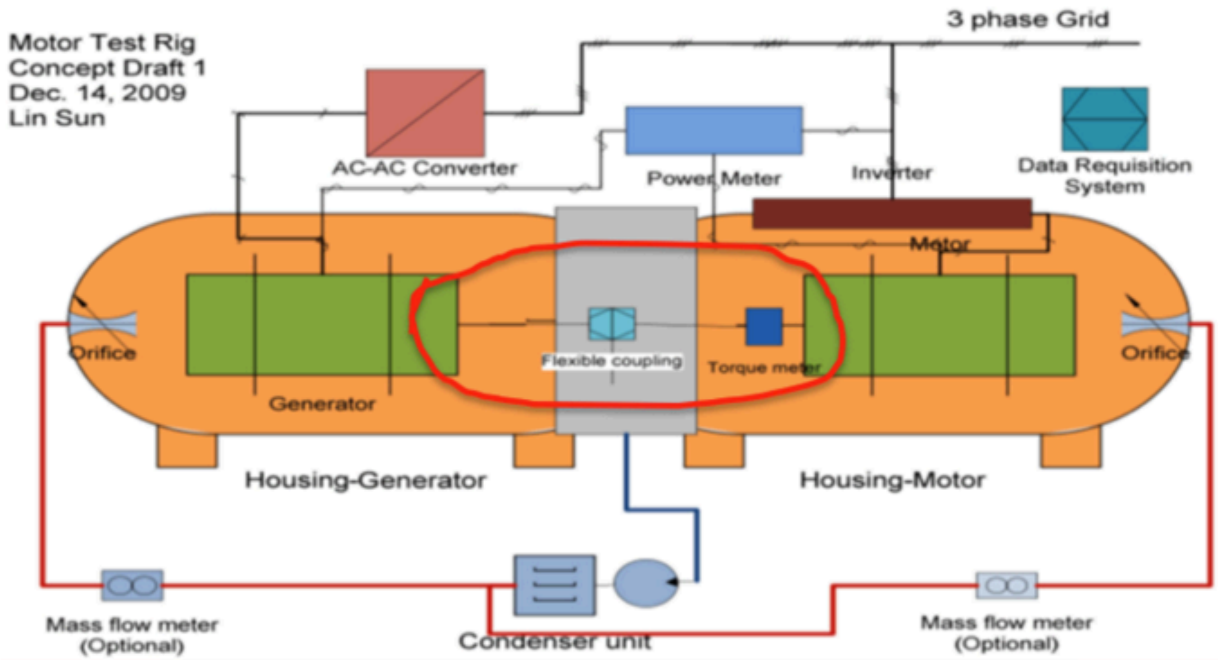

FIGURE 1: HIGH SPEED MOTOR TEST RIG DESIGN DRAFTED BY TURBOCOR

The area enclosed by the red circle in Figure 1 is the area that Team 4 has been focusing on. It includes the drive shaft, the flexible coupling (highlighted in teal), and the torque meter (highlighted in blue). It must also be noted that Team 4 was fortunate to have their sponsor be a local business. This made it easy for the team to be trained on how to run the compressors. The team was also able to keep a TT500 compressor on the FAMU-FSU College of Engineering's campus for experimental purposes.

C. Problem Statement

Danfoss Turbocor needs a High Speed Motor Test Rig to qualify motor performance. The high speeds it will reach require innovative thinking to achieve accurate and precise alignment requirements.

D. Key Technical Aspects

Turbocor has requested that the High Speed Motor Test Rig be compatible with multiple compressors. These compressors have the same exterior dimensions but output different speeds and torques. Therefore, the team must find components compatible with all compressors. Due to the speeds up to 40,000 RPM and maximum torque of 73 Nm, the team must ensure their designs or purchase parts are qualified to operate at those high speeds. The magnetic bearings have a limited amount of radial support (200lb max), this means that severe harmonic oscillations could damage the compressors. A torque transducer must be used that can give instant torque readings, which will be used for efficiency calculations. This transducer must also be qualified to operate at the high speeds and torque values.

II. Design and Analysis

A. Requirements

This high-speed motor test rig requires attention to four characteristics that will achieve successful compressor motor testing. These characteristics are: balanced rotating components, flexible couplers, alignment system, and the torque transducers. It was decided by the client company that individual components be qualified to operate up to 50,000 rpm and 100 Nm of torque. Danfoss Turbocor chose these requirements beyond the literal output of the motors to insure a safe design margin in the mechanical system.

I. Component Balancing

When a radial force of 200 pounds or greater is exerted upon the compressor shaft, the system goes into a lockdown mode. This mode deactivates the motor and magnetic bearings, thus seizing the shafts rotation. If the components in rotation are not properly balanced, severe harmonic vibrations that would exert forces in the radial direction. Because of this scenario, strict precision and accuracy for balancing must be insured for all components in rotation. The Danfoss Turbocor compressors operate under a wide range of rotational speed. Table 1 shows the maximum torque and RPM specifications of various TT series compressors. The listed torque is the maximum output from the compressor, and the RPM is the speed at which that torque is made. This shows that the high standard of 50,000 RPM and 100 Nm will produce a good safety factor for each component, and therefore a good overall safety factor.

TABLE 1
COMPRESSOR MODELS AND THEIR RATED TORQUE AND RPM

Compressor	Shaft Torque [Nm] (Max)	Speed [rpm]
TT300	22.8	37762
TT350	38.0	30598
TT400	37.2	25091
TT700 (Four Poles)	73	17000

II. Flexible Coupling

To compensate for possible shaft misalignment, flexible couplers will be used. Flexible couplers allow a limited amount of angular, parallel, and axial misalignment. Figure # illustrates the possible misalignment orientations that can occur. Parallel misalignment is when the axis of the shafts are parallel, but do not connect. Angular misalignment occurs when the axes of the shafts may connect through intersection, but are not parallel. Axial misalignment is when the distance between the ends of the shafts changes during operation. While parallel and axial misalignment need to be considered in this project, axial alignment is not of huge concern. Since the compressor will be rigidly mounted to a rigid base, and the couplings securely

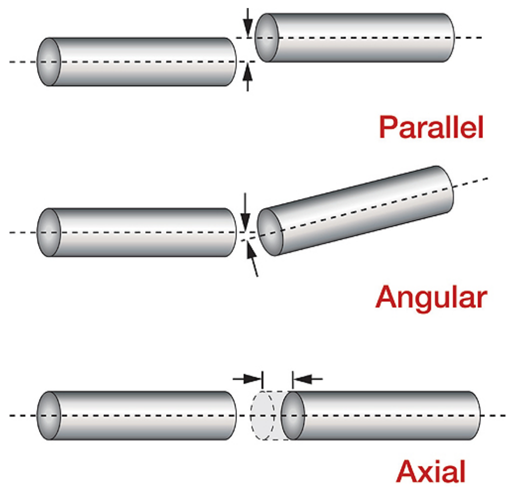

FIGURE 2: SHAFT MISALIGNMENT SCENARIOS

Another reason that a flexible coupler is desired, is that it maintains a high Eigenvalue. If a rigid coupler were used in place of the flexible one, the dynamics of the characteristic equation for the systems rotation would be poorly affected. By using a rigid coupler, the two coupled shafts would be considered to be one shaft in the differential equation to find the eigenvalue, which would increase the mass of rotating component. In turn, this mass increase would lower the eigenvalue of the shaft. The flexible coupler will allow each shaft to be considered independent when analyzing the characteristic equation, which would lower the mass value, thus increasing the Eigenvalue.

III. Alignment System

While the flexible couplers can compensate for some inevitable misalignment, efforts must be made to develop a precise and accurate alignment system to insure the misalignment is within the allowed range (determined by the flexible coupler). The precision and accuracy of the alignment will primarily stem from the tool used to measure parallel and angular alignment of the shafts. It is required that this tool have an accuracy that is less than the maximum misalignment tolerance of the flexible coupler. For example, if the alignment measuring tool can get the parallel alignment to an offset of 0.1mm, and the coupler can handle 0.2mm of misalignment, then the 0.1mm misalignment will be acceptable.

In addition to an alignment tool, the alignment system will require methods to incrementally adjust the positioning of the compressors in multiple directions. To induce a shaft angle change, it is required that there be a process to adjust the elevation of the compressors in the four corners of its mounting locations. This elevation adjustment will also assist in parallel alignment. Compressors will also need to have lateral adjustment to horizontally position the compressors' shaft axis. Figure 3 is an anonymous screen shot from a shaft alignment tool. In this picture the black motor can represent a compressor, it shows how the compressor will require correct positioning in various directions to achieve alignment.

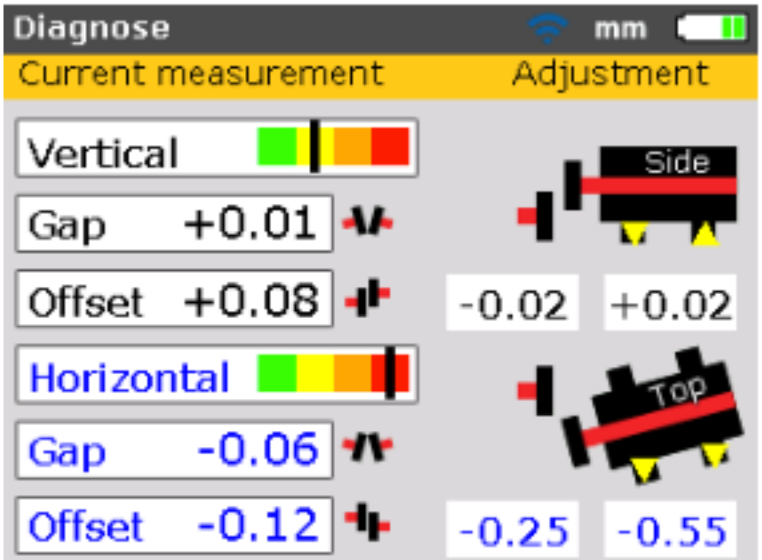

FIGURE 3: ANONYMOUS ALIGNMENT TOOL SCREEN ILLUSTRATING THE REQUIRED MOVEMENT OF A COMPRESSOR TO ACHIEVE ALIGNMENT

IV. Torque Transducer

Since this compressor test rig is monitoring the efficiency during operation, it is required that a device be integrated that will monitor the output from the motor driving the system. It was decided by the client company that a torque transducer be implemented to detect the output torque. This transducer must be capable of operating up to the previously mentioned 50,000 RPM and 100 Nm. To ease efficiency calculations, this transducer must have the capability to connect to a computer that will give a user an easy ability to see the torque produced at the output shaft.

B. Component Selection

To ensure the most precise system possible, it is imperative that every component and material considered be assessed and scrutinized thoroughly. The components and materials considered are for the base plate, torque transducer, coupler, and alignment system. Since the system, as previously mentioned, will spin at a maximum of 37,000 RPM and produce a torque of 73 Nm, team 4 will have to make sure the precision tolerances of the components are within microns to tens of microns in accuracy. For each component, a few existing models and or materials were evaluated based on cost, functionality, strength, and accuracy and precision. Each component was placed in a morphological chart, which is shown in Table 2, and the selected component is highlighted.

TABLE 2
MORPHOLOGICAL CHART FOR DEISGN CONCEPT SELECTION

	Concept 1	Concept 2	Concept 3
Alignment Tool	TSK (Smart Phone Compatible)	TSKA 31	Fluke 830
Torque Transducer	Magtrol TMHS308	Kistler 4530A	Magtrol TMHS311
Horizontal Alignment	Set Screws	Caster Wheels/Rails	Manual
Vertical Alignment	Set Screws	Shims	Hydraulic
Base Stand	Channeled Steel	Boxed Steel	Single Piece Aluminum
Coupler	Gam KHS200 Bellows Coupling	R&W BKC	R&W BKL

I. Alignment Tool

Being that there is such an emphasis on precision, the alignment system will be the most important component to be considered since it will determine how precise both shafts will be connected. It was brought up by some of the employees at Danfoss Turbocor that the alignment system be set with dial indicators like one seen in Figure 4.

FIGURE 4: DIAL INDICATOR FOR ALIGNMENT

The dial indicator system is definitely cost effective and can be found for about \$30-\$100 depending on the quality and are accurate to about 10-20 μm and that is definitely within the design specification parameters. Dial indicators have a drawback for shaft alignment: human error. Using dial indicators for shaft alignment has a learning curve, the user must use intuition to interpret dial readings into compressor position adjustments. Due to the amount of human error that can be associated with using a dial indicator, the importance of precision/accuracy, and possible dangerous side effects of excess error, the team decided to go with a laser alignment tool.

Keeping in mind that laser alignment tools are much more expensive than a dial indicator, the laser aligner selected is in the median to lower end of laser alignment price and still allows a precision under 20 µm. The SKF TSKA 31 alignment tool (Figure 5) was selected and has an of accuracy of ±5µm and comes in at a price of roughly $4,000. This may seem quite expensive but when compared to the Fluke 830, which was in consideration, it is less than half the cost. It also has many features which a dial indicator does not, like an animation that tells the user where the shafts need alignment and does so interactively.

FIGURE 5: SKF TSKA 31

The TSKA 31 features innovative functions that expedite the alignment process. This will shorten system downtime, as well as be of use to a wider variety of users, regardless of the level of one's technical knowledge. First a user would fasten the laser devices to each shaft, next they would follow the manual to measure the shaft misalignment. Once this is completed, the tool will make calculations to interpret how the compressor must be moved to align the shaft. Figures 6 & 7 shows an actual screenshot from the TSKA 31, which is what the user will see once they are adjusting the compressor position.

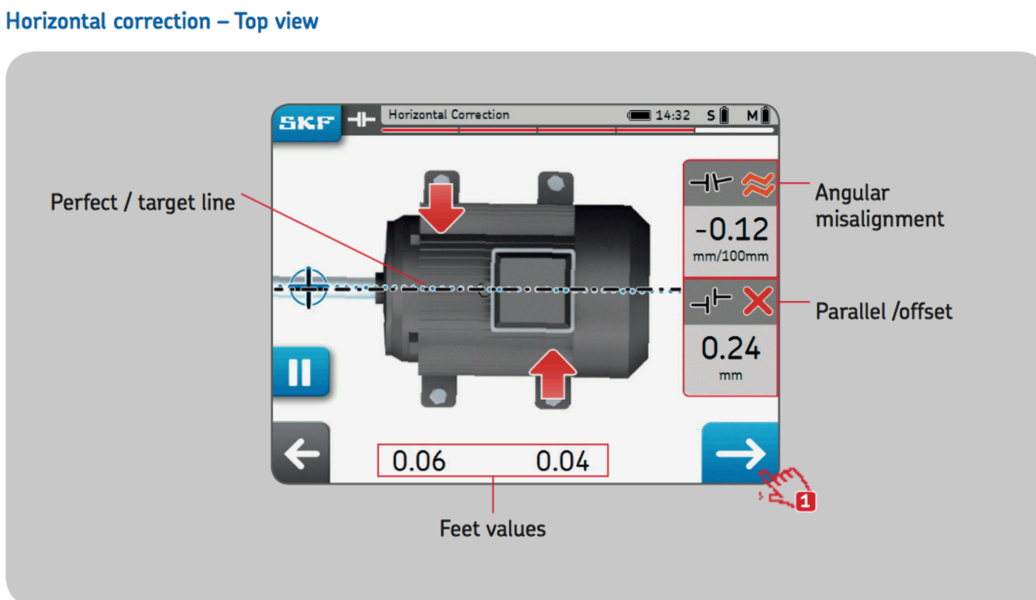

FIGURE 6: TSKA 31 HORIZONTAL ADJUSTMENT GUIDE

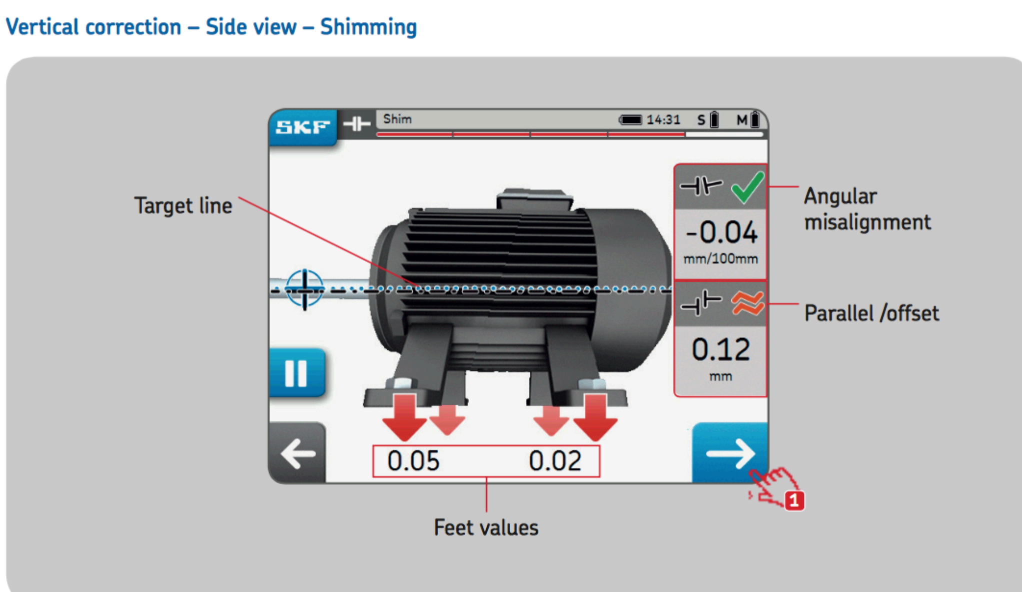

FIGURE 7: TSKA 31 VERTICAL ADJUSTMENT GUIDE

II. Torque Transducer

The torque transducer is another piece of equipment that is quite expensive but is required by the system. As stated previously, the torque transducer must be able to handle the speeds up to 50,000 rpm while still being able to handle 100 Nm of torque. As previously stated, these values were chosen to over design the system and give a reasonable factor of safety. Upon research of these components team 4 found that there is a caveat to these transducers. There isn't a transducer that can handle the given parameters and that is because when the angular speed is increased, the torque is decreased and vice versa. To accommodate this, the advisors at Danfoss Turbocor suggested that the team design a system that can handle multiple torque transducers for low torque and high RPM, and high torque and low RPM. Magtrol is a manufacturer with a good reputation for it's torque transducers and the group chose to use this company's product. For the high RPM range, the Magtrol TMHS 308 (Figure 8) can handle the 50,000 RPM speeds and a rated torque of 20 Nm which was verified and deemed proper for this application by Turbocor. The 308 has a safety factor of 1.06. For the 100 Nm case, the Magtrol TMHS 311 (Figure 9) was selected for its maximum RPM range of 32,000 and a rated torque of 100 Nm. The 311 has a safety factor of 1.4.

FIGURE 8: MAGTROL TMHS 308

FIGURE 9 MAGTROL TMHS 311

Because the transducers have very different geometries, the team has designed spacers that will adjust the transducer elevation to align with the compressors' shaft axis. The TMHS 308 will need a spacer block with a height of 174.45mm. Because the mounting bosses on the 308 is under the transducer body, the elevation block will need to have clearing within the body to access the mounting bolts. The TMHS 311 will need a. elevation block of 149.45mm in height. As you can see in figure 9, the mounting holes can be accessed from the top. Therefore, this allows the TMHS 311 to be elevated by a solid block of machined material. Both elevation pieces for the transducer will be tapped on their undersides and be bolt to a baseplate.

III. Base Frame

The base frame is the heart of the design. The precision alignment system is most important once this baseplate is constructed, but to ensure the accuracy of the SKF TSKA 31 the baseplate must be designed to accommodate all components. To ensure that the base plate can carry the weight of two 300-pound compressors, it must be designed with a material that has a good strength when in compression and that can be easily machined. The two materials in question were steel and aluminum. Benefits to using aluminum would be a lighter overall weight of the frame and ease to machine. Motor-generator test rigs, by nature, are stationary during operation. During a visit to the client company, the team viewed the testing room that the test rig would be operated within. It became evident that the test rig would likely not be moved frequently. This led the team to select mild grade steel for the base frame material. Danfoss Turbocor's machine shop has a 2x2 inch square (boxed) steel (mild grade) tubing that has a ¼ inch wall thickness and is perfect for the application of this project. The quarter inch thickness will allow for thread tapping and ensure that bolts can be used to fasten the majority of the baseplate. This is important because it will cut the amount of welding, which can warp the material and cause the surface to no longer be as flat as possible. While the team is trying to avoid welding where possible, it may become necessary in the future that some pieces require welding. The team has done research in order to understand the preventative steps that can be made to minimize the thermal expansion of the steel. Expert welders recommend tacking pieces first and avoid long passes. This may increase the time it takes to weld, but by spreading out the time and allowing pieces to cool, they will receive a lesser amount of heat transfer. The baseplate surface in contact with the transducer and compressors must be level; this will set the foundation for an accurate shaft alignment.

IV. Alignment System

The horizontal and vertical alignment systems will be integrated into the base plate design. At first the team was considering a setscrew method for both horizontal and vertical movement but when it was suggested that the team visit the CAPS (Center for Advanced Power Systems) that idea was scrapped. The CAPS building has multiple motor generator rigs on site and with the guidance of the CAPS staff the team came up with the most effective and efficient way to move the system for alignment. In the vertical direction, it was suggested that the design use a shim method. It is possible to find shims that can be machined to as small as 20 microns, so a set of shims will be ordered in the near future once a price and vendor are decided on.

While the width of the shim is clearly important, as it dictates the elevation increments, the other profile dimensions are also important. Figure 10 labels these dimensions that are dependent upon the fastener and mounting surface. C, is the width of the opening that will slide around the mounting bolt. Figure 11 shows an actual shim with a profile that will be extremely similar to the ones integrated in to the compressor test rig. As Figure 12 shows, this slot must be wider than the bolt to allow easy installation of the shim. If A and B are too small, it will cause a large amount of force to be directed to a small surface area, which may fatigue the shim and cause it to lose width over time. Therefore, A and B should be set to the size of the smaller surface that it is in contact with. In the test rig design, the shims will be between two pieces of 2”x2” square tubing, therefore it is unnecessary for dimensions A and B to be beyond 2”x2”

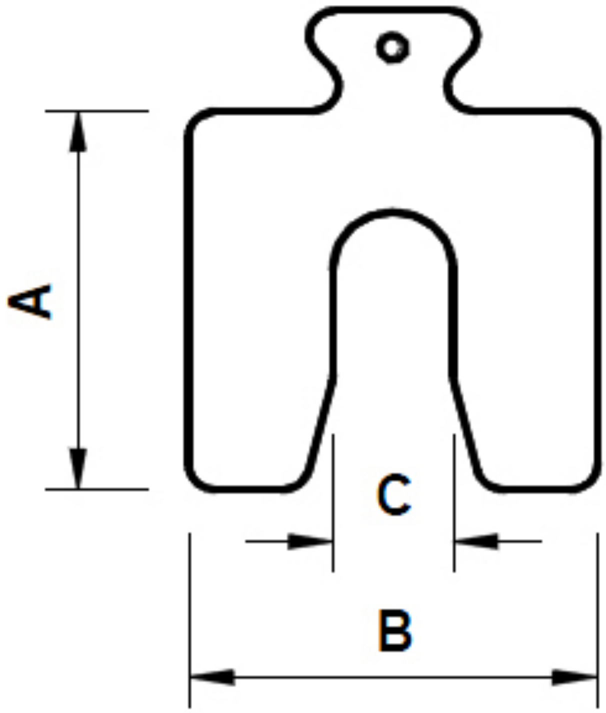

FIGURE 10: SHIM DIMENSIONS

FIGURE 11: CLOSE EXAMPLE OF THE SHIM PROFILE THAT WILL BE USED

The horizontal alignment mechanism will still be a set screw system the like the one seen in Figure 12. This screw will push on the feet of the compressor in order to move and for each compressor there will be a set screw on each of the four feet.

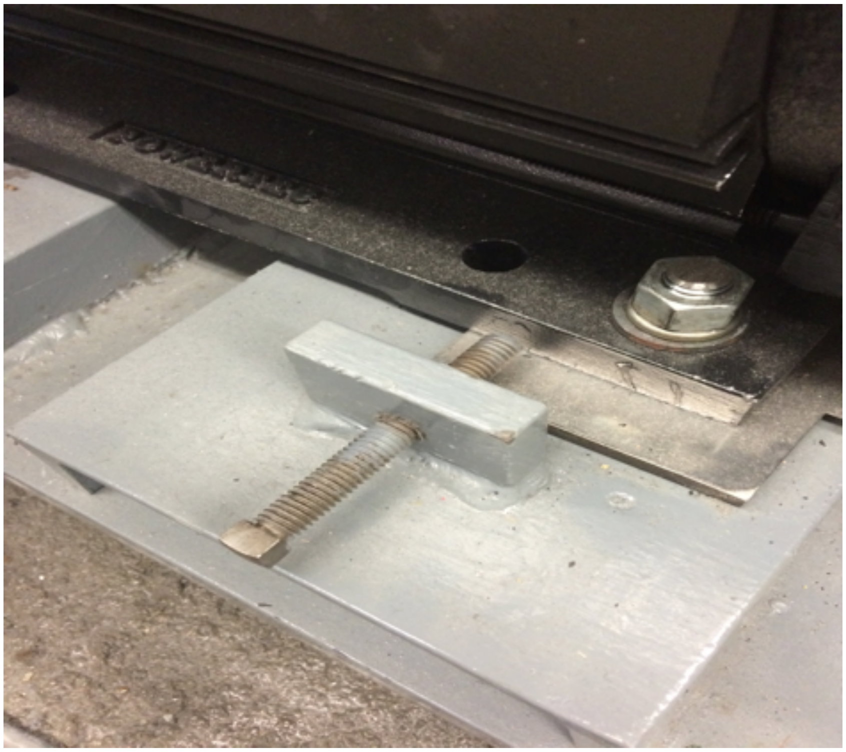

FIGURE 12: CAPS MOTOR TEST RIG HORIZAONTAL SET SCREWS

The screw alignment method will not require any particular vendor for its design. A solid piece of steel will be drilled and tapped for an accompanying bolt. The bolt will have a hex head that will allow the connection of a socket and wrench to turn it. A weld will mate the tapped steel piece to the base frame, and the bolt will be threaded through the hole. Each compressor will have four of these screw alignment apparatuses at the four corners where the compressor mounts to the frame. The screws will push into the square tubing that the compressor sits upon. To allow movement, yet still securely fasten to the frame; the hole for the mounting bolts will be drilled out to be larger than the bolts. This will allow a small amount of lateral movement, which will be sufficient for the alignment process. Figure 13 below shows this component in CAD. The adjustment bolt is the brown piece, which is threaded through the support bracket (gray). The support bracket can be built from two pieces of welding steel, or a cut from angled steel bar.

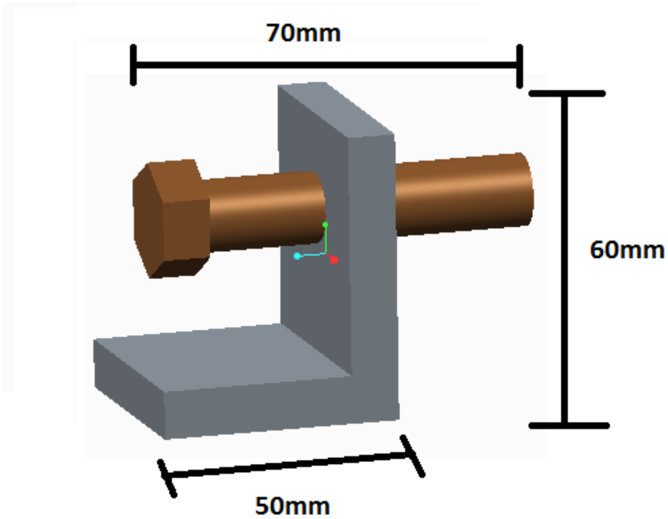

FIGURE 13: CAD DRAWING OF THE ADJUSTMENT BOLT AND SUPPORT BRACKET

V. Coupling

The final component selected was the coupler. Since the torque transducer will be the median between the two compressors the shaft of each compressor will need to be coupled to the shaft of the transducer. The coupler must be able to compensate for the misalignment that is going to be generated at such a high angular speed, up to 37,000 RPM. The R&W BKC 150 series coupler (Figure 14) is perfect for this application. This coupling was chosen because it can hand speeds up to 80,000 RPM. Meaning, that the manufacturer can guarantee it will be free from harmonic oscillations during operation in the High Speed Motor Test Rig. It also can tolerate up to 150 Nm of torque and also be easily clamped to the shafts since the bolting access is from the outer shell of the cylinder and not on the faces. From the rates of the BKC, it was found that it has a safety factor of 2.2, which is acceptable. The BKC is a bellows type coupling and that means that there are conical flexible bushings integrated in the design to allow for flex and misalignment. It was noted by our Turbocor advisor, William Sun, that the coupler needs to allow for 1 mm of axial misalignment and this can surely cover that with an allowable of 2 mm. Being that it does fit the shaft of the Magtrol 311, the only issue with this coupler is that it does not fit the smaller Magtrol 308 transducer shaft diameter. The Magtrol 308 has a shaft that is 10 mm and the BKC 150 series coupler fits from 19-42 mm in diameter. This does pose an issue for the team but it was decided that a rigid coupler could be fit to the smaller shaft of the 308 to provide a thicker diameter extension and therefore fit into the BKC 150 series coupler. It is desired that the rigid coupler have a safety factor no less than that of the flexible coupler. The team is in the works of deciding whether to outsource this product or machine and balance it in house.

FIGURE 14 : R&W BKC COUPLER

C. Analysis

I. Alignment

It was recommended by faculty advisor, Dr. Patrick Hollis that analysis be done to understand the effects upon the shaft orientation that the different width shims have. The TT series compressors that the team is design the system around, has its shaft positioned directly over the front base frame mounting location. Figure 15 represents this design. Because of this, if one is to shim the front feet of the compressor, it will elevate the shaft by the same amount of the shim width. Not only will the shaft have a change in elevation, but an angle will be induced. To predict the changes, trigonometry was used to analyze the changes in shaft orientation. Equation 1 shows the angle induced (θ_1) if a shim of width a_1 is used under the front mounting locations. The distance of 485mm is the displacement between the front and back mounting locations.

$$\tan^{-1}\left(\frac{a_1}{485mm}\right) = \theta_1 \tag{1}$$

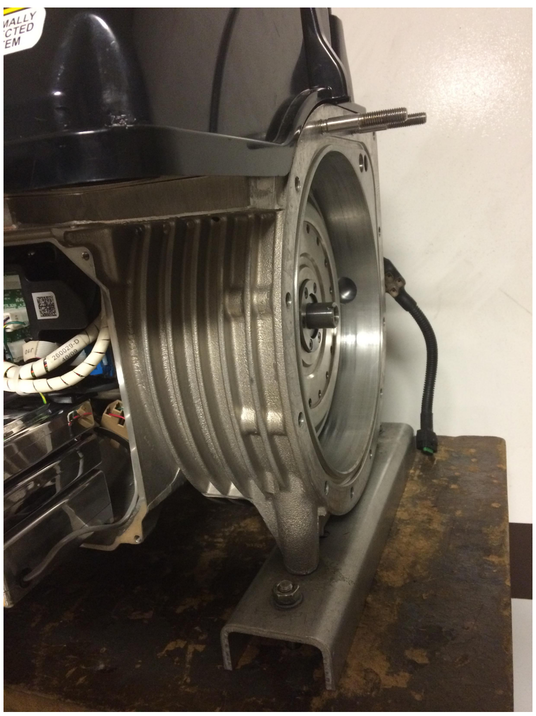

FIGURE 15: COMPRESSOR SHAFT IS DIRECTLY OVER THE FRONT MOUNTING HOLES

Elevation on the rear of the compressor was also analyzed. This analysis found that the elevation at the end of the shaft changes with a fraction of the size of the shim used. Trigonometry was used and the angle induced (θ_2) from a shim of width a_2 is expressed in equation 2.

$$\tan^{-1}\left(\frac{a_2}{485mm}\right) = \theta_2 \tag{2}$$

By using the angle induced from rear shims, the shaft elevation will change by the amount "y". The value c is the shaft height above the mounting surface.

$$y = c - cos(\theta_2) \cdot c \tag{3}$$

To finalize the adjustment analysis, a table (table 3 below) was created to see the actual values that the shaft will be oriented by. The chosen shim widths were the smallest shim sizes that the team found from a vendor. By using the smallest shims in this analysis, the team can see what the smallest possible amount the shaft can be incrementally moved by. It is still undetermined by the team if larger shim sizes will be needed. However, the team has determined that these shims (10 μm, 25 μm, and 250 μm) produce very small increment amounts that are acceptable.

TABLE 3

SHIM SIZES AND CORRELATING SHAFT INCREMENT AMOUNTS

Front Shim Width (um)	Shaft Angled Induced (degrees)
10	0.0012
25	0.0023
250	0.0143
Rear Shim Width (um)	Shaft Angle Induced (degrees)
10	0.0012
25	0.0023
250	0.0143
Rear Shim Width (um)	Shaft Elevation Induced (mm)
10	0.0001188
25	0.000436425
250	0.016870138

II. FINITE ELEMENT ANALYSIS (FEA)

Once the final design of the baseplate was sketched in Pro Engineer, the model analysis commenced. Finite Element Analysis was conducted under the static load of the compressors just to validate that the base plate material and design selection was adequate. This is the only analysis that can be done at this time since the torque transducer, coupler, and compressors are qualified to run under the specified loads. The von Mises stresses (Figure 16) and displacement (Figure 17) models were created and it can be noted that the von Mises stresses are of no concern since the maximum displacement is going to be minimal due to the low magnitude of 1.034E-7 meters. This qualifies that the selected 2" steel tubing is an acceptable material and the design is safe.

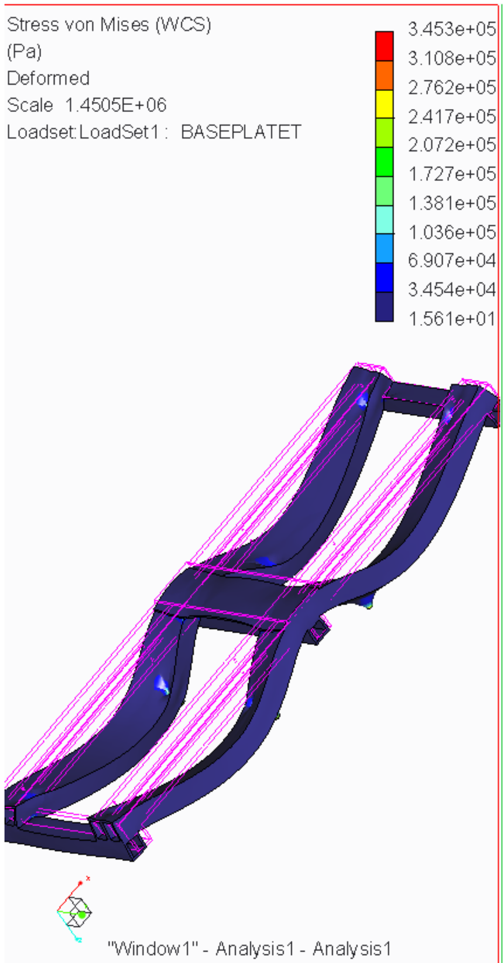

FIGURE 16: FEA, VON MISES STRESSES

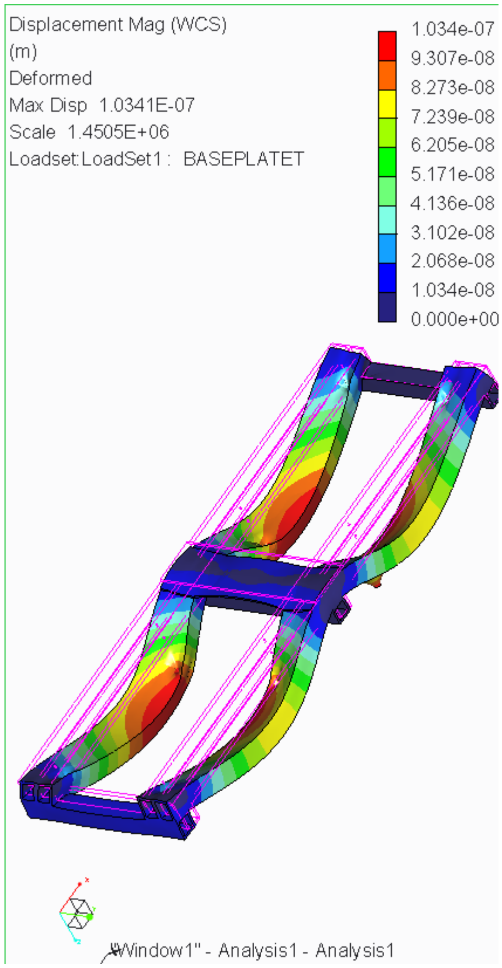

FIGURE 17: FEA, DISPLACEMENT

To further test the reliability of the results, the strain energy was plotted versus the number of passes the program used to compile the data. This was run to check against a 10% convergence and as one can see in Figure 18 the strain energy converges and levels off at the 8th pass, which gives a reasonable accuracy of the data.

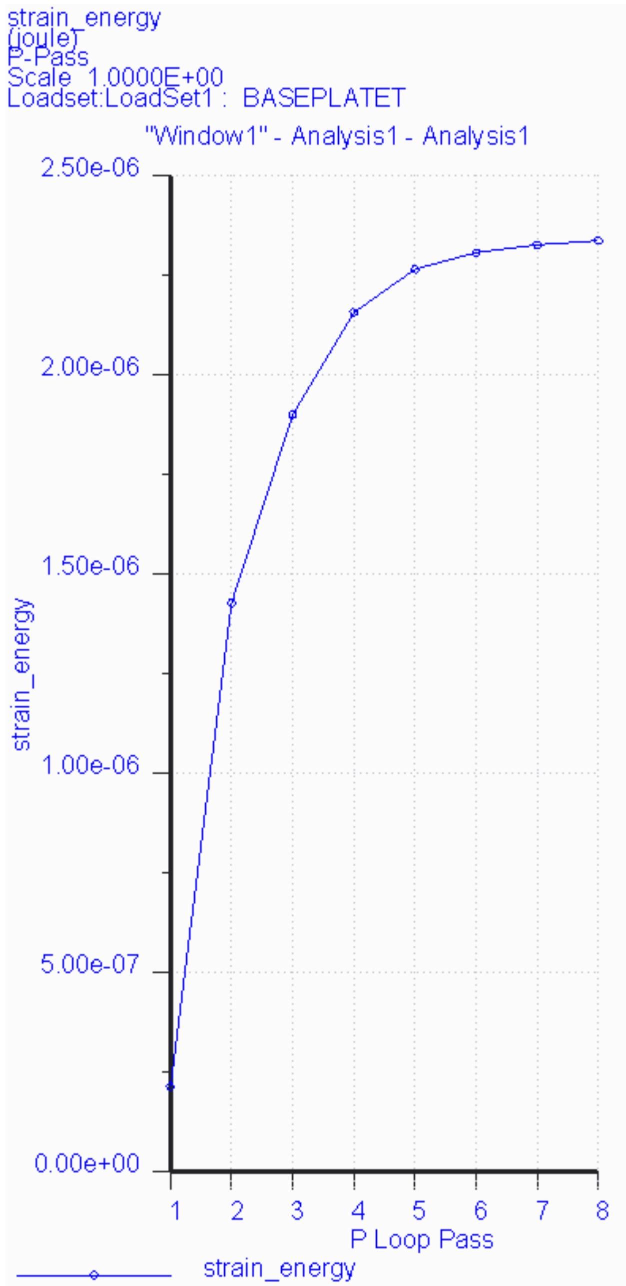

FIGURE 18: STRAIN ENERGY VALUES AT 10% CONVERGENCE

D. CAD Assembly

An assembly was made in Pro-E with all of the design drawings. The team was able to acquire the CAD files for the compressors, flexible couplings, and torque transducer from their manufacturers. This CAD assembly can be seen in Figure 19.

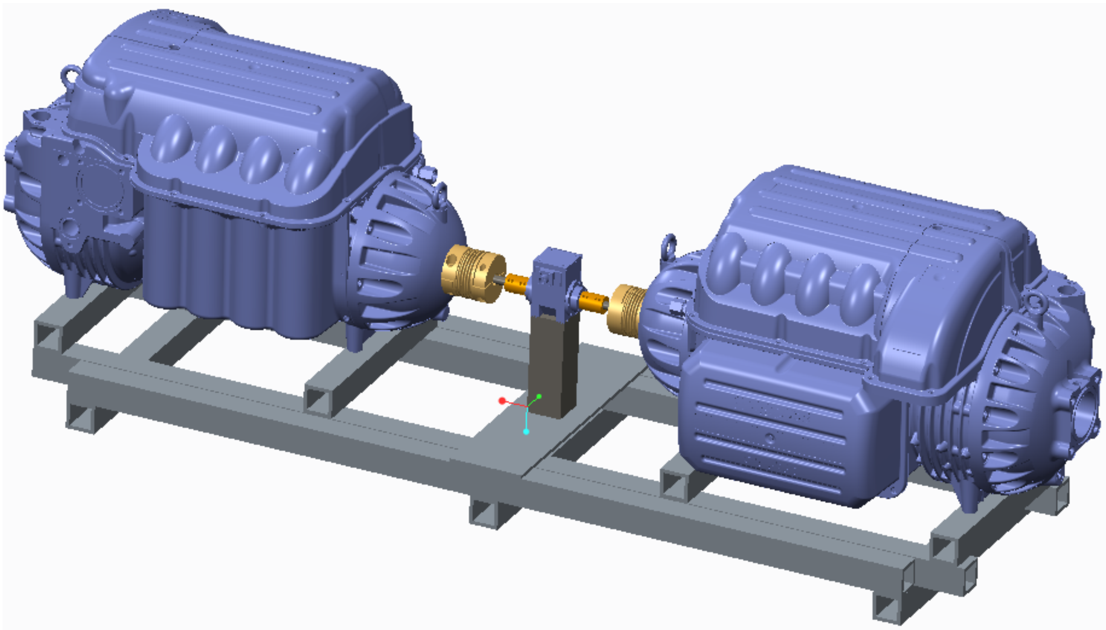

FIGURE 19: CAD Assembly of the compressor test rig.

The outside blue parts are the Danfoss Turbocor compressors. In this drawing, the inside shaft covers are not removed. The team does not have permission to remove these pieces. In the literal assembly, these covers will be removed. The tan pieces are the R&W BKC 160 flexible couplers. The middle blue piece is the Magtrol TMHS 308 torque transducer. Between the transducer and flexible coupling are gold pieces, which are the rigid couplers. These rigid couplers fasten to a shaft, which is also fastened into the flexible couplers.

III. Project Management

A. RISK ANALYSIS AND RELIABILITY ASSESSMENT

I. TEST RIG CONSTRUCTION ACCIDENTS

The team is working with compressors that have weight of about 300 pounds, it is important to prevent accidents such as a compressor dropping onto a person or onto the floor and damaging the floor or the compressor itself. The construction process may require the use of tools such as: impact wrench, grinder, and hydraulic lift. To use these tools, the operator must have a previous training. If one team member wants to operate such equipment he or she must be properly trained.

II. TEST RIG OPERATION ACCIDENTS

The test rig will work at extremely high speeds; therefore if one small component, such as a screw, is ejected at high speeds it would be a serious danger to surrounding people. The use of a protective shield is essential to prevent future problems. To prevent any other accident, it is recommended that the individuals working on the test keep a safe distance from the test rig and don't stand by the side of the test rig, where a loose component could go.

III. COUPLING FAILURES

Mistakes made with the shaft coupling process can escalade into serious failure. Generally, the failures arise from improper coupling selection, human errors made during the installation process, and also due to the operation beyond design capabilities. These failure sources are mainly because of the severe vibrations that may occur and considering this phenomenon it is notable that the life of the coupling will dramatically decrease. Signs of coupling failure will be propagating crack, elongated bolt holes, and discoloration. It is important that precision balancing be performed upon the coupling due to the high speeds of the system to comply with safety requirements. This component balancing must be done for all pieces in rotation because of the radial loads that would shut down the system if server harmonic oscillations occurred. As mentioned, if the radial loads exceed 200 pounds the system will be shut down.

IV. BEARING CALIBRATION

A preventative measure that must be made by the operators is magnetic bearing calibration. Julio Lopez, an electrical engineer at Danfoss Turbocor, trained the team to use a unique software that communicates with the compressors. This software allows the team to calibrate the bearings to the weight upon the shaft. Safety guidelines will require users to calibrate the bearings after impellers have been removed and the shafts have been coupled together. This will ensure an accurate shaft rotation during high speeds, which will avoid excess displacement between the coupled shafts. Excess displacement could fail the coupler, thus producing possible projectiles, as mentioned in the coupling failure section.

All these failures can be avoided by increasing the attention to detail during design, installation, and use of the system. During design, members must thoroughly understand the constraints and insure that the coupling selection meets the criteria. In installation, it is important to follow assembly procedures provided by the manufacturer. This may include, tightening hardware to torque specifications. Besides all these precautions measures it is extremely important that every person that operates the test rig use IPE and have the proper training to calibrate the magnetic bearings.

B. PROCUREMENT

Turbocor did not specify a budget to our team. The components selected by Team 4 generally have high technology parts due the high precision required for us. The team has to develop a method to calibrate within small tolerances. To do so Team 4 selected the components, which fill the requirements and also looked for fast delivery.

The Bellow Coupler selected is the model R&W BKC 150 which will be purchased on the R&W website. Both couplers will be purchased from the same website, the estimate cost for each coupler is $150.00.

The Laser alignment tool selected is the model SKF TSKA 31, which will be purchased from tequpiment.net website by an estimated cost of $4,057.77. This component has the highest price between all the components but it is important to guarantee a high precision alignment.

The shims will be purchased from American Metals Company; the estimate cost from them is $24.45. The team will order the shims with different thickness in the same pack to reduce cost.

Due to different relations between torque and speed rotation required from Turbocor the team will order two different torque transducers, the first is the TMHS 308 for high speed (50,000 RPM) and low torque (20 Nm), which will be purchased from magtrol.com. The other torque transducer is TMHS 311 for low speed (32,000 RPM) and high torque (100Nm), this equipment will be purchased from the same website.

The steel to construct the base frame will with be purchased from metalsdepot.com. The shipping time will be roughly 7-10 business days. This order will be of four pieces of 6 feet steel tubing (2”x2”x1/4”) which prices at $171.12. In case the team needs additional steel tubing, they can likely use from the supply of steel that the client company keeps in their machine shop. Because of this, it will save down time that could occur while waiting for shipped materials. Additional steel will also be ordered from metalsdepot.com. This will be a 2’x2’ pieces that will cost $46.64.

Before the team order any component Turbocor have to approve the purchase, they will be provided with information about the model that is needed, an explanation about why is needed and where from we want to purchase the component.

C. GANT CHART & RESOURCE ALLOCATION

The Gantt chart for the end of fall semester, winter break and the beginning of spring semester is split into ordering the components, starting the assembly process and evaluate the design efficiency. The next step for team it is to define the quantity of material that is going to be needed to build the mounting base stand and also define the number of shims for the vertical correction – these tasks should be completed until December 10.

Due to the difference of the diameters between the torque transducers and the shaft of the compressor it will be necessary two rigid couplers to adapt to these diameters – until December 10 the design of this component should be done. The pricing of all the components must be defined by the same date to facilitate the ordering process.

The safety shield needs to be designed and ordered by January 11 so in the next week (January 18) it is possible to assembly the frame with the steel acquired. Also in this week the assembly will begin to be considered for the shims, couplers, torque transducers, laser alignment tool and the safety shield. To evaluate properly all the assembly processes, tests will be conducted from January 27 and on so finally on February 3 additional parts can be ordered.

The final assembly is expected to be complete by February 10 so it will be possible to start conducting tests from February 15 and on. Due to the possibility of unpredictable errors or obstacles, these dates are all subject to change.

To help in the developing process of the project there are several of resources available for the Senior Design Team 4. The team has to deal and manage different kind of resources. Classify and stipulate how the team will manage this resources in order to achieve the results expected for the project it’s a very important part of the Project Management. Essentially, these team resources can be classified as financial, physical and human resources.

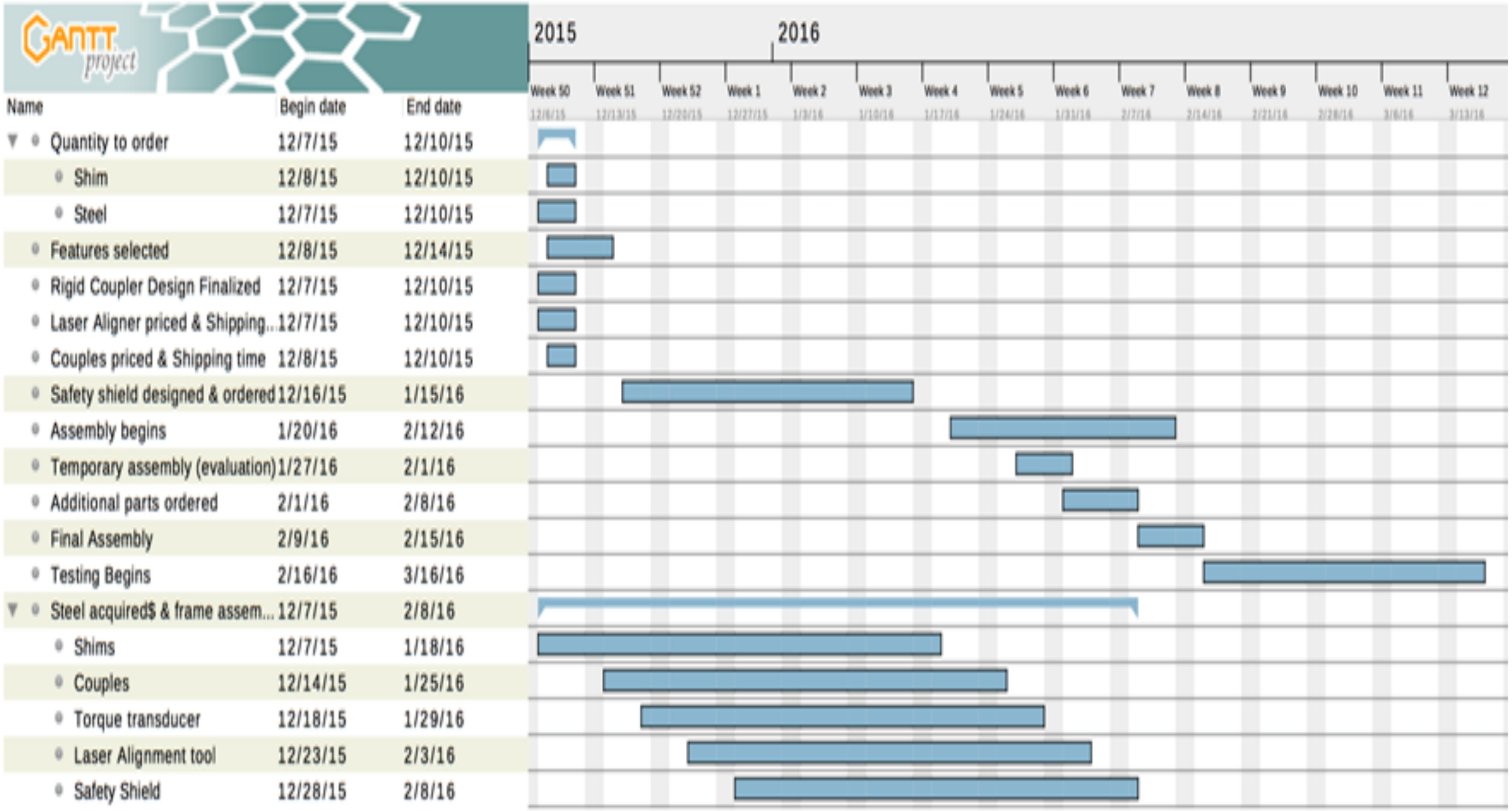

FIGURE 20: GANT CHART FOR TEAM 4

I. FINANCIAL RESOURCES

Turbocor is responsible for providing financial support to the team. Support will be used to acquire equipment, materials, components, and tools and even though the budget is open ended, all expenses must be proven to be beneficial to the project in order to receive financial compensation. It was advised to the team to make educated decisions with purchases to ensure that the expense can be well justified. Up till now, the team is planning to order the components previously stated. These purchases will be made through the coordination with the financial office at the College of Engineering (COE) to ensure proper protocols are followed.

II. PHYSICAL RESOURCES

Turbocor and FAMU-FSU College of Engineering (COE) facilities are available for the team to work on the project. Mainly, the team will work in the Senior Design Lab at the COE, but this facility doesn't have the requirements to fully operate Turbocor's compressors, such as the power supply needed, so the real tests must be done at Turbocor's facilities. Besides the Senior Design Lab at COE, there are other buildings available that can help in the conceptual design phase of the project; one example of that would be the actual test rig that served as a source for the benchmarking process, this test rig is located at CAPS building and it has been extremely useful for the team,

III. HUMAN RESOURCES

The tasks are divided between the team members, even though each member is responsible for a single task the team has to work cohesively in order to achieve the results. The tasks division is represented as following: Matthew is responsible for the communication with sponsors and with our faculty advisor, Dr. Hollis. Francisco is responsible for product ordering and outsourcing. Leonardo is responsible for developing and maintaining the team website. Thyeasha and Durval are responsible for leading the CAD design. On the product design it is necessary to emphasize that all team members will work together to achieve the best results.

A network of people who have technical knowledge to help on the project are also considered as part of the human resources available. Dr. Patrick J. Hollis is the team's faculty advisor, responsible for helping the team to develop design concepts among all other technical concepts. Willian Sun is the team contact in Turbocor, responsible for providing the specifications for the product as well acquiring the equipment requested from the team. Michael Coleman from the CAPS building explains concepts about the test rig that the building has and provides ideas for shaft alignment. Julio Lopez is an engineer at Turbocor and is responsible for providing specifications and technical knowledge about the compressor that the team has and how to work with it. Dr. Shih and Dr. Gupta are responsible for evaluating the overall team project and providing feedback for areas of improvement.

IV. Results

With the results from analysis and research preformed regarding the component design and selection, with respect to the constraints, the team has come to conclusions for the High Speed Motor Test Rig. The overall dimensions of the base frame will be 1.67

meters long, 0.5 meters wide, and 15.24 centimeters high. The frame will be bolted together with 2”x2” square steel tubing with ¼” thick walls. This frame has been proved to be structurally adequate for the project, as proven with the Finite Element Analysis shown in figures 16, 17, and 18. Two torque transducers will be used, a Magtrol TMHS 308 and TMHS 311. These will use different leveling blocks to align them with the compressor shafts. A rigid coupler will be used for the 308 series transducer to step up the shaft diameter size that will fix into the flexible coupler. It will be decided in the next week if the team will buy a rigid coupler from a vendor or design and machine it in house. Two identical flexible couplers from R&W Engineering will be purchased, the BKC 160 series. To align the compressor, the SKF TSKA 31 laser aligner will be used. Vertical alignment increments will be made with shim, and horizontal increments will be made with eight setscrews, four on each compressor. It has not been decided yet which material will be used for safety shielding, once it has been selected, the design for the shield will begin.

V. Conclusion

To satisfy the client company, Danfoss Turbocor, the team has broken the project into these main focuses: base frame, alignment tool, alignment adjustment, couplers, and torque transducers. The accuracy and precision is crucial to the High Speed Motor Test Rig, most effort has been put into ensuring that the flexible couplers will tolerate the maximum misalignment. From the components selected, the team is confident that the design process is nearing an end and can begin acquiring the majority of components starting spring semester of 2016. In the next week, efforts will be made to determine if the team will buy or build a rigid coupler for the test rig. Spring semester will first be focused upon components purchasing then on test rig construction. As construction moves along it may be necessary to make design changes. It is the team’s goal to have the High Speed Motor Test Rig assembled by February 15 to begin to perform tests to maximize the product’s performance.

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